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ADVANCED DIAGNOSTICS FOR REACTING FLOWS

AFOSR Grant F49620-04-1-0009

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SUMMARY/OVERVIEW:

Recent advances in this program's research and development of non-intrusive diagnostics for air-breathing combustion applications are reported. Progress is highlighted on: the validation of infrared-planar laser induced fluorescence (IR-PLIF) models for quantitative CO₂ detection; quantitative NO PLIF in high-pressure flames; increased tunable diode laser (TDL) absorption sensor temperature fidelity in scramjet flowfields using wavelength-modulation techniques; differential-absorption with novel new light sources in the mid-IR for fuel sensing; use of wavelength-multiplexed TDL sensing for gas temperature in non-uniform flow fields; and advances in toluene photophysics to enable tracer-based PLIF imaging of temperature fields.

TECHNICAL DISCUSSION:

1. Infrared-PLIF Imaging Diagnostics using Vibrational Transitions

IR-PLIF allows for imaging a group of molecular species important for hydrocarbon combustion that are not accessible using single-photon UV/visible PLIF; this includes CO, CO₂, and hydrocarbon fuels. IR-PLIF is the excitation of IR-active vibrational modes with imaging of the subsequent vibrational fluorescence. Quantitative interpretation requires knowledge of the vibrational energy transfer processes, and hence in recent years we have been developing models for infrared fluorescence. During the past year, measurements at atmospheric pressure and room temperature have been used to validate portions of the vibrational energy transfer model for CO₂. This model has been used to estimate IR-PLIF performance and design experiments for previously untested conditions, including high-speed flows at sub-atmospheric pressures and low-speed flows at elevated pressures (1-10 atm).

2. PLIF of NO at High Pressures and Temperatures – Multi-Wavelength Detection Strategies

LIF of NO at high pressures is complicated by pressure broadening of the excitation transitions and interference from O₂ and CO₂, as we have described previously. We now report a multi-wavelength detection strategy optimized for sensing NO with simultaneous detection in other wavelength windows to quantify signals from O₂ and CO₂. The concept of the three detection bands is illustrated in Fig. 1 by overlap of detection bandpasses with the fluorescence spectra of NO, O₂ and CO₂. Design rules have been developed to select the optimum bandpasses for NO detection and correction for O₂ and CO₂ interference. Fig. 2 illustrates

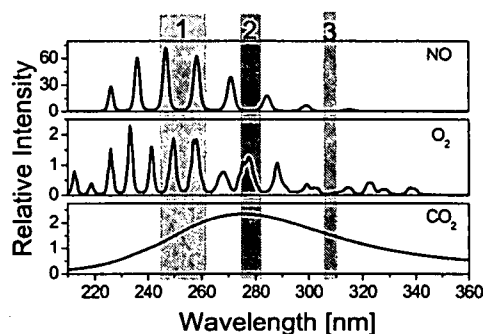


Fig. 1. Illustration of LIF from NO, O₂, and CO₂ at 2000K and 40 atm with detection windows (1) for NO and (2) and (3) to quantify the interference from O₂ and CO₂

corrected images for NO in slightly-lean ($\phi=0.9$) and slightly-rich ($\phi=1.1$) flames over the range of pressure investigated (1–60bar). This concept offers the potential for simultaneous imaging of all three species, and work is underway to understand how to optimize the excitation wavelengths and detection bandpasses for measurements in rich and lean high-pressure flames.

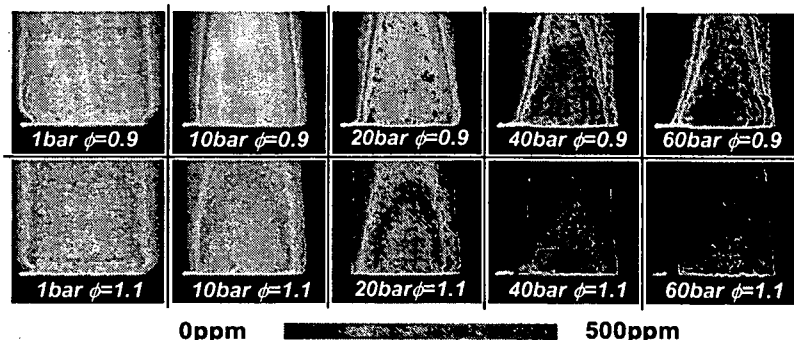


Fig. 2. NO concentrations from multi-wavelength NO-PLIF imaging (1–60 bar, $\phi = 0.9$ and 1.1 with 300 ppm NO seeding). In fuel-rich flames the NO concentrations are reduced by NO reburn.

3. Advanced Absorption Spectroscopy

3.1 Wavelength-Multiplexed WMS-2f TDL Sensing in a Scramjet Combustor Previously, our TDL sensor development concentrated on scanned-wavelength direct-absorption spectroscopy for aeroengine ground-test applications because of this method's simplicity, accuracy, and capability for time-resolved measurements. However, complications of mechanical and gasdynamic beam-steering, weak absorption at high temperatures and fiber-mode noise conspire to reduce signal-to-noise ratios (SNRs). In practice, we have found that the scanned-wavelength direct-absorption technique requires careful optical engineering to reduce these noise sources to acceptable levels in large-scale facilities. As a result, we have explored an alternative approach, namely wavelength modulation spectroscopy (WMS) with second harmonic detection (2f), and

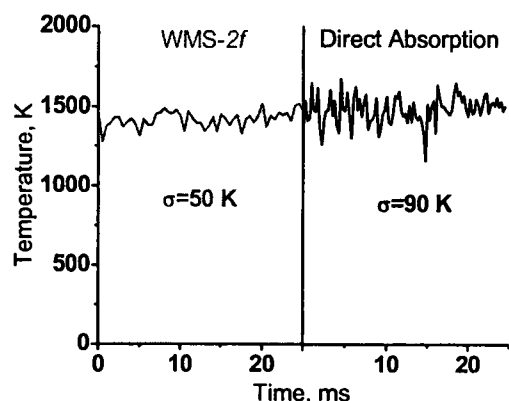


Fig. 3. Comparison of measured temperature using direct absorption and WMS-2f with the 1392/1469 nm line pair in a scramjet combustor. The direct absorption data was filtered from 4 kHz to 2 kHz to match the WMS-2f sampling rate.

have shown this method to offer advantages for sensitive detection of absorption in noisy environments. In the past, this technique has seen limited use with practical sensors, because of calibration requirements. During the past year, however, we have discovered how to take advantage of the intensity modulation of injection-current-tuned diode lasers to provide simultaneous calibration and normalization signals. This advance has enabled absolute WMS-2f measurements of temperature and gas concentration with relative simplicity. Figure 3 illustrates TDL absorption measurements of time-resolved gas temperature in a model scramjet combustor at Wright Patterson AFB; note a twofold improvement in the scatter of the data using WMS-2f versus direct absorption with the same optical engineering and sensor installation.

3.2 Mid-IR Differential Absorption for Fuel Sensing Monitoring and control of fuel concentration is critical to maximizing performance and efficiency and minimizing pollutants emitted by propulsion systems. Mid-infrared absorption diagnostics using a single, fixed-wavelength laser can provide sensitive, time-resolved measurements of fuel concentration in these environments. However, often laser sources of suitable wavelength are not available, and in addition single-fixed-wavelength absorption is sensitive to optical interferences common in practical engine environments, including droplet scattering, window fouling, and interference absorption. Recently, we have acquired a novel mid-IR laser based on difference-frequency-

generation from two near-IR diode lasers to provide tunable single-wavelength output. We have subsequently modified this laser to provide two rapidly alternating ($\sim 100\text{kHz}$) wavelengths of mid-IR output, thereby enabling either two channels of single-wavelength absorption or a direct measurement of differential absorption at the two wavelengths, with $10\mu\text{s}$ time resolution. Differential absorption uses the beam of two alternating wavelengths (colors) and extracts the species concentration from the difference in absorption at the two wavelengths. This difference technique allows rejection of interference and noise common to the two beams. The basic absorption data for differential absorption of n-dodecane, a representative large hydrocarbon fuel surrogate is illustrated in Fig. 4. Recent work has illustrated that this technique can be used to sensitively detect gas concentrations in the presence of interference from aerosol scattering. We believe this new multi-color diode-laser-based diagnostic has the potential for a wide variety of practical applications.

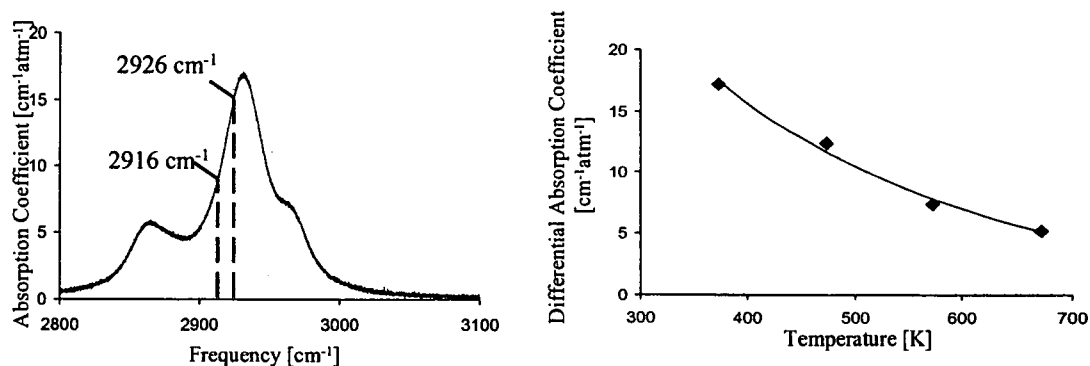


Fig. 4. Left: absorption coefficient via FTIR of n-dodecane vapor dilute in 1 atm. of nitrogen @675K. Right: differential absorption coefficient versus temperature for n-dodecane vapor @ 2916 and 2926 cm^{-1} .

3.3 TDL LOS Absorption Diagnostics for Non-Uniform Flows TDL absorption spectroscopy has proven to be a successful line-of-sight (LOS) gas-sensing strategy for a variety of important applications. However, quantitative measurements have been hampered by the usual assumption of a uniform temperature and species concentration along the line-of-sight. During the past year, we have begun the systematic development of a multi-line thermometry strategy that seeks to extend TDL absorption spectroscopy to temperature sensing in non-uniform flows. The sensor concept is to measure the LOS absorptions for multiple transitions with different temperature dependences, from which the non-uniform temperature distribution along the LOS can be inferred using either of two strategies. The first strategy, called profile fitting, fits a temperature distribution profile postulated using physical constraints; the second strategy, called temperature binning, determines the temperature probability distribution function (PDF) along the LOS using prescribed temperature bins. Investigation of this concept has included simulations and initial experimental proof-of-concept tests using water vapor absorption in combustion gases, and the results include the development of systematic selection criteria for the absorption transitions.

4. Fuel Tracer Photophysics for Quantitative Diagnostics

Previous studies of the photophysical properties of toluene have shown that its fluorescence quantum yield is highly sensitive to temperature. Current work has demonstrated that this sensitivity can be exploited for precise PLIF temperature imaging of gas flows seeded with toluene. Fig. 5 illustrates a single-shot temperature image of a nitrogen flow, seeded with

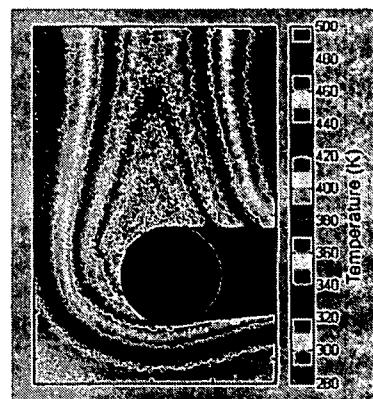


Fig. 5. Single-shot PLIF temperature image using toluene tracer of a nitrogen flow around a heated cylinder.

toluene, passing over a cylinder heated to 500 K. Temperature differences of 5 K can be identified in this image. Fundamental work on the photophysical properties of toluene has revealed that the fluorescence yield is significantly higher than with previously studied ketone tracers. Current work focuses on characterization of toluene's photophysical properties over a wider range of temperature, pressure and gas composition (e.g. O₂) to create a fundamental database of toluene's photophysical properties, from which a physics-based model will be developed (similar to our current model for acetone). This model will facilitate more quantitative use of toluene PLIF and the development of new measurement strategies, e.g. simultaneous imaging of concentration and temperature. The strong dependence of the fluorescence yield on O₂ concentration may additionally provide a means of quantitatively imaging fuel/air ratios.

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13. Ronald K. Hanson (Invited), "Diode laser sensors for ground testing," *24th Applied Aerodynamics Conference*, American Institute of Aeronautics and Astronautics, AIAA 2006-3441.
14. A.E. Klingbeil, J.B. Jeffries, and R.K. Hanson, "Temperature- and pressure-dependent absorption cross-sections of gaseous hydrocarbons at 3.39 μ m," *Measurement Science and Technology* (2006) in press.
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