Smart Sensors for Advanced Combustion Systems

Investigators
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Introduction

This research is directed at the development and application of a new class of optical sensors, based on absorption of light from tunable diode lasers, which enable *in situ* measurements of temperature and gaseous composition, in real time and in a variety of research-oriented and practical energy-conversion systems. These sensors have significant potential to enable exploratory research on new energy conversion concepts, to expedite the pace of development of new combustion technologies with reduced pollutant and greenhouse emissions, and to facilitate gains in performance (reduced greenhouse emissions and reduced maintenance) in existing combustion systems. In addition, the real-time capability of these sensors will enable explorations of new, unsteady energy-conversion schemes with the potential for reduced emissions through real-time control.

This report highlights three important accomplishments: First, a novel multi-wavelength sensor based on tunable near-infrared diode lasers (TDL) has been developed that enables simultaneous measurements of temperature and the concentrations of water vapor, oxygen, and carbon monoxide. This sensor is capable of use in large-scale stationary combustors used for power generation and was successfully demonstrated in two coal-fired power plants during the past year (in collaboration with colleagues at Zolo Technologies). The facility in Colorado is illustrated in Fig. 1.

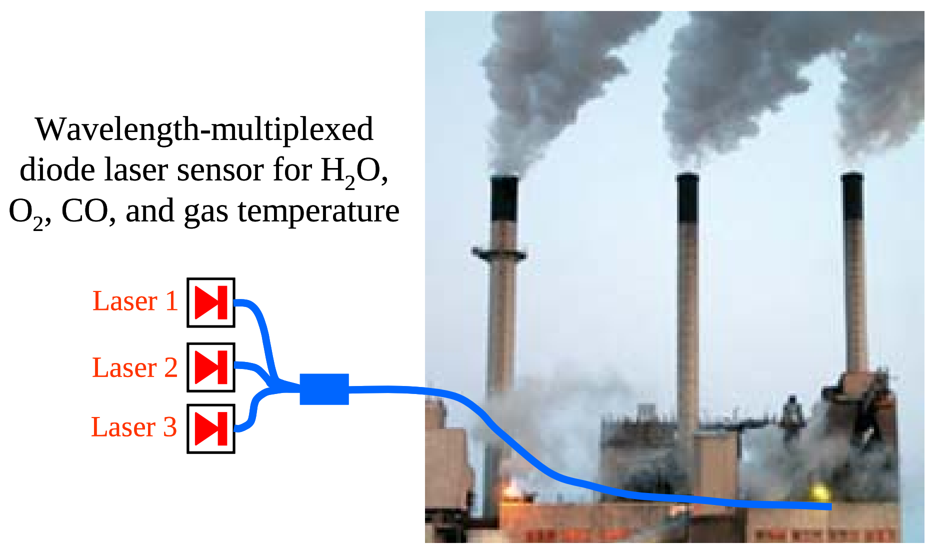

Figure 1: 220 MW, coal-fired power plant in Valmont, Colorado, where tunable diode laser measurements of gas temperature were made. Successful measurements were made with less than 1% optical transmission.

Unique information was obtained on the spatial and temporal variations of species and temperature in this large-scale energy-conversion system, revealing significant potential to improve efficiency (hence reducing fuel usage and greenhouse emissions) as well as to reduce maintenance costs. Plans are now being developed to allow installation of a sensor system to demonstrate long-term performance and to promote development of control algorithms which will capitalize on the TDL sensor to improve overall combustion performance.

Second, a compact, rapid-response TDL sensor has been developed for *in situ* measurement of temperature in an internal combustion engine. The sensor is based on absorption of light by water vapor (naturally present in air and in re-circulated exhaust gas). The work (collaborative with the University of Michigan and the Combustion Research Facility at Sandia National Laboratory) is motivated by the critical importance of temperature in the development of next-generation combustion strategies, such as HCCI (homogeneous charge, compression ignition) for internal combustion engines.

Third, a novel diode laser sensor has been developed enabling real-time, *in situ* measurements of temperature, unburned fuel, and combustion products (water vapor and carbon dioxide) in a liquid-fueled combustor relevant to gas turbine engines. This sensor has provided the first real-time, continuous measurements of these parameters in a liquid-spray combustor, thereby allowing real-time Fourier analysis of the frequency content of combustion instabilities. Such information is likely to prove critical in control strategies aimed at extending the operating range of gas turbine combustors to lower equivalence ratio where pollutant and greenhouse emissions are reduced.

The accomplishments highlighted above serve to illustrate the high potential of **smart optical sensors** to impact both research and practice of energy-conversion systems. Our goal is to reduce greenhouse emissions in two ways: (1) by enabling improved performance of existing systems, such as stationary power plants and internal combustion engines, while (2) also contributing to research on new energy-conversion schemes, such as pulsed combustors and fuel cells, where real-time *in situ* sensing of critical parameters will hold a key to proper understanding and optimization of such systems. We hope to increase the leverage of our research in the future by building partnerships with other groups focused on development of new energy conversion schemes with potential for reduced greenhouse emissions.

Background

The Stanford University research on **smart optical sensors** investigates a unique sensor strategy that exploits the use of wavelength-multiplexing to combine the beams from multiple diode lasers onto a single path as shown in Fig. 2. The optical absorption signal expected in a practical combustion application is modeled using laboratory-validated quantitative spectroscopic constants. These models enable selection of the optimum molecular transitions from the tens of thousands of potential candidates. The combination of process and spectroscopic modeling enables the design of smart absorption-based sensors tailored to the specific combustion application. This sensor design strategy is quite different from that used by past researchers.

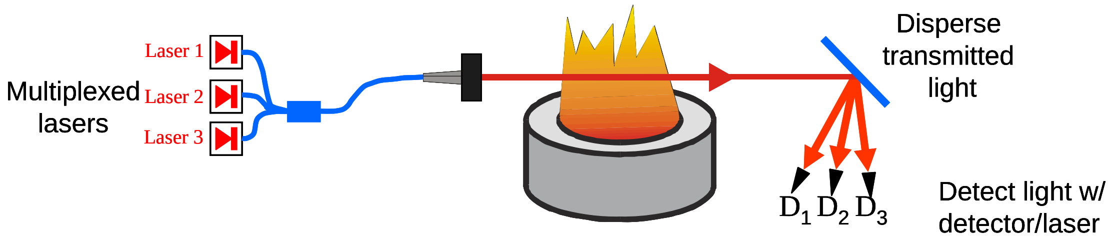

Figure 2: Wavelength-multiplexed absorption concept for **smart optical sensors**.

Tunable diode laser-based 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-scale 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, Ebert et al. demonstrated quantitative detection of O_2 and CO concentration in a rotary-kiln hazardous-waste incinerator using a multiplexed-wavelength laser sensor [3], although no effort was made at combustion control. In Japan, Deguchi et al. measured CO and O_2 concentration in a waste incinerator [4] and more recently in a coal-fired boiler. However these past researchers have utilized free-space propagation of the laser beams as opposed to the fiber optics approaches now used by the Stanford group. We believe our use of fiber-optics is a critical distinction that will enable practical implementation of our sensor technology in industrial applications.

Other researchers at PSI and Air Liquide have applied diode laser absorption to combustion sensing using a broad-scanned-wavelength approach where a single diode laser is tuned over transitions of H_2O, CO, and CO_2 [5]. They have recently applied this for gas temperature and composition sensing in metal smelting applications. The spectral region with overlapped transitions is not optimum for any of the target species and the laser must be slowly tuned over the full range. Thus, this type sensor is only capable of a measurement rate of a few Hz, which is too slow for the combustion control applications envisioned below, which we believe will enable new combustion technologies with lower emissions load on the atmosphere.

During the past year, we also collaborated with researchers at GE Research Laboratories to design a sensor for post-turbine gas temperature measurements in a portable power plant [6]. The Stanford **smart optical sensor** design approach was used to choose laser wavelengths to determine gas temperature from measurement of the ratio of absorption in two water vapor transitions. The laser sensor provides the potential for much faster measurement rates than was feasible with previous instrumentation.

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 fiber-coupled, wavelength-multiplexed sensor for gas temperature, O_2, and CO suitable to monitor large-scale coal combustors, 2) a tunable diode laser (TDL) absorption sensor for crank-angle-resolved in-cylinder temperature measurements, and 3) a rapid response gas temperature sensor for application in spray combustion environments. All three of these sensors have the potential for **smart combustion control** targeted at reducing the atmospheric CO_2 and NO_x load from conventional combustion sources.

Multi-wavelength TDL sensor for large-scale combustion applications

A wavelength-multiplexed diode laser absorption sensor was designed to detect combustion product water vapor in a coal-fired power plant. This environment offers significant challenges for such measurements, and the bright emission from the particulate-laden coal flame is evident in Figs. 1 and 3 from the Valmont, Colorado power station. Particulate scattering in the long optical paths nearly block the laser transmission. However, wavelength scanning techniques have enabled successful and accurate absorption measurements even when less than 1% of the laser light is transmitted across the 13 m path in the combustor. Our wavelength-multiplexed design approach enables the selection of optimum transitions for the measurement conditions. The long optical paths require the selection of relatively weak absorption transitions to optimize the signal-to-noise determination of optical absorbance. Optical access to the combustor is often out-of-doors, and the use of optical fiber to route the light to and from the combustor has allowed isolation of the laser and detection electronics far from the measurement location. We have teamed with a small company, Zolo Technologies, who developed fiber-coupled laser multiplexing and de-multiplexing technology for the telecommunications industry, to make these pioneering measurements based on our smart sensor concepts.

Figure 3: Adjustment of the optical collection near an access port used for preliminary measurements. Note the bright emission from the hot particulate coal and soot is evident. Successful wavelength-tuned sensor measurements are made even though this particulate limits the optical transmission to less than 1%.

Figure 4 shows a time-resolved measurement of gas temperature from the 280MW coal-fired power plant at TVA, and illustrates the influence of weather on the operating conditions inside the combustor. These real-time measurements illustrate the potential for control of these practical flames to improve efficiency and reduce the atmospheric load of combustion effluent. The high sensitivity of the sensor is evident in the temperature record, which revealed the 25K change in combustion gas conditions upon the onset of a thunderstorm. The influence of the wet coal fuel persists for several hours.

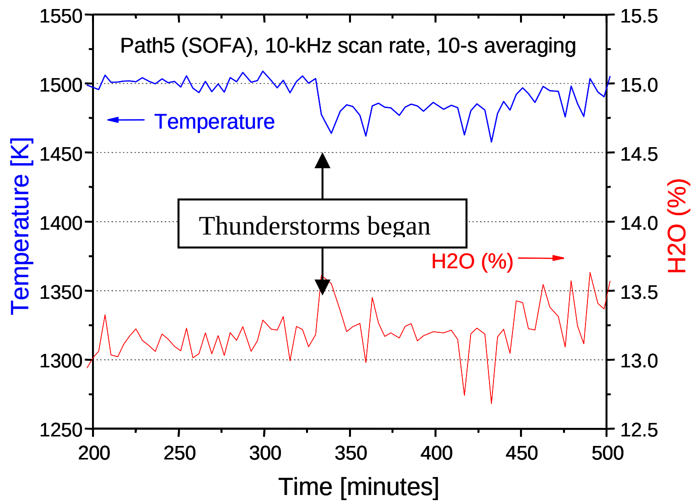

Figure 4: Gas temperature and water vapor concentration in the coal combustor of a 280MW power plant at full load, and illustrates the influence of weather on the combustion gases.

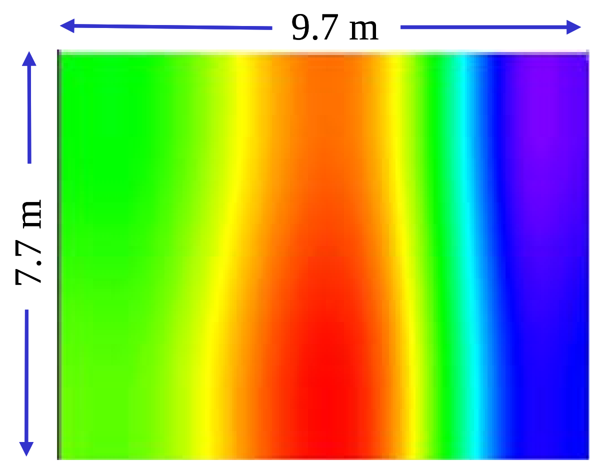

Figure 5: Coarse tomographic reconstruction of the temperature field (max 1528K (red) and minimum 1425K (blue)) at a location 10 m above the 280MW combustor at the position for injection of secondary over-fire air.

A longer-term goal of this sensor is to enable spatially resolved measurements though tomography. Figure 5 shows the temperature field extracted by coarse tomography from temperature in the combustor using multiple lines-of-sight (first ever from diode laser absorption in a coal combustor). This temperature field is reconstructed from only six measurement paths (2x4 grid), and illustrates the potential to recover small temperature variations from a relatively small number of measurements. From data such as shown in Fig. 5, the fuel distribution in the combustor can be tuned to account for variations due to weather, atmospheric conditions, changes in coal energy content, and other power plant and environmental variations. Currently coal power plants are tuned infrequently, and this near-real time adjustment could improve operational efficiency 1-2%, resulting in enormous savings of energy and atmospheric load of combustion effluent.

TDL sensing of crank-angle-resolved in-cylinder temperature

Innovative combustion concepts offer the potential of internal combustion engines with improved efficiency and lower pollutant emissions. The development of real-time sensors for gas temperature for in-cylinder measurements would provide critical new tools to perfect these advanced combustion concepts, as temperature is a primary determining factor in combustion chemistry, e.g. for engine cycles of current interest based on homogeneous-charge-compression-ignition (HCCI). Figure 6 illustrates our vision of a fully instrumented research IC-engine, where measurements of fuel, air, and temperature are made in the intake manifold; fuel air, residual gas, and temperature in-cylinder, and unburned fuel and pollutants in the exhaust manifold. During the past year, measurements to realize this vision have begun. Initial proof-of-concept measurements were made in an optical engine at the University of Michigan. These preliminary measurements showed that humid intake air provided sufficient water vapor concentration for crank-angle-resolved measurements of temperature and water vapor concentration. Stanford design rules were used to select the optimum water vapor transitions for this fiber coupled wavelength-multiplexed sensor. A prototype sensor was assembled and test measurements performed in heated cells and shock-heated gases to validate the sensor performance. We believe this TDL sensor has significant potential to facilitate research and development of advanced concept, high-efficiency, low-emission engines. Work is now in progress to install this sensor in a research engine at Sandia National Laboratory in Livermore, CA.

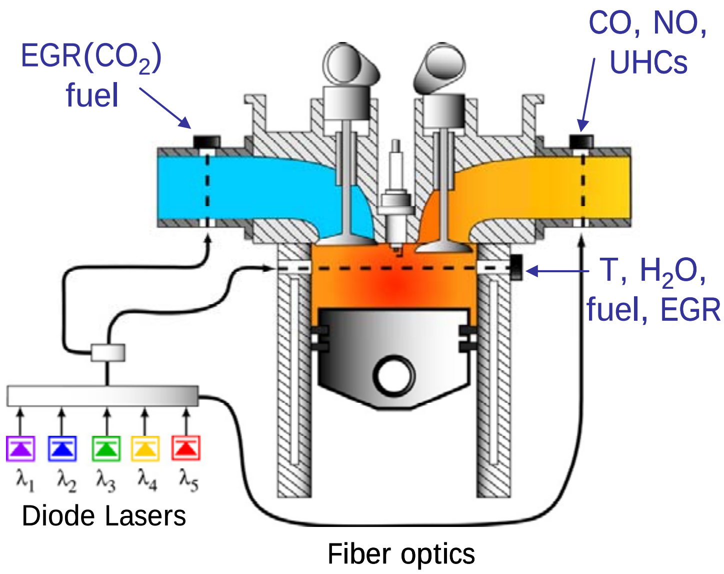

Figure 6: Vision of diode-laser-based sensors for the intake manifold, in-cylinder, and the exhaust manifold of an internal combustion engine.

Real-time temperature measurements for combustor control

We believe there is a critical need and opportunity for a real-time temperature sensor that could provide *in situ* measurements in liquid-fueled gas turbine combustors, e.g. as part of a control scheme to enable operation at fuel-lean conditions near the blow-out (stability) limit. Such a device could enable significant increases in combustion efficiency and hence reduce greenhouse emissions. Hence we have pursued development of a TDL sensor using a novel scanned-wavelength technique with wavelength modulation spectroscopy (WMS) and 2f detection. The sensor is based on a single diode laser, operating near 1.4 μm and scanned over a spectral range targeting a pair of H_2O absorption transitions (7154.354cm^{-1} & 7153.748 cm^{-1}) at a 2 kHz repetition rate. Stanford design rules were used to select these two transitions from more the approximately 1000 absorption transitions of water vapor in the HITRAN database [7] between 1μm and 2μm that have sufficient absorbance (10^{-3}) for precise measurements using WMS. These design rules were further used to reduce the number of potential absorption features to four line pairs. Experiments were then performed to evaluate the quantitative spectroscopy, and the most favorable line-pair was then selected.

This new laser sensor was scanned in wavelength over the two absorption features at a 2 kHz rate and the wavelength was simultaneously modulated at 500kHz; the 2f component of the absorption signal was detected at 1 MHz. Gas temperature is inferred from the ratio of the second harmonic signals of the two selected H_2O transitions. The fiber-coupled-single-laser design makes the system compact, rugged, low cost and simple to assemble. The sensor design includes considerations of hardware and software to enable fast data acquisition and analysis; a temperature readout rate of 2 kHz has been demonstrated for measurements in a laboratory flame at atmospheric pressure illustrated in Fig. 7.

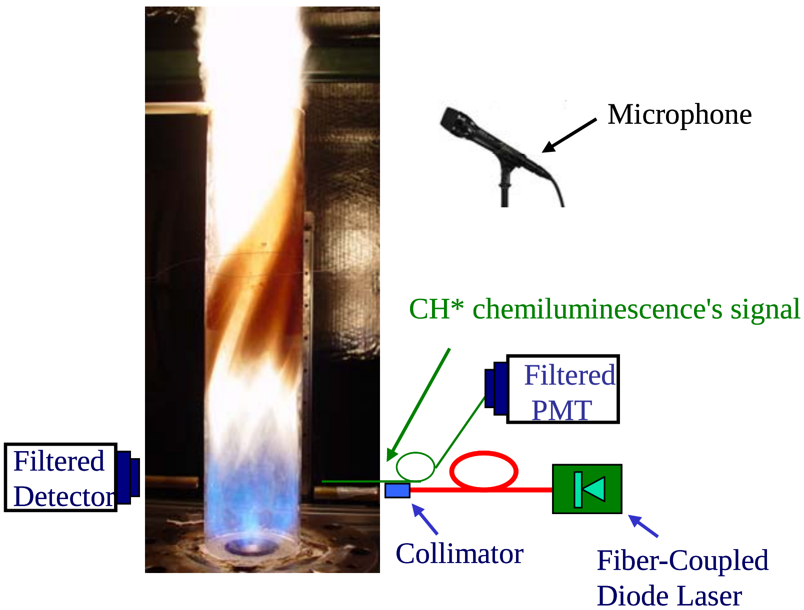

Figure 7: Wavelength-scanned WMS gas temperature sensor and a swirl-stabilized ethanol flame.

The combination of scanned-wavelength and wavelength-modulation minimizes interference from emission and provides a robust temperature measurement that should prove useful for combustion control applications and particularly to extend the operating range of liquid-fueled combustors to leaner (i.e. lower fuel-air ratio) operation.

Figure 7 shows the sensor set-up for measurements in a swirl-stabilized laboratory flame operated on ethanol fuel. The bright yellow emission indicates the formation of soot in the flame. The time-resolved gas temperature is shown in Fig. 8, along with the power spectrum of the time-resolved temperature data, which is able to reveal a large-scale flame instability at 350 Hz. Even though the average temperature shown in Fig. 8 is relatively constant (as would be measured with thermocouples), the fast time-resolution enables real-time calculation of a power spectrum, clearly capturing the $60K_{rms}$ temperature fluctuation at 350 Hz. These data confirm that this sensor has potential for real-time combustion control applications, and work is underway to investigate the use of the sensor to identify lean-blow-off and control instabilities illustrated in Fig. 8.

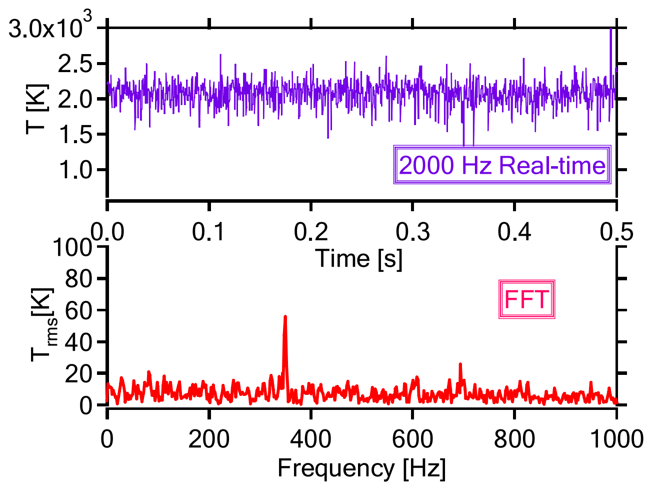

Figure 8: Real-time gas temperature measurements at 2kHz (top panel). Power spectrum of temperature data captures frequency of flame instability (lower panel); flame instabilities limit the practical implementation of low NOx industrial burners.

Progress

During this program, the development of our smart optical sensors has evolved from initial concept, to laboratory evaluation, to demonstrations in practical combustion environments. Our measurements in coal flames are the most mature, and we have now collaborated with a small company to install these sensors in active power plants. Demonstration measurements have occurred in two coal fired power plants (Boulder, Colorado and the TVA Authority in Tennessee). The proof-of-concept measurements for time-resolved gas temperature were successful and coarse tomography was used to provide a temperature field inside the combustor. Measurements are underway to validate and demonstrate simultaneous measurements of oxygen and carbon monoxide. This sensor has the potential improve the efficiency of current power plants by 1-2%, resulting in the short term reduction in the combustion effluent deposited in the atmosphere.

Our concepts for in-cylinder sensing in piston engines have been demonstrated in a laboratory test engine at the University of Michigan. Based on the success and lessons learned from this demonstration a second generation sensor has been designed and experiments in an engine at the Combustion Research Facility of Sandia National Laboratories are planned.

Finally, our development of a real-time 2 kHz gas temperature sensor based on water vapor absorption has provided a new tool to allow study of **smart combustion control.** This sensor has been validated in our laboratory swirl-stabilized flame and has good potential for applications to combustion control. Furthermore this sensor should find use in research on advanced combustion concepts with the potential for reduced atmospheric emissions.

Future Plans

Quantitative measurements of fuel are crucial to combustor development and combustion control applications. Earlier in the project we investigated the potential of fuel sensing in the mid-infrared and concluded that a wavelength tunable light source near 3.3μm was needed. We have contracted to have such a specialty light source fabricated and anticipate delivery in the next few weeks. This diode laser-based light source uses difference frequency mixing to provide tunable light for hydrocarbon fuel sensing. Our first measurements are anticipated to be on gasoline for internal combustion engine applications. The ability for combined in-cylinder sensing of fuel, water vapor, and temperature will allow us to realize our vision of a multiplexed optical sensor of broad use in the development of advanced-concept transportation engines. Such advanced engines could realize enormous reductions of atmospheric pollution from transportation sources. We expect to propose further sensor research based on this unique laser source.

Measurements to demonstrate control in a laboratory swirl-stabilized flame are also planned. We anticipate using our real-time temperature sensor to sense lean-blow-off (an important gas turbine engine problem) and incipient acoustic instabilities (an important problem for low NOx turbine driven electric power sources).

Publications

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