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.

The societal impact of improvements in efficiency of existing fossil-fuel infrastructure can be very substantial. According to the International Energy Agency’s 2002 World Energy Outlook, renewable energy sources (including hydro) provided about 5% of the world’s energy use in 2000, and they project the growth in renewables to barely keep-up with the growth in demand providing 6.5% in 2030. The energy market penetration by hydrogen is even smaller, with an estimate that hydrogen technology might provide 0.01% of the world’s electricity in 2020, which might grow to 1% in 2030. The tiny penetration of the renewable and hydrogen fuels into the US marketplace means that incremental improvements to existing fossil fuel use has a bigger impact than huge changes in renewable or hydrogen fuel use. Thus, if we can develop sensors that would improve fossil fuel use by 5% it would be an equivalent impact to energy imports to doubling the use of renewable fuels. Similarly a 1% improvement in fossil-fuel efficiency is predicted to have the same reduction in atmosphere loading of CO_2 as the doubling of the predicted use of hydrogen fuels in 2030. Given the huge fossil-fuel infrastructure, it is clear that incremental improvements in fossil-fuel utilization will have the biggest impact on the atmosphere for the next thirty to fifty years. New laser-based fuel sensors have the potential for significant improvement in efficiency for large-scale power plants and for IC-engines used for transportation and are the focus of this GCEP sponsored work.

This report highlights three important accomplishments: First, 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. The results from these successful demonstration experiments have been accepted for presentation at the 31st International Symposium on Combustion in August of 2006[1], the world's most prestigious forum to report advances in combustion science and engineering.

Second, a novel diode laser sensor using water vapor absorption has been developed for real-time, *in situ* measurements of temperature in a swirl-stabilized combustor relevant to gas turbine engines. If gas turbines can be operated closer to their fuel-lean limit, their production of pollutant NOx and system maintenance can be reduced. Although the gas composition and temperature are not uniform along the line-of-sight, we demonstrate that the low-frequency components in the FFT power spectrum of the sensor signal provide a control signal that enables new control strategies. The use of diode laser sensors is a new frontier in combustion control, and the promising, yet preliminary, results of our successful demonstration experiments have also been accepted for presentation at the 31st International Symposium on Combustion in August of 2006.[2]

Third, we have begun to apply a novel mid-IR laser source to the quantitative sensing of hydrocarbon fuels. Understanding fuel loading is crucial to optimization of a wide variety of combustion processes. Liquid hydrocarbons are practical for transportation uses because of the ability to store and transport large amounts of energy, which can be released in combustion. However, the injection of liquid fuels into combustors produces a complex two-phase mixture of fuel as a gaseous and liquid aerosol. Light scattering from the fuel aerosol can make the gas phase measurement difficult. However, during the past year, in a collaborative effort involving partial support from AFOSR and ARO, we have begun to investigate differential absorption in the mid-IR as a strategy for gas phase measurement in the presence of aerosol scattering. Although the these results are preliminary, they are quite promising, and a paper based on this work has been accepted for presentation at the 31st International Symposium on Combustion in August of 2006.[3]

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 groups focused on development of new energy conversion schemes, as well as with groups seeking to reduce greenhouse emissions through improvements in performance of current combustion systems.

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. 1. The optical absorption signal expected in a practical combustion application is modeled using laboratory-validated spectroscopic data. 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.

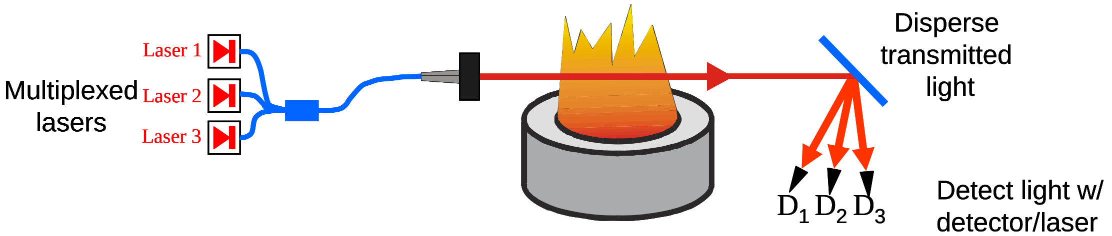

Figure 1: Wavelength-multiplexed absorption concept for **smart optical sensors**.

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 by our Stanford University group. Although the majority of this work was done in well-controlled, laboratory-scale flames at Stanford, there are some notable exceptions.[4] For example, a Stanford student, Ted Furlong, performed the first-ever closed-loop combustion control with laser sensing. He utilized a wavelength-multiplexed TDL sensor of gas temperature and adaptive control to reduce the CO and unburned hydrocarbon emissions from a 50kW incinerator (at a Navy facility in China Lake, CA) by more than an order of magnitude.[5] 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,[6] although no effort was made at combustion control. In Japan, Deguchi et al. measured CO and O_2 concentration in a waste incinerator [7] and more recently in a coal-fired boiler. However, these past researchers all utilized free-space propagation of the laser beams as opposed to the approach now used by our Stanford group, which avoids the use of free space optics by employing fiber optics technology developed for the telecommunications industry. 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.[8] They have recently applied their sensor for gas temperature and composition 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 a subsequent lower emissions load on the atmosphere.

During this project, we also collaborated with researchers at GE Global Research Laboratories to design a sensor for post-turbine gas temperature measurements in a portable power plant.[9] The Stanford **smart optical sensor** design approach was used to choose laser wavelengths to determine gas temperature from a measurement of the ratio of absorption in two water vapor transitions. This 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 tunable diode laser (TDL) absorption sensor for crank-angle-resolved in-cylinder temperature measurements in collaboration with DoE via the Sandia National Laboratory, 2) a rapid-response gas-temperature sensor for control of a swirl-stabilized flame in collaboration with the AFOSR and the ONR, and 3) a novel mid-IR sensing technology for vapor phase fuel in the presence of fuel aerosol interference in collaboration with the AFOSR and ARO. 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.

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 2 illustrates our vision of a fully instrumented research IC-engine, where measurements of fuel, air, and

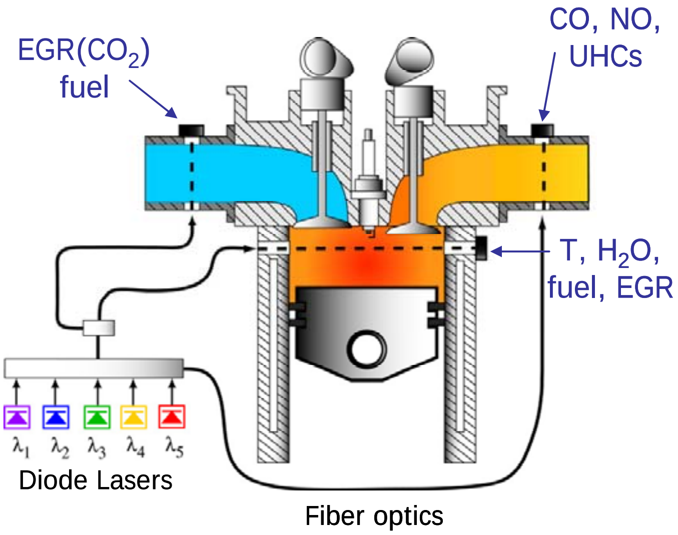

Figure 2: Vision of diode-laser-based sensors for the intake manifold, in-cylinder, and the exhaust manifold of an internal combustion engine.

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, significant progress to realize the feasibility of this vision has begun. Building on the initial proof-of-concept measurements conducted last year in an optical engine at the University of Michigan, we designed a second-generation fiber-coupled wavelength-multiplexed sensor, which we assembled and tested at Stanford in heated cells and shock-heated gases to validate the sensor performance. We then performed preliminary measurements to test sensor performance in a research engine at Sandia National Laboratory in Livermore, CA.

This second generation absorption diagnostic was targeted at measuring crank-angle-resolved, in-cylinder temperature in HCCI engines. Two water vapor transitions were chosen to provide gas temperature from a ratio of the absorption measured over the LOS across the cylinder in an optically accessible HCCI piston engine at Sandia National Laboratory. A schematic of this wavelength-multiplexed sensor is shown in Fig. 3. An initial demonstration of the sensor provided microsecond time-resolved temperature data for both motored- and fired-engine operation under conditions ranging from 300K to 1700K and 1bar to 55bar. An example of these results, given in Fig. 4., represent the first time-resolved, cross-cylinder measurements of temperature and water concentration in an internal combustion system utilizing a wavelength-multiplexed, diode-laser system. The fiber-optic coupling employed for this sensor enables measurements on vibrating engines and simplifies the implementation of the sensor in this harsh environment.

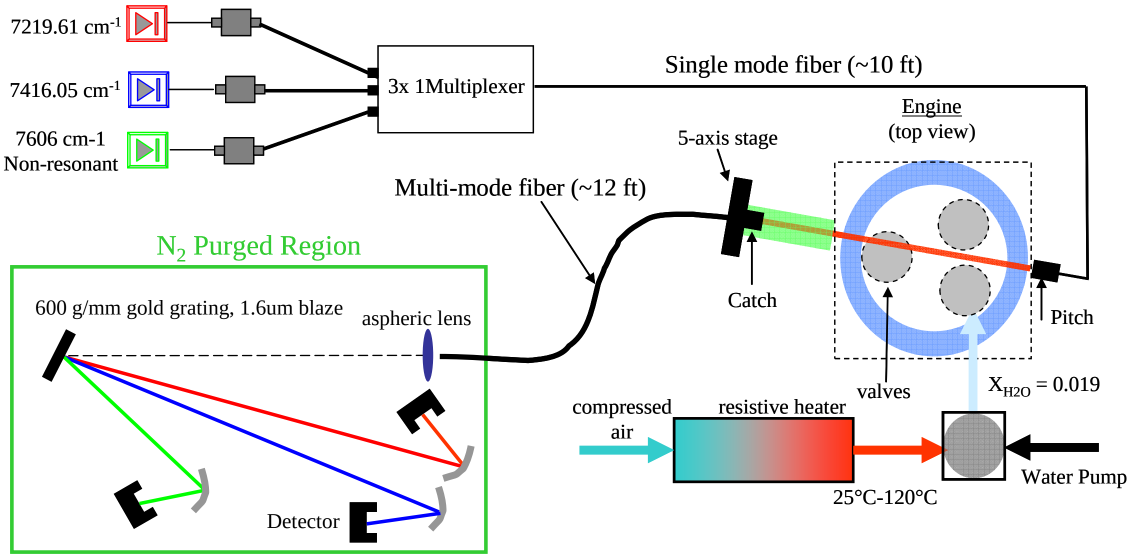

Figure 3: Experimental setup for the TDL absorption measurements of gas temperature inside a single-cylinder engine with optical access. Three diode lasers are wavelength-multiplexed onto a single fiber and the beam pitched across the cylinder, caught on a fiber and demultiplexed with a grating in a nitrogen purged container.

The current wavelength-multiplexed technique utilizes two resonant wavelengths and one non-resonant wavelength to track water absorption throughout the engine cycle. The non-resonant beam successfully tracks fluctuations in the transmitted beam intensities resulting from particulate attenuation (if present), window fouling, and beam steering. Key solutions required to suppress crank-angle-dependent noise in the transmitted laser signals were found. These solutions include careful spectroscopic design and optical engineering to accommodate beam-steering, engine vibration and polarization-related interference. A spectroscopic line-selection process was used to identify the most appropriate water absorption linepair for thermometry under these conditions. The straightforward data reduction allows for rapid reduction of the raw data to temperature.

An example of the temperature data is reported in Fig. 4. The data accurately track the simulated temperature as illustrated in the upper panel. The lower panel of Fig. 4 gives the measured pressure and the water vapor mole fraction determined from the TDL sensor data. Note the rise in H_2O after ignition; hence the sensor has the potential to measure the combustion efficiency. The sensor also provides autoignition and peak-combustion temperatures during fired-engine operation which can prove critical for understanding the ignition and pollutant formation processes. We estimate that this two-line temperature sensor has an uncertainty of <3% during the compression stroke and <5% at the higher temperatures after ignition. These uncertainties could be improved and the dynamic range increased by addition of additional absorption transitions with a DWM architecture.

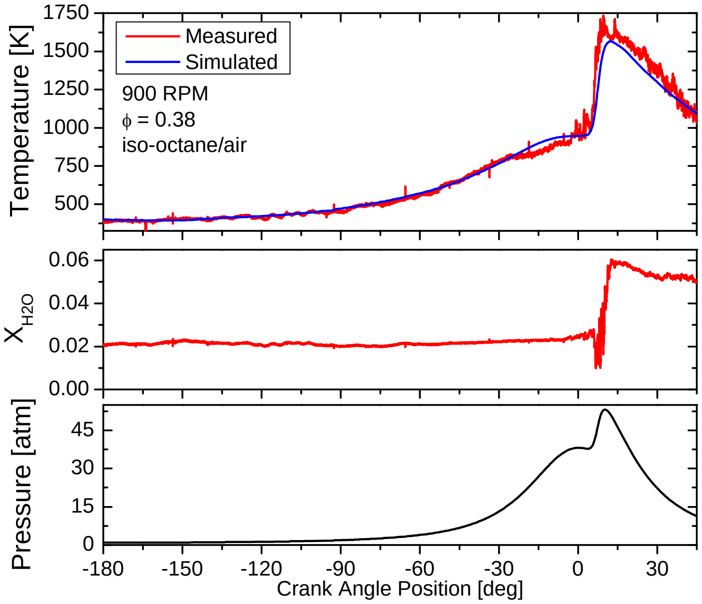

Figure 4: Measurements in versus crank angle for a single-cylinder engine fired via HCCI using iso-octane fuel. Top panel shows data from the TDL temperature sensor, Middle panel shows the TDL sensor data for water vapor mole fraction, Lower panel shows the measured in-cylinder pressure from a transducer.

While this initial demonstration focused on the development and application of a two-line water temperature and concentration sensor, the flexibility of the wavelength-multiplexed architecture will allow straightforward addition of other wavelengths. This could increase the dynamic range, reduce uncertainty, and enable characterization of non-uniformities along the line-of-sight. Other diode-laser-based sensors could be developed to measure hydrocarbon fuel concentration and combustion species such as CO and CO_2. By adding additional diode laser wavelengths to the wavelength-multiplexed system, these important parameters can potentially be measured simultaneously with temperature. Further details may be found in Ref. 1.

Active control of combustion instabilities using a single tunable diode laser

The drive towards improved fuel economy, reduced pollutant emissions (CO, NOx, …) and increased turbine lifetime has prompted interest in combustors that operate at very lean fuel/air equivalence ratios. However, fuel-lean combustion is susceptible to instabilities in the form of thermoacoustic oscillations or blowout. Thermoacoustic instability comes from the coupling of heat release to acoustic (pressure) oscillations, and leads to decreased combustion efficiency and increased pollutant emissions. Lean blowout (LBO) causes significant safety hazards and risk-based costs, and reduces engine lifetime and availability. Therefore, practical operations of low-emission, fuel-lean gas turbine combustors will require a real-time control system to suppress acoustic instabilities and prevent LBO.

Gas temperature is an important combustion parameter, and thus has potential for use as a control variable in physics-based control strategies. TDL sensors for gas temperature have the potential to provide control signals to suppress combustion instabilities and LBO. TDL sensors have better spatial resolution and less sensitivity to background noise and luminosity than the traditional pressure (microphone) and chemiluminescent emission sensors, and thus may offer significant advantages. Therefore, we have investigated the potential for TDL temperature sensor control of combustion instabilities and LBO in a swirl-stabilized flame used as a laboratory model of a gas turbine combustor.

A fast, real-time (2 kHz) temperature sensor using a single tunable, fiber-coupled telecom diode laser is used for the demonstration measurements. This sensor was developed earlier and fundamental design rules were discussed in detail.[10] The sensor and swirl-stabilized combustor setup are illustrated in Fig. 5. A specific H_2O line pair near 1.4μm is selected for measurements using a scanned-wavelength technique with wavelength modulation and $2f$ detection (WMS-$2f$). The gas temperature is inferred from the ratio of the second harmonic signals of the two selected H_2O transitions.

The combustor is constrained by a cylindrical quartz tube which permits uncooled operation and provides optical access for the diode laser sensor. The circular duct generates a natural flame instability, and a 388Hz oscillation is clearly visible in the FFT spectrum of the real-time TDL sensor data for temperature in the left panel of Fig. 6, which confirms the ability of the sensor for quantitative, accurate identification of flame instabilities. It follows that the real-time FFT of the TDL sensor data can be used in

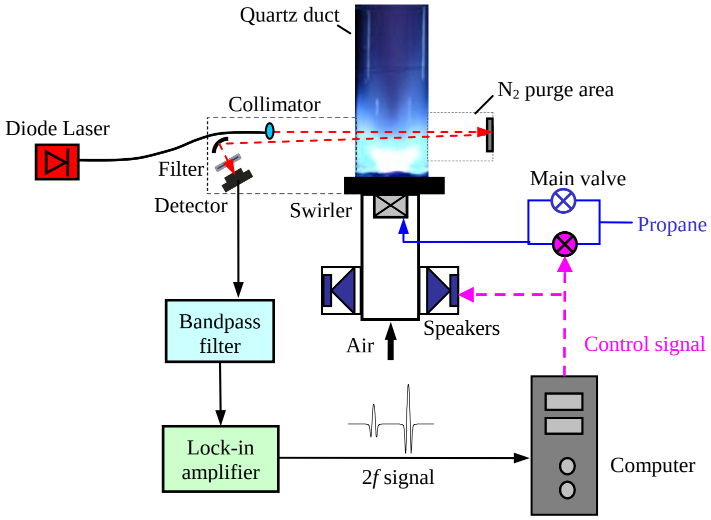

Figure 5: Schematic diagram of the real-time TDL temperature sensor and the swirl-stabilized combustor.

active control to suppress flame instabilities, and a phase-delay feedback control strategy is demonstrated here. The sensor output signal is time-delayed and amplified to drive four audio speakers to modulate intake air flow. The FFT power spectrum of the sensor output signal with control on shown in the right panel of Fig. 6 illustrates the >7dB suppression of the thermoacoustic instability at 388Hz. Experiments were also performed to optimize the delay time and gain in the control strategy.

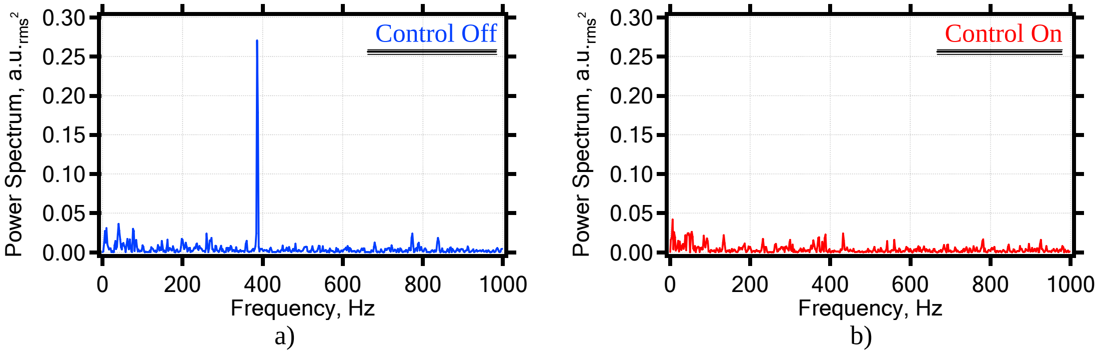

Figure 6: FFT power spectra of the real-time temperature sensor data; left panel: control off and right panel: control on.

Suppression of LBO also was demonstrated using the real-time TDL temperature sensor. We found that low-frequency temperature fluctuations increase sharply near LBO, e.g., the fraction of FFT power of the TDL sensor signal in the 0-50Hz range increases by as much as a factor of 8 at LBO (see Fig.7). This signature is then used to detect the proximity to LBO and prevent LBO through a corrective signal to fuel flow. The control valve, in parallel with the main valve (see Fig.5), is used as the actuator of the LBO control system. LBO was suppressed during a transient process by modulating the fuel flow with the main valve based on the TDL absorption signal. The control system successfully prevented LBO without knowing the LBO limiting stoichiometry, which changes with air intake flow rate. The results obtained demonstrate the utility of diode laser sensors for close-loop combustion control applications. Further details may be found in Ref. 2.

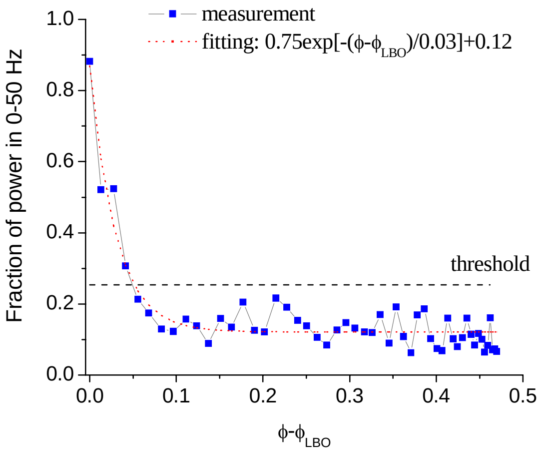

Figure 7: Fraction of FFT power in 0-50Hz of TDL sensor output signal as a function of equivalence ratio.

Mid-IR Sensing of Hydrocarbon Fuels using Wavelength Tunable Absorption

Understanding the fuel concentration distribution in practical combustors is of primary significance because it directly affects operating efficiency and regulated emissions. For this reason we are actively pursuing a new mid-infrared (mid-IR) technology that will enable optical absorption measurements of fuel concentration in harsh environments. It is long recognized that hydrocarbon fuels have strong absorption features in the mid-IR; however, until recently this sensing strategy has been limited by the lack of mid-IR laser sources. Although previous workers have successfully used the 3.39μm output from HeNe lasers to monitor fuel concentration, this approach has several limitations. First, absorption measurements with a single, fixed wavelength are subject to uncertainty and noise from transmission losses from window fouling, scattering from fuel aerosol or soot particles, and beam steering from index of refraction gradients in the target gases. All of these problems plague measurements in practical combustors. In addition, the HeNe laser is quite noisy, and the 3.39μm laser light can be so strongly absorbed as to severely limit the dynamic range of the sensor. We have chosen to address these problems using tunable wavelength-multiplexed mid-IR laser light enabled by a novel difference-frequency-generation (DFG) laser.

A new generation of wavelength-tunable mid-IR light sources has recently become available. Two near-IR diode lasers are mixed in periodically poled lithium niobate crystals and a laser beam at the difference frequency in the mid-IR is produced. Wavelength tuning the near-IR laser produces a wavelength-tuned mid-IR beam, and the intensity noise on this mid-IR beam reflects the very stable operation of the telecommunications quality of the input near-IR lasers. The tunability allows us to select a mid-IR sensor wavelength with appropriate absorption strength to optimize the dynamic range for amounts of fuel expected in the combustor. These laser sources can be wavelength- or time-division-multiplexed to enable a sensor beam with two colors of mid-IR light. This enables the use of differential absorption techniques to minimize the interference losses in transmission from non-absorption sources like beam steering, window fouling, scattering, etc.

The first demonstrations of a two-color DFG mid-IR laser for differential absorption of fuel in a heated gas cell, shock-heated vapor, and shock-heated aerosol have recently been completed and will be presented at the 31st International Symposium on Combustion this summer.[3] The success of these demonstration measurements suggests that this new sensing strategy has significant promise for fuel sensing in a wide variety of combustion applications. See Ref.3 for further details.

Progress

During this program, the technique of LOS wavelength-multiplexed absorption sensing using robust tunable diode lasers has been successfully demonstrated in a wide variety of practical environments including: in large-scale coal-fired power plants (collaboration with Zolo Technologies), in the cylinder of firing piston engines (collaboration with DoE via Sandia National Laboratories), and to suppress instabilities in spatially inhomogeneous model gas combustor flames (collaboration with AFOSR and ONR via the University of Cinncinati). Collaborations have significantly amplified the impact of the GCEP sponsored work by enabling us to test sensor performance in practical combustion environments. In every application attempted, we have been successful. This progress indicates that wavelength-tunable TDL absorption sensors have the potential to enable new control strategies to optimize the operation of a wide variety of practical combustion devices to increase overall efficiency and reduce the atmospheric load of combustion-generated pollutants and products.

In addition to control of practical combustors, we have demonstrated that TDL absorption sensors are quite promising for test-bench diagnostics to enable engineers to optimize a variety of combustion systems including piston engines (collaboration with DoE via Sandia National Laboratory), gas turbines (collaboration with GE Research Laboratory), and new combustion technologies.

Finally, a significant advance in has been achieved by extending TDL sensors to fuel measurements. In collaboration with projects sponsored by AFOSR and ARO, our GCEP work has led to the first tunable TDL combustion sensing in the mid-IR, thereby enabling quantitative sensing of hydrocarbon fuels even in the presence of interference from aerosol scattering.

Future Plans

The results of this GCEP project will be presented in three contributed papers at the 31st International Symposium on Combustion to be held in August 2006 in Heidelberg, Germany. Preparation of additional archival publications will follow.

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