II.4.3 Sensors for Advanced Combustion Systems

Investigators
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Introduction

The objective of our research has been the development of advanced sensors that have the potential to: (1) minimize the environmental impact of energy conversion via control of combustion-generated pollutants such as NO, CO and unburned hydrocarbons; (2) reduce greenhouse gas (CO_2) by improving combustion efficiency; and (3) monitor the fugitive emissions from greenhouse gas sequestration efforts. These novel sensors should enable a new generation of strategies for active monitoring and control of combustion and energy conversion technologies of the future.

During the past year, multiple new sensor strategies have been developed and demonstrated, all based on tunable near-infrared (NIR) diode lasers and absorption spectroscopy. Our longterm goal is to incorporate this new sensor technology into closed-loop control strategies to maximize combustion efficiency and/or minimize key emissions (UHC, CO, and NO). Eventually these sensors should enable active combustion control strategies to suppress combustion instabilities for advanced combustor development.

Our research has focused on three sensor technologies: 1) a robust, rapid-response gas temperature sensor using fiber-coupled laser technology and a combination of scanned-wavelength and wavelength-modulation strategies; 2) a fiber-coupled, wavelength-multiplexed sensor for gas temperature, O_2 and CO suitable for monitoring large-scale coal combustors; and 3) novel fuel sensing strategies for the sensitive detection of unburned hydrocarbons in combustor exhaust and for fast, robust sensing of hydrocarbon fuels as needed for active combustion control of instabilities. These sensors thus offer great promise for monitoring and control of combustion and energy conversion technologies of the future.

Background

Efficiency improvements in large-scale combustors can produce immediate benefits. First, savings on the order of $1M/year in coal accrue for an average 600 MW boiler with an efficiency increase of only 1% with a simultaneous reduction in CO_2 emissions. In the near future, one can envision that CO_2 credit arbitrage will become the norm just as NO_x credit trading occurs today. Second, efficiency improvement can also reduce NO_x emissions, enabling a utility to sell NO credits or avoid expenditures for pollution-control equipment. For the average 600 MW boiler, a 20% NO reduction amounts to elimination of 1800 tons per year of NO_x, which is valued near $4,500,000 at a typical NO_x credit price (varies by state and year). Third, efficiency improvement via complete combustion could improve some of the deleterious conditions that can occur in boilers such as slagging and corrosion, and these improvements will ultimately reduce maintenance costs.

Coal-fired boilers are routinely only tuned or optimized at monthly or sometimes even yearly intervals rather than on a continual basis. There are many reasons for this *laissez faire* situation including a lack of sensors to provide useful information for feedback into the optimization process, antiquated equipment, and a general ambivalence on the part of some utilities. However, this state of affairs is beginning to change. A few companies have developed optimization software that takes current sensor inputs from diverse sources such as oxygen sensors, CEMs measuring pollutants, airflow measurements, and coal loading measurements and optimizes the combustion process. Improvements on the order of 0.5 - 1% for heat rate and 20% NO reduction are routinely attained. However, all information regarding combustion efficiency currently comes from sensors placed well downstream of the boiler. Often these sensors are extractive, which can lead to serious measurement errors if great care is not taken in their installation. One expects that better measurements could be made if sensors were available that would measure combustion parameters directly in the combustion zone without extractive probes. Clearly this presents a challenge due to the extremely hostile environment of the boiler. Optical diagnostics have a significant advantage in this regard since no intrusive probes are required.

Laser-based sensors are *in-situ*, non-intrusive devices, which remotely interrogate the reactive gas/liquid stream and avoid the problems of wall-mounted or extractive sampling sensors in common use. These modern sensors, based on absorption spectroscopy, target specific chemical components and/or local temperature and thus enable novel new control strategies for a wide range of applications.

Tunable diode laser (TDL) spectroscopy for combustion diagnostics have been developed over the past 20 years by a variety of practitioners with much of the pioneering effort performed in our laboratory at Stanford University. Although the majority of this work was done in well-controlled, laboratory-scaled flames, there are some notable exceptions.[1] At Stanford, Furlong et al. performed the first-ever closed loop combustion control with laser sensing. They utilized a wavelength-multiplexed TDL sensor of gas temperature and adaptive control to reduce the CO and unburned hydrocarbon emissions from a 50kW incinerator by more than an order of magnitude.[2] Recently in Germany, Teichert et al. demonstrated quantitative detection of CO, H_2O concentration and temperature in a coal-fired utility boiler using a multiplexed-wavelength laser sensor,[3] although no effort was made at combustion control. Similarly, in Japan, Deguchi et al. measured CO and O_2 concentration in a waste incinerator.[4] Finally, our research group at Stanford has demonstrated quantitative species detection and temperature measurement in a variety of realistic aerospace combustion applications including pulse detonation engines, SCRAMJET combustors, and gas turbine combustor sector test rig using multiplexed wavelength laser sensors.[5,6]

Results

During the past year, we have made significant progress on three different TDL sensor technologies, all with good potential for combustion control applications: 1) a rapid response gas temperature sensor, 2) a fiber-coupled, wavelength-multiplexed sensor for gas temperature, O_2, and CO suitable to monitor large-scale coal combustors, and 3) novel fuel-sensing strategies.

a. Rapid-response gas temperature sensor

A diode-laser sensor system has been developed for non-intrusive measurements of gas temperature in combustion systems using a combined scanned-wavelength and wavelength-modulated strategy with 2f detection. The sensor is based on a single diode laser (distributed-feedback), operating near 1.4 microns and scanned over a spectral range targeting a pair of H_2O ro-vibrational transitions. The single-fiber-coupled-laser design makes the system compact, rugged, low cost and simple to operate. Gas temperature is inferred from the ratio of the second harmonic signal of two selected H_2O transitions.[7] The sensor design includes software for fast data acquisition and analysis to provide rapid temperature measurements, and a temperature readout rate of 2.5 kHz has been demonstrated for measurements in a C_2H_4/air laboratory flame at atmospheric pressure. The combination of scanned-wavelength and wavelength-modulation avoids interference from emission and provides a robust temperature measurement that is useful for combustion control applications.

Water is a primary combustion product and its prevailing and relatively strong absorption spectra in the near-infrared region make it an ideal species for temperature measurement. By suitable choice of laser wavelength it is possible to measure temperature using a single diode laser. The use of a single diode laser greatly simplifies the sensor system and reduces cost compared with wavelength-multiplexing techniques developed previously in our laboratory.

In an earlier study we showed that temperature inferred from water vapor is a good control variable for complete combustion and reduced emissions in a forced vortex incinerator [2]. Optimal selection of specific water vapor absorption features is an important step in sensor design. Figure 1 shows a segment of the calculated H_2O (10%) spectra near 1.4 μm based on HITRAN parameters and a pressure of 1 atmosphere. This pair of features (7154.354cm^{-1} & 7153.748 cm^{-1}) is selected for several reasons. Most importantly, both features are well resolved at one atmosphere pressure avoiding interference by neighboring transitions, and both features have similar absorption coefficients and thus will have similar measurement uncertainty. Additionally, these two features have sufficiently different lower state energy E" to yield a high temperature sensitivity; the E" values of 1789 cm^{-1} and 2552 cm^{-1} insure that the transitions will be strongest at temperatures much larger than room temperature while their relatively weak absorption at room temperature minimizes interference from ambient air in the measurement path. The selection of these two transitions offers the opportunity to simplify the equipment needed for a practical combustion temperature sensor.

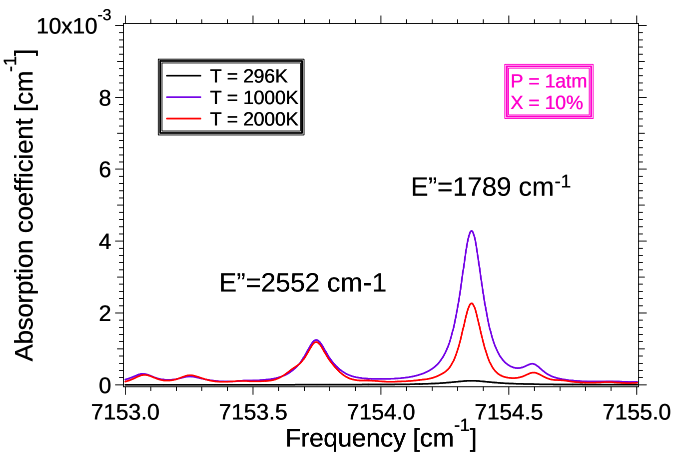

Figure 1: Calculated spectroscopic features for water (10%) line pair near 1.4μm based on HITRAN parameters.

It was necessary in our research to measure the needed spectroscopic parameters in a heated cell (including line strengths, line center frequencies, broadening coefficients and lower state energies). Discrepancies were found between our measured quantities and the database known as HITRAN, hence our research has already yielded important contributions toward an accurate scientific database for water vapor spectroscopy.

Though the 2f peak height depends on many parameters such as linestrength, mole fraction, pressure, laser intensity, and lock-in settings, etc., the 2f peak ratio of two transitions can be made equal to the linestrength ratio by optimizing modulation depths. [7] Example results confirming the accuracy of this proposed method are shown in Fig. 2. Note that the individual data points, obtained with different values of 2f modulation depths (denoted by 'a') agree very closely with the simple linestrength ratio.

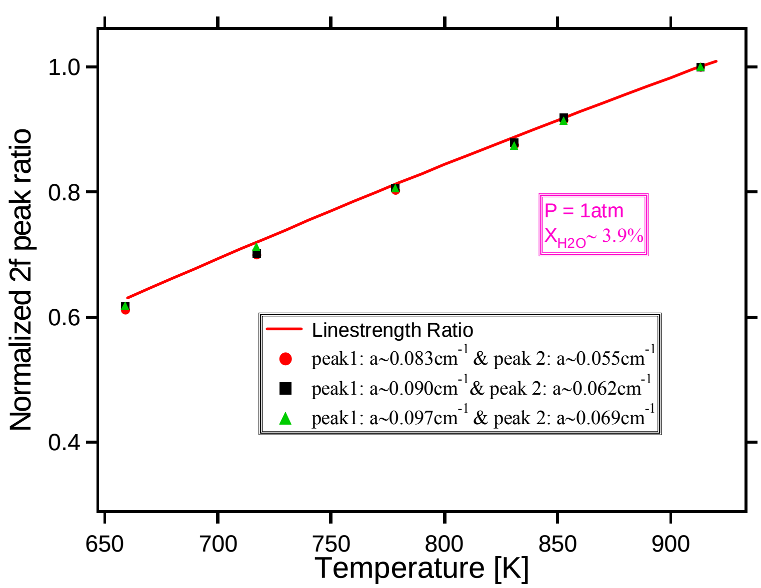

Figure 2: Normalized 2f peak ratio versus temperature.

Figure 3 illustrates the general arrangement of experimental setup for the 2f- single-laser sensor. Light from the DFB diode laser is coupled into a single optical fiber and directed across the Hencken laboratory burner. The wavelength of the laser is scanned across the spectral region of interest at a repetition rate of 2.5 kHz; superimposed on this is a small modulation at f=100 kHz. The ratio of the absorbance for the two water vapor absorptions provides 2.5 kHz temperature measurements. Combustion instabilities can be identified from the gas temperature measurement. Temperature fluctuations in the Hencken burner are induced by modulating fuel flow through a speaker to mimic the expected response from combustion instability. The Fourier transform of a time series of gas temperature clearly identifies the dominant and harmonic modes of the temperature fluctuations. The results obtained demonstrate the utility of this sensor for quantitative, accurate identification of temperature fluctuations needed for combustion control.

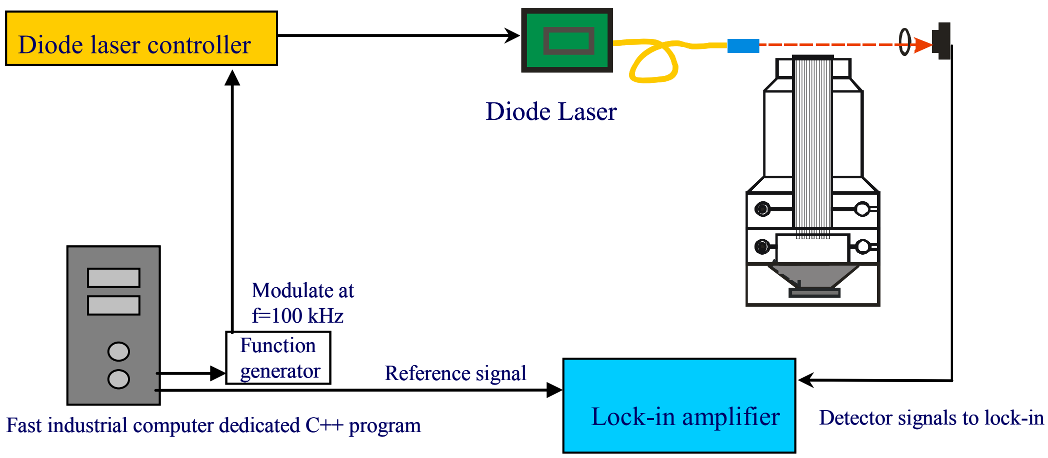

Figure 3: Schematic of diode laser based T sensor in a laboratory flame.

b. Wavelength-multiplexed TDL sensor for T, H_2O, O_2, and CO in large-scale combustors for electric power generation

We have teamed with Zolo Technologies to design a wavelength-multiplexed diode laser sensor for application in a coal-fired electric utility combustor. A wavelength-multiplexed sensor using optical fiber technology allows the lasers, control electronics, detectors, and data acquisition to be remotely located in the control room of the utility far from the harsh environment of the combustor. The fiber-based sensor is possible because of a unique wavelength-multiplexer technology developed by Zolo Technology for the telecommunications industry. The sensor illustrated in Fig. 4 combines light from five individual diode lasers into a single fiber for delivery to the combustor. The transmitted light is collected into a multimode fiber and returned to the control room where a second Zolo device disperses the light onto separate detectors. Each beam monitors the absorption on a different segment of the spectrum. Light near 760nm is used to monitor oxygen, near 1559 nm for carbon monoxide, and three regions between 1350 and 1400 nm are used to monitor multiple absorption features in water vapor. Temperature is determined by ratios of the water vapor absorption. In addition to the lasers, the demonstration sensor shown in Fig. 4 included a multiplexer, transmission optics, receiver optics, a demultiplexer, detectors, and a signal digitization and processing system. The switch allows the beam to serially probe multiple spatial locations using the same laser source and detection system.

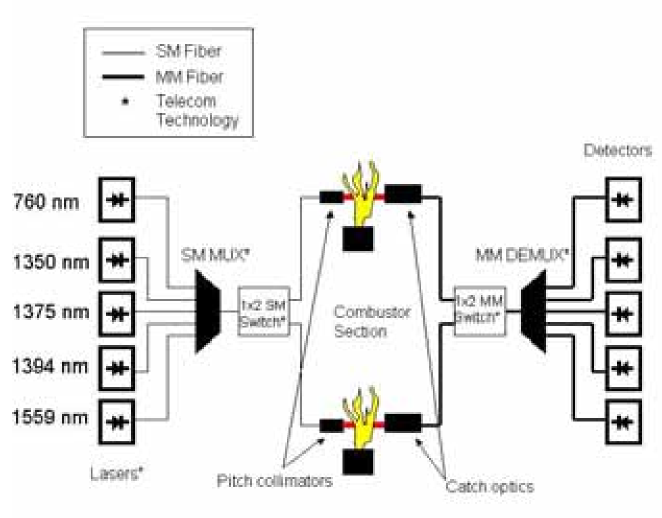

Figure 4: Schematic diagram of wavelength-multiplexed TDL sensor using a Zolo Technologies multiplexer/demultiplexer.

A preliminary measurement campaign was conducted with this prototype Zolo/Stanford sensor at the Valmont Station, Boulder, Colorado coal-fired electric utility. The tangentially fired boiler ran at full load burning Powder River Basin (PRB) coal and produces 220 MW of electricity. Two measurement positions were located ~ 10 meters and ~ 13 meters above the coal injectors. In spite of significant transmission losses due to obscuration by coal dust and fly ash (average transmission = $1–5x10^{-4}$ ten meters above the coal injectors over a 15 meter path), we were able to measure temperature and monitor the target species with a typical signal to noise shown in Fig. 5. Several such scans in multiple wavelength regions are analyzed to determine temperature.

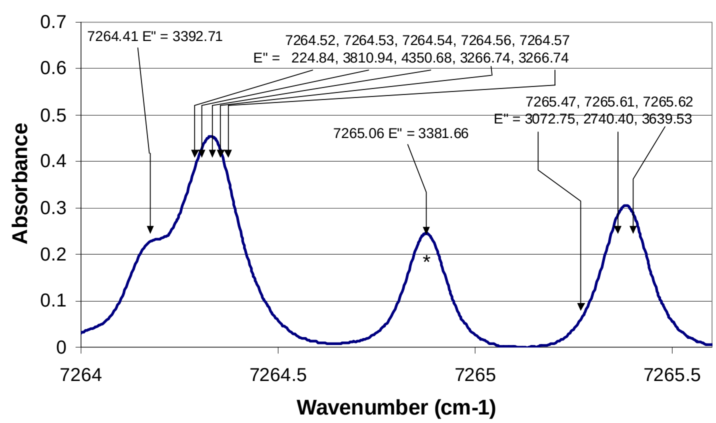

Figure 5: Experimental wavelength scan encompassing several water absorption features in the 1376 nm spectral region.

This work represents several notable accomplishments including the first use of an all-fiber-coupled device for measurements on a coal-fired boiler and the first simultaneous detection of three species (CO, H_2O, and O_2) and temperature in a coal-fired utility boiler. The good signal-to-noise illustrated in Fig. 5 can be collected on each laser channel in less than 100 ms; and high quality operation point control signals can be reported at 3 second intervals. This measurement bandwidth is much faster than any actuation strategies for a combustor of this size. Thus, this sensor offers excellent potential to as part of a control system for closed-loop optimization of the power plant combustor.

c. Fuel sensor development

Modern combustion control strategies require fuel sensors for two different applications: 1) sensitive detection of unburned hydrocarbons in the combustor exhaust and 2) measurement of local fuel/air stoichiometry in the combustor. Although the smallest fuel molecules CH_4, C_2H_2, and C_2H_4 have rotationally-resolved (or near-rotationally-resolved) spectra at one atmosphere, optical detection of most hydrocarbon fuels is complicated by the broad, unstructured infrared absorption spectrum as illustrated in Fig. 6. Therefore, the sensing of fuel is not as well developed as is the sensing of O_2, CO, or H_2O. During the past year, we have investigated the potential for detection of C_2H_4 and C_3H_8 using tunable near-infrared laser light, and fixed-wavelength absorption in the mid-infrared for a variety of practical fuels.

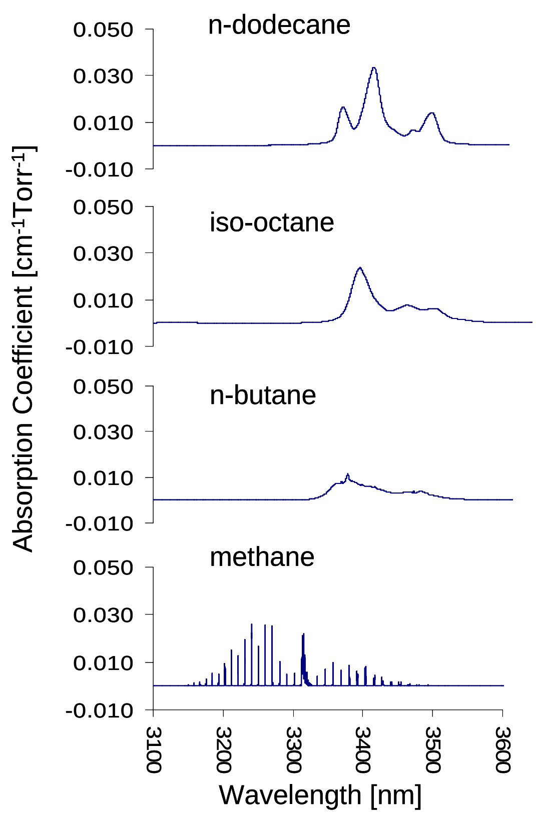

Figure 6: Example absorption spectra for hydrocarbon fuels.

The mid-infrared does not have the robust, inexpensive laser and fiber technology available in the near infrared. Therefore our choices are limited to available fixed wavelength lasers. The HeNe laser at 3.39 μm is readily available and provides a stable laser source to investigate sensitive strategies for hydrocarbon fuel detection. During the past year we have built a heated flow cell with mid-infrared optical access to quantify the temperature dependence of the 3.39 μm absorption coefficient over the range of temperatures expected in a variety of practical propulsion combustors.

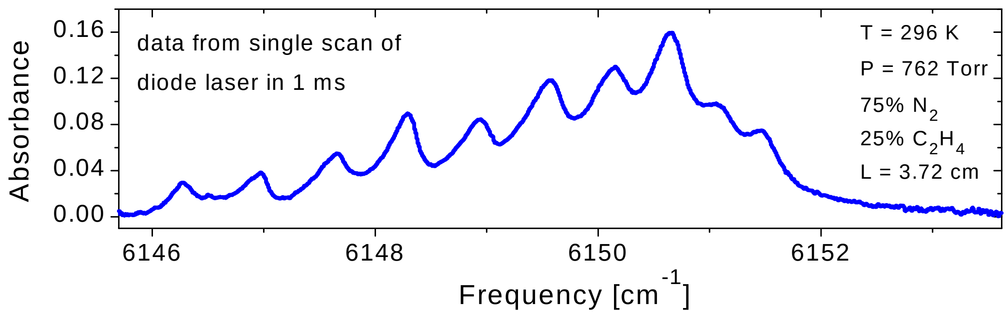

Figure 7: Segment of the C_2H_4 spectrum in the NIR at atmospheric pressure.

The near-infrared absorption of C_2H_4 provides an opportunity to develop TDL sensors for fuel to test control strategies in the anticipation of new mid-infrared laser sources for practical fuels. During the past year we have investigated a novel differential absorption strategy to measure C_2H_4 fuel concentrations, and Fig. 7 shows the segment of the C_2H_4 spectrum used. We are now prepared to monitor C_2H_4 in a swirl-stabilized laboratory flame.

Progress

Good progress has been made toward development of a new class of combustion sensor, based on TDL absorption spectroscopy, for active and operating point combustion control. Scanned-wavelength and wavelength-multiplexed sensors have advanced to a stage of readiness for combustion control demonstrations. Exploratory measurements in a large-scale coal fired power plant suggest that efficiency improvements of 1-3% may be feasible with simultaneous reductions in CO_2 and NO_x emissions. The economic and environmental consequences of such improvements are very large.

Control of combustion using feedback from advanced fast-response sensors has the potential to minimize the environmental impact of energy conversion; for example, lean, premixed firing of gas turbines can significantly reduce NO_x emissions. However, lean, premixed flames are sensitive to instabilities and prone to flame blow-out or flashback. Active combustion control of the pressure fluctuations leading to these failures could decrease the current large safety margin and thereby reduce the flame emissions. Similarly, emissions from coal-fired utility boilers are the focus of increasing scrutiny. Early emphasis on reduced emissions of NO_x and SO_x is now being coupled with a desire to reduce CO_2 emissions. These goals can be simultaneously achieved by improving the efficiency of the combustion process in the boiler. In general, coal-fired boilers are poorly controlled devices with tuning or optimization occurring at monthly or yearly intervals rather than on a continual basis. Here operating point control could be used to alter the local fuel/air ratio and provide continuous flame optimization to improve overall system efficiency.

Future Plans

Measurements are planned to investigate the use of the rapid-response temperature sensor for closed loop control of a swirl-stabilized laboratory flame. Here we are poised to investigate the feasibility and potential for active combustion control of instabilities in an important practical class of combustors, i.e. gas turbine combustors.

Measurements to demonstrate the use of the wavelength-multiplexed sensor to optimize coal-fired power plants are underway with our industrial partner, Zolo Technologies. Here there is significant potential to bring modern operating-point control to the coal-fired production of electricity.

The development of a new class of fuel sensors is only now emerging, however these sensors may also offer high potential for combustion control

Publications

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