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Recent Advances in Laser-based Diagnostics for Gaseous Flows

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Abstract**:** Laser-based diagnostic techniques offer unique capabilities for experimentation on gaseous flows. In this paper, we overview recent progress of two concepts: spectrally resolved absorption and planar laser-induced fluorescence (PLIF) imaging. The absorption measurements utilize tunable diode lasers (TDLs) as light sources. Recent TDL applications include a wavelength-multiplexed system for rapid temperature sensing for use in combustion control, and absorption probes for time-resolved measurements of temperature, velocity and species concentrations in a hypersonic shock tunnel. Recent PLIF work includes applications to supersonic, exothermic flowfields relevant to ram accelerators, and development of a method for imaging temperature in air flows using acetone seeding.

Keywords**:** PLIF, diode laser, absorption spectroscopy, combustion control, hypersonic, supersonic, acetone.

1. Introduction

Since the invention of the laser more than thirty years ago, a number of laser-based diagnostic methods have been successfully developed for nonintrusive measurements in gaseous flows. Among the most promising of these methods are tunable laser absorption and laser-induced fluorescence (LIF). These methods are attractive particularly because of their signal strength, species specificity and relative simplicity of equipment and signal interpretation. Furthermore, absorption and fluorescence diagnostics are sufficiently mature that strategies have been developed and demonstrated for quantitatively sensing a variety of flowfield parameters including species concentration, temperature, pressure, density and velocity. Although there are exceptions, laser absorption is typically conducted with cw laser sources, while fluorescence utilizes pulsed lasers. Laser absorption is generally simpler, less expensive and more quantitative than laser-based fluorescence; on the other hand, LIF can provide spatially resolved measurements while absorption yields path-integrated (i.e., line-of-sight) data.

Although laser absorption can be performed using either fixed-wavelength or wavelength-tunable laser sources, the use of wavelength-scanned lasers enables recording of spectrally-resolved absorption lineshapes which contain useful information on temperature, pressure and velocity as well as species concentration. The relevant theory for spectrally resolved absorption is the well-known Lambert-Beer law

$$\left(\frac{I}{I_o}\right)_\nu = \exp(-k_\nu L)$$

where I and I_o are the transmitted and unattenuated laser intensities (power) at frequency ν, $k_\nu L$ is the spectral absorbance, with k_ν the spectral absorption coefficient and L the absorption path length. Diagnostic strategies based on spectrally resolved absorption have been developed for several types of lasers, including lead-salt infrared (IR) diode lasers (in the 1970s; e.g., see Hanson, 1977), ring dye lasers (in the 1980s; e.g., see Rea, 1984) and, more recently, near-IR diode lasers. The latter lasers, while limited at present to several spectral intervals in the overall range 600 nm to 2 microns, are extremely attractive for practical applications owing to their reasonable cost and compatibility with optical fiber transmission. Important example combustion-related diagnostics based on near-IR TDLs include a mass flux sensor for supersonic air flows (Philippe, 1992) and a monitor for pollutant species (e.g., methane and methyl chloride, as in Chou, 1996). In the present paper, we illustrate the capability and status of diode-laser diagnostics by summarizing two current efforts in our laboratory: (1) a dual-wavelength temperature sensor for combustion control applications; (2) a wavelength-multiplexed absorption probe for time-resolved characterization of hypersonic flows in ground test facilities. Another TDL project from our group, involving absorption analysis of probe sampled gases, will be reported in a separate session at this meeting (Mihalcea, 1998).

Laser-induced fluorescence was originally employed as a single-point combustion diagnostic, but the method was extended in the early 1980s to allow planar imaging through the use of 2-D array cameras and sheet illumination with pulsed laser sources. The planar LIF method (known as PLIF) has been rapidly accepted by the combustion and fluid mechanics communities owing to its value for visualizing complex flowfields. As an illustration of the continued development and status of this diagnostic method, we present brief overviews of two projects currently underway in our laboratory: (1) application of PLIF to supersonic exothermic flows in an expansion tube facility; and (2) development of a PLIF method for imaging temperature in air flows using acetone seeding.

2. Spectrally Resolved Absorption Using Tunable Diode Lasers

2.1 Dual-wavelength Diode Laser Sensor for Combustion Control

Diode lasers offer prospects for use as sensors in process control systems. Work at Stanford has been aimed at developing line-of-sight absorption diagnostics, for measurements of temperature and species concentrations, and implementing these diagnostics as sensors in open- and closed-loop control of laboratory and industrial-scale combustors (Furlong, 1996a, b and 1998).

The schematic diagram in Fig. 1 indicates the experimental arrangement recently applied for measurements and control of a (50-kW) pulsed annular dump combustor at the Naval Air Warfare Center at China Lake (California). The combustor serves as a model of an afterburner in a waste incineration system under development for use aboard Navy ships. The afterburner utilizes the concepts of forced-vortex combustion for a compact and efficient design. Details of the afterburner, including the design, application of advanced diagnostics, and determination of the destruction and removal efficiency (DRE) have been described previously (Parr, 1996).

The primary air flow (900 *l*pm [liters/min]) through the central jet (3.84-cm dia) was acoustically forced to create coherent vortices at the preferred mode of the jet. Secondary air flow (180 *l*pm) was also acoustically modulated and injected circumferentially at a 15° angle relative to the primary air. The fuel mixture (either 355-

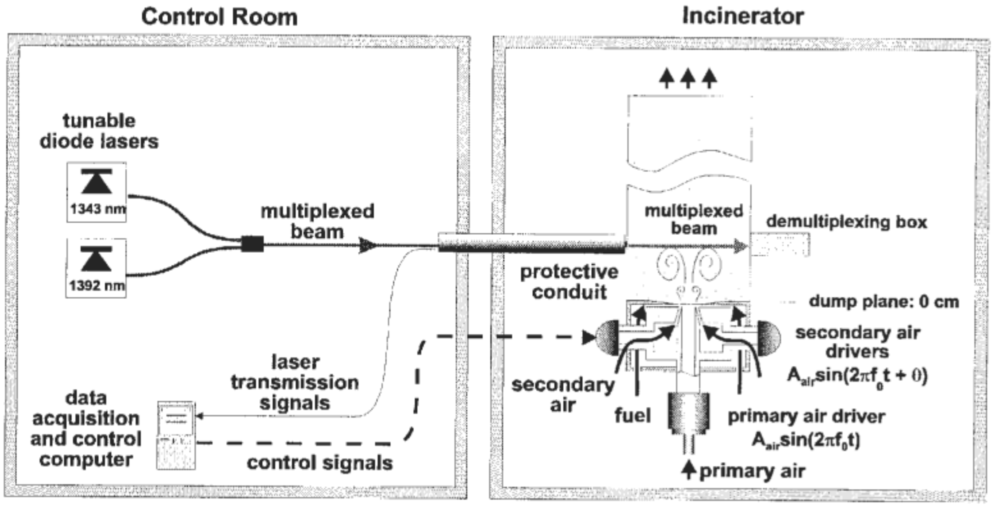


Fig. 1. Schematic diagram of the combustion-control experiment.

*l*pm N_2 and 43-*l*pm C_2H_4; or 355-*l*pm N_2, 123-*l*pm CO, and 180-*l*pm H_2), which served as a pyrolysis surrogate, was preheated to near 900 K and circumferentially injected normal to the primary air flow. A water-cooled aluminum duct (18-cm dia., 61-cm length) was sealed to the injection nozzle.

The laser system includes two independently operated DFB (InGaAsP) diode lasers tuned at a 10-kHz repetition rate over the desired transitions by ramp-modulating the individual injection currents to yield single-sweep spectrally resolved absorption records every 100 μs. The individual laser outputs were combined into a single path using appropriate fiber splitters and couplers. The multi-wavelength beam was brought to the incinerator via an optical fiber and directed through the flowfield using a GRIN lens. The transmitted multi-wavelength light was de-multiplexed (spectrally separated) into the constituent laser wavelengths by directing the beam at a non-normal incidence angle onto a diffraction grating. The beams were diffracted at angles specific to each wavelength and were subsequently monitored with InGaAs photodiodes. The detector voltages were digitized by an A/D card installed in a personal computer. The measurement cycles were repeated at a 3-kHz rate (each required 200 μs for data transfer and 100 μs for signal acquisition and computation of gas temperature and control signal). The relatively short delay between the measurement and the subsequent control output (0.4 ms) was approximately 10 times shorter than the effective response time of the actuator (τ_{act} = 5 ms), which was limited by the gas flow time to the probed region.

Figure 2 (upper frame) shows a time history of temperature measurements recorded at a 3-kHz rate, 8 cm from the dump plane. The large periodic oscillations at the forcing frequency (f_0 = 175 Hz) are suggestive of strong coherent vortices and a proper relative phase between the primary and secondary air forcing. The power spectral density of the measured temperature (lower frame) confirms that the temperature oscillations are a result of the applied forcing. In the present work, the rms magnitude of the spectral component near 175 Hz (the forcing frequency) was used as a measure of coherence. For the case of optimized forcing, shown in Fig. 2, T_{rms} = 38 K.

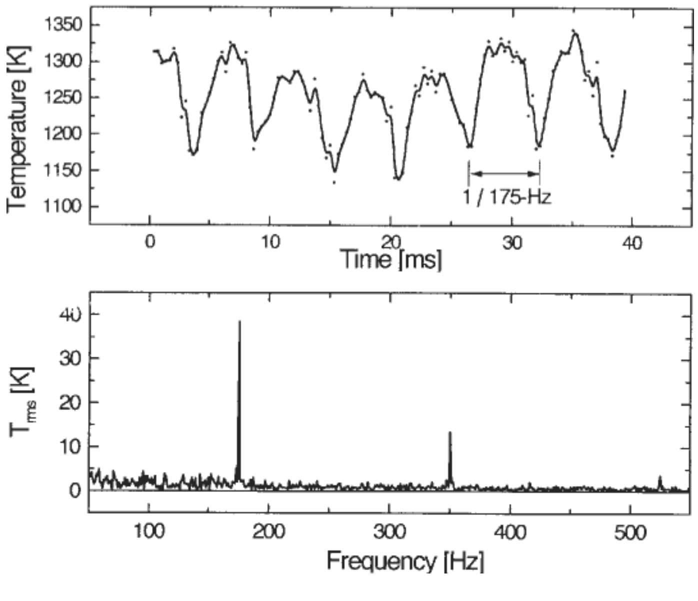


Fig. 2. (top frame) Temperature measured at 3-kHz rate, 8 cm from the dump plane. (bottom frame) Power spectral density (1-Hz resolution) of a 1-sec history of temperature measurements.

The temperature measurements were used in a closed-loop control strategy, based on a least-mean-squares algorithm, aimed at optimizing the coherence of the oscillations by varying the phase (θ_{air}) and amplitude (A_{air}) of the air forcing. The internal variables (phase, amplitude) associated with the control are shown in Fig. 3. The control was initiated with the phase at 180°, which was near a performance minimum in the open-loop experiments. The amplitude (bottom frame, right axis) decreased initially but then quickly increased to the power upper limit as the phase began to converge (bottom frame, left axis). Note that the phase reached the open-loop operational bounds (i.e., anticipated CO levels within 20% of the minimum), within approximately 100 ms. As the oscillations grew in phase with the primary air forcing (top frame, left axis), the error signal (temporally averaged magnitude) begins to decrease, indicating convergence (top frame, right axis).

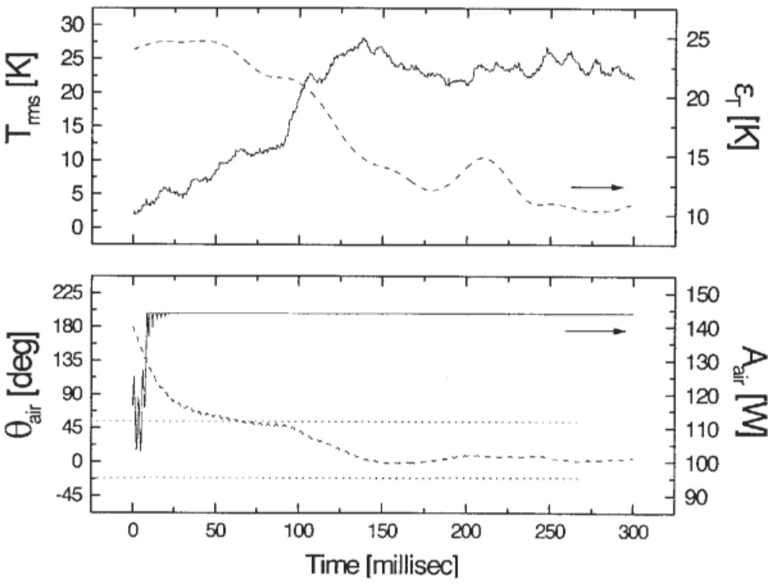


Fig. 3. Overall time response of the closed-loop system which adaptively varied θ_{air} (bottom frame, left axis), and A_{air} (bottom frame, right axis), to minimize the error function, ε_T (top frame, right axis).Steady parameters: equivalence ratio = 0.575, f_0 = 175 Hz.

The successful demonstration of closed-loop control in a realistic combustion system illustrates the high potential of diode-laser absorption sensors for improved measurement and control of combustion and other high temperature process streams, particularly for applications that require remote and non-intrusive monitoring. Further work to extend TDL sensing and combustion control is in progress, including measurement of combustion-generated pollutants (NO, CO and unburned hydrocarbons) in the exhaust stream (Mihalcea, 1998).

2.2 TDL Absorption Probes for Hypersonic Flows

Recent interest in supersonic combustion and hypersonic aerodynamics has led to a variety of experimental programs conducted in ground-based hypersonic flow facilities. Characterization of the freestream conditions in these facilities, especially for high-enthalpy flows, is of significant importance and yet few of the critical flow parameters have been measured directly. For the past few years, we have been exploring a new approach to this problem based on the use of tunable diode lasers, spectrally resolved absorption, and physical probes.

The present versions of the absorption probes are shown schematically in Fig. 4. These intrusive probes were designed for direct installation into flowfields such as the large hypersonic shock tunnels at Calspan (Buffalo, NY), and incorporate optical and electronic elements similar to those used in our research on combustion control (described above). The probes have been applied for high resolution measurements of water vapor (H_2O) and potassium (K) absorption lineshapes in high enthalpy flows. Although the primary test medium is air, water and potassium are useful tracer species, because they are naturally present in many cases or may be added at low levels to the test gas. In the water-vapor measurement scheme (Fig. 4, left), the output beams from two distributed-feedback TDLs, wavelength-tuned repetitively over absorption features near 1396 nm and 1401 nm ($\nu_1 + \nu_3$ band), are transmitted by optical fiber from an instrumentation room to the shock tunnel test section and into the hard-mounted probe. One of the beams undergoes multipass (5 passes) transmission across an 18-cm open gap between the fingers of the probe, while the other beam propagates at a 54-degree angle to the probe axis in a single pass. The probe is aligned with the flow direction and mounted adjacent to a rake of pressure gauges and thin-film heat transfer gauges, which comprise the conventional instrumentation for characterizing hypersonic flows in these pulsed-flow facilities.

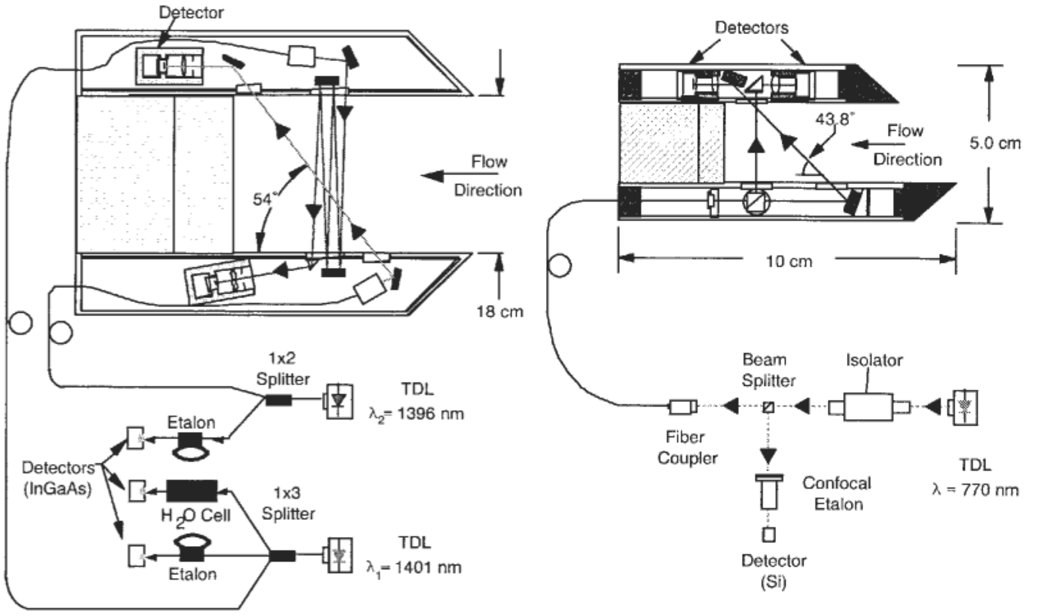


Fig. 4. Schematic of the TDL absorption probes for absorption measurements of water (left) and potassium (right) in hypersonic flows.

For potassium absorption measurements, the large linestrength of the measured transition permitted the design of a probe approximately 1/3-scale of the probe used for H_2O measurements. In this measurement scheme (Fig. 4, right), the output from a single DFB diode laser is wavelength-tuned across the potassium D_1 ($^2S_{1/2} \rightarrow {}^2P_{1/2}$) transition near 770 nm and directed to the (smaller) probe. Inside the probe, the beam is split into paths propagating at a 43.8-degree and a 90-degree angle with respect to the bulk flow direction. Due to its compact size, the potassium probe may be used for measurements in a range of facilities from relatively small-scale to large government and industrial facilities.

The measurement strategy for measurements of either H_2O or K is to current-tune the wavelengths of the lasers over selected transitions to record spectrally resolved absorption lineshapes. Typically the current repetition rate is 10 kHz, corresponding to a measurement interval of 100 μs. The shape of the individual features is dominated by Doppler broadening at the typical flow conditions (high Mach numbers, low pressures simulating high altitude flight, and hence the width or shape of the absorption spectra can be used to establish the gas translational temperature. In the case for H_2O measurements, the rotational temperature may be determined from the ratio of absorbances recorded at two spectral regions. The bulk gas velocity may be determined from Doppler-shifted absorption measurements.

Single-sweep absorption lineshapes near λ_1 and λ_2 obtained simultaneously during a high-enthalpy test (~10 MJ/kg) using the water-based TDL probe are shown in Fig. 5. Note that both of the traces may be used to infer the translational temperature and H_2O partial pressure, while only one of the beams (λ_1) is Doppler-shifted and hence sensitive to the local flow velocity. In the left panel (measurements at λ_1), the small absorption peak to the right is due to the static sample of water present in the open portion of the beam near the laser. This peak provides a convenient means of simultaneously monitoring both the unshifted and Doppler-shifted line positions. The measured values of translational (inferred from the line width) and rotational (inferred from the absorbance ratio) temperatures are in excellent agreement. In addition, the measured velocity (~4630 m/s) is in good agreement with flowfield calculations based on the reflected shock conditions and the expansion produced by the hypersonic nozzle. Further details of the probe and the measurement results may be found in Wehe (1997).

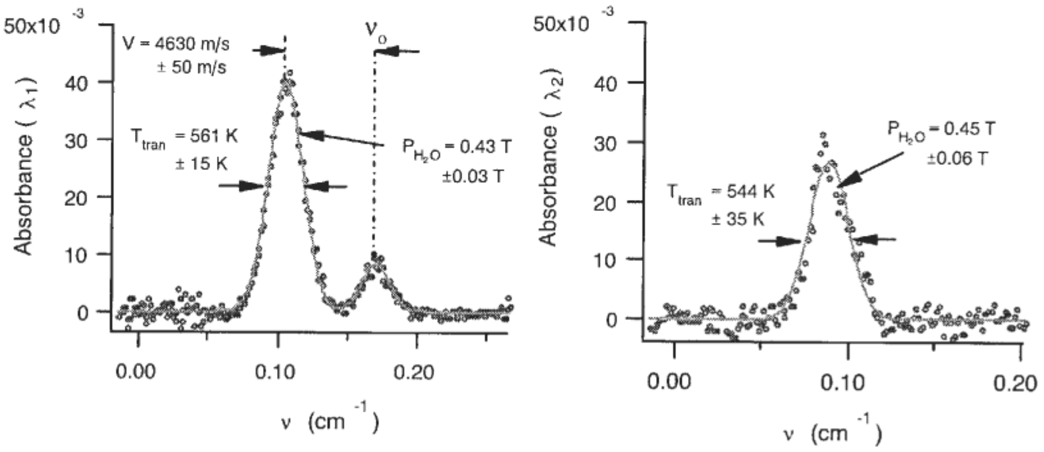


Fig. 5. Single-sweep data traces of H_2O absorption near 1401 nm (left) and 1396 nm (right) recorded in a hypersonic flow (10 MJ/kg enthalpy) used to determine rotational and translational temperatures.

The water-based TDL probe has been used successfully in over 20 tunnel firings during two different test programs at Calspan demonstrating the durability of the hardware. Based on that success and the desire to probe conditions where water may not be present, the potassium probe was developed and applied in over 10 runs in a recent test program at Calspan (Wehe, 1998). Both probes have performed reliably, yielding unique information on the freestream conditions produced at very high enthalpies. The data obtained will allow more quantitative use of expensive hypersonic flow facilities and can also be used in programs aimed at improving facility performance. We believe that variations of this technique could potentially prove useful in flight testing.

3. Planar Laser-induced Fluorescence Imaging

3.1 PLIF Imaging in Supersonic Exothermic Flows

Planar laser-induced fluorescence (PLIF) imaging is now a relatively mature diagnostic method, having been under continuous development for seventeen years since the first PLIF images were acquired (in 1981) in a combusting flow. The bulk of ongoing work on PLIF is aimed either at applications or at extending the method to new variables and/or more quantitative measurements. One of the more interesting applications is to supersonic reacting flows, where the complexity (and unsteady behavior) of most flows and the need for nonintrusive, species-specific measurements at multiple points effectively preclude probe-based or single-point optical methods. PLIF is especially suited for studies of exothermic flows such as found in the ram accelerator, which is a novel new propulsion strategy (e.g., see Hertzberg, 1988 by Hertzberg and his colleagues, who have pioneered this concept).

Our approach to studying ram accelerator flows has been to fix the model projectile and flow the combustible mixture over the body at relevant speeds, using an expansion tube to produce the high-speed flow. The current experimental arrangement is shown schematically in Fig. 6. The expansion tube facility consists of multiple sections of tubing, in tandem, each with different composition and pressure. The driver and driven section function like a normal pressure-driven shock tube in that a strong shock wave is propagated into the driven (test) gas following breakage of the primary diaphragm. The Stanford expansion tube also has an additional short buffer section to avoid ignition of the combustible test gases, but this does not otherwise affect the performance of the driven and driven sections as a shock tube. However, when the shock wave reaches the end of the driven section, it is not reflected (as would occur in a reflected shock tunnel) but rather is transmitted into a section of tube filled to low pressures (typically with helium). The result is an unsteady expansion wave fixed at the entry to the expansion tube which accelerates the test gas to higher speeds while reducing the gas temperature. The result is a stream of gas, first helium and then test gas, which exits the expansion section and enters a test chamber (viewing section) containing the model of interest. The test gas flows at high velocity, but without having been raised to the same temperature which would have been required when using a reflected shock tunnel (where the gas is fully stagnated prior to expansion) to reach the same ultimate flow conditions. This approach, while yielding reduced test times relative to a reflected shock tunnel, is very attractive for studying reactive mixtures, since the maximum temperatures, and hence the tendency for preignition, are much reduced.

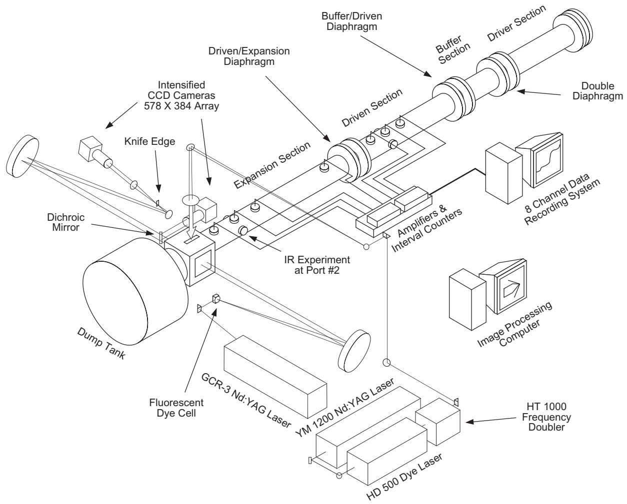
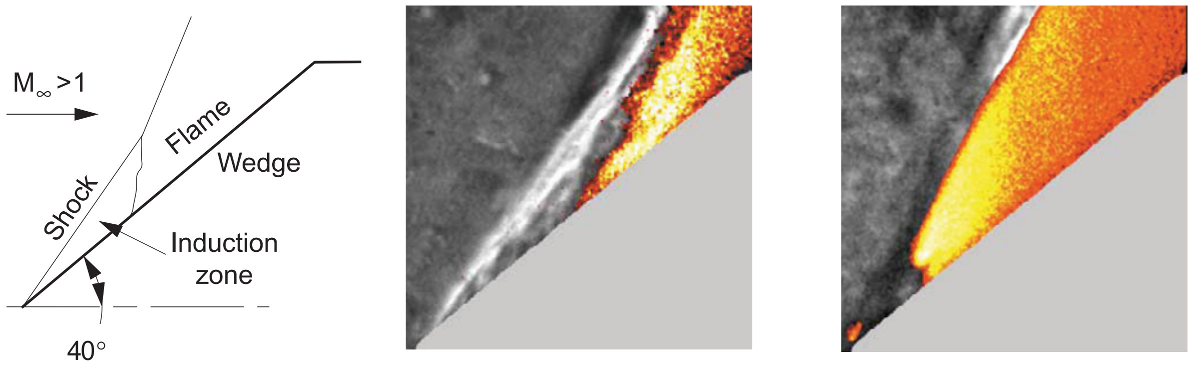


Fig. 6. Schematic of expansion tube facility and optical arrangement used for simultaneous OH PLIF and schlieren imaging of reacting flows.

The expansion tube diagnostics consist of conventional techniques for monitoring the shock speed and static pressures, and combined schlieren and PLIF imaging for the flow over the test object. The schlieren system is of standard Z-configuration, with two *f*/8, 31.8 cm (dia) concave mirrors, a razor blade for a knife edge, and an intensified (time-gated, typically 50 ns) CCD camera (576×384 pixels) for detection. The light source was provided by the fluorescence from a dye cell (Rhodamine 6G, 550-600 nm) pumped by a frequency-doubled Nd:YAG laser (Quanta-Ray GCR-3). A 1 mm iris was used to limit the size of the source and maintain good collimation of the light while passing through the test section. The PLIF system has been used to image NO (226 nm excitation), OH (283 nm) and acetone in various experiments. The results to be shown here are for OH, in which case the laser sheet was formed from a pulsed dye laser (Lumonics HD-500 dye laser, frequency-doubled, pumped by a Lumonics YM-1200 Nd:YAG laser) with pulse energies of about 6 mJ near 283 nm in the (1,0) band of the A-X system of OH. The laser sheet was about 0.5 mm thick×2.5 cm wide at the viewing section; the fluorescence was collected (within 1μs of the schlieren image) with a *f*/4.5, 105 mm UV lens and recorded on a gated (100 ns) ICCD (578×384 pixels). For the present flow conditions, the PLIF signal is proportional to the mole fraction of OH in the reacting flowfield.

In this early work, simple test objects have been used including 2-D wedges (with various half-angles) and hemispherically blunted cylinders. Thus far the objects have been placed in the freestream without flow confinement, though confined flows are planned. Example results for a flow of combustible hydrogen-oxygen-nitrogen mixtures over a 40 degrees (half-angle) wedge are shown in Fig. 7. Here the stoichiometric mixture,



(a) (b) (c)

Fig. 7. (a) Schematic of shock-induced combustion of a 40 degree wedge test body. (b) and (c) Overlaid schlieren and OH PLIF images of reactive flow of 2 H_2 + 1 O_2 + 17 N_2 at T_∞ = 290 K, V_∞ = 2130 m/s, and M_∞ = 5.8 over the 40 degree wedge. V_∞/V_{CJ} = 1.6. (b) P_∞ = 0.12 atm. (c) P_∞ = 0.18 atm. In both cases the two images were acquired nearly simultaneously (Δt < 1 μs).

diluted in nitrogen, is expanded to 290 K, 0.12 bar (for Fig. 7(b)) or 0.18 bar (Fig. 7(c)), and a velocity of 2130 m/s ($M = 5.8$); this velocity is 1.6 times the detonation velocity of the mixture.

The expected behavior of this superdetonative reactive flow is illustrated schematically in Fig. 7(a) and depends critically on the ignition time of the mixture at the flow conditions downstream of the oblique shock wave attached to the leading edge of the wedge. When the ignition time exceeds the flow time along the surface of the wedge, the PLIF images obtained indicate no formation of OH along the wedge front surface (the region imaged) and the schlieren images recover a simple oblique shock wave at the angle expected for a nonreacting flow with the test gas composition (54 degrees, for the present conditions). The more interesting case, indicated schematically in Fig. 7(a) and in actual data in Fig. 7(b), is when ignition occurs at some point in the boundary layer region along the wedge. The result is then appearance of OH in the PLIF image and a transition in the shock angle (in the schlieren image) from the initial unreacting case to that appropriate for the energy release associated with this reacting gas mixture. The specific angles can be obtained from a standard shock polar analysis (e.g., see Morris, 1996). The wave at 62 degrees, is termed an overdriven oblique detonation wave (ODW). As the pressure is increased, the ignition time is reduced and the reaction zone moves forward along the wedge surface, as indicated in Fig. 7(c). Here the reaction is more closely coupled to the shock front and the transition in shock angle from 54 degrees to 62 degrees, occurs much closer to the leading edge of the wedge. At yet higher pressures (and hence reduced ignition time), we observe that the reaction couples strongly to the shock wave very close to the leading edge of the wedge. Since analysis reveals that the maximum flow-turning angle for this gas mixture is about 35 degrees, there is a question as to whether the leading edge of the shock remains at an (unreacted) angle of 54 degrees, or detaches from the wedge. Further details of this work have been presented (Morris, 1996) and recent results for flow over blunted axisymmetric bodies have been reported previously (Kamel, 1997).

3.2 PLIF Temperature Imaging with Acetone

Most past work to develop PLIF methods for imaging temperature has utilized nitric oxide (NO), iodine I_2 or combustion radicals such as OH, all of which have serious limitations and are not readily applicable in air flows. Thus there is a continuing need to identify a relatively simple and accurate means of measuring instantaneous 2-D temperature distributions in air, ideally over a wide temperature range. One promising approach is to seed air with a tracer species with desirable temperature-sensitive fluorescence properties. Based on work over the past few years in our laboratory, it appears that acetone may be an attractive species for this purpose, at least up to about 1000 K. Here we summarize recent efforts to characterize the fluorescence properties of acetone and demonstrate its use for temperature imaging.

Acetone (CH_3COCH_3) has many advantages as a tracer for PLIF imaging and in fact is already widely used in experiments to image mixing of gases (e.g., see Lozano, 1992 and Tait, 1992). In particular: the absorption feature of acetone (220-320 nm, depending on temperature) is readily accessible by fixed-frequency pulsed laser sources; the fluorescence is in the visible, thereby facilitating detection with unintensified CCD cameras with high quantum efficiencies; the fluorescence yield of acetone is generally dominated by intersystem transfer, and hence is effectively immune to the presence of oxygen; and of course acetone has a high vapor pressure and is easily and safely handled. Interestingly, although use of acetone PLIF has spread rapidly to a substantial number of laboratories with applications ranging from low temperature supersonic flows to high-pressure combustion in engines, the photophysics of acetone (i.e., the temperature, pressure and wavelength dependence of acetone absorption and fluorescence) has received relatively little attention. Our work on this subject was in fact prompted by a need to explain the influence of temperature on acetone images acquired in a supersonic compressible flow with significant pressure and temperature variations.

Here we summarize key results from experiments on the absorption and fluorescence properties of acetone at atmospheric pressure (see Yuen, 1996 for a recent treatment of the pressure dependence of acetone fluorescence, which is relatively weak near one atmosphere). In brief, the absorption coefficient was measured (see Thurber, 1996 and the references therein for further details) as a function of wavelength and temperature, and significant changes in the spectral distribution of absorption were observed at both the short- and long-wavelength extremes of the distribution. The fluorescence yield was found to decline with increasing temperature, but was only weakly dependent on excitation wavelength (except at the shortest wavelengths studied). The results of these measurements are summarized in Fig. 8(a), which is a plot of the fluorescence signal (per unit laser energy and per unit mole fraction of acetone) as a function of temperature for a selection of excitation wavelengths. The curves are normalized by the value at room temperature for convenience. The important conclusions are: (1) only the longest wavelength, 320 nm, yields a signal which is nearly independent of temperature and thus could be used for

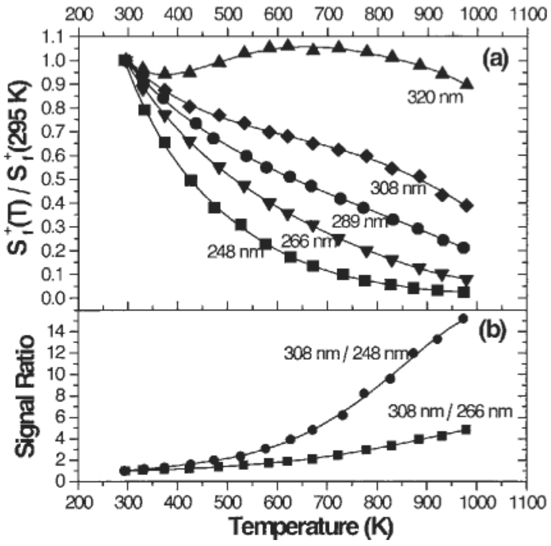


Fig. 8. (a) Plots of S_f^+ (fluorescence per unit laser energy per unit mole fraction) with temperature at p = 1 atm, normalized to the room temperature value. (b) Temperature behavior of the fluorescence ratio, generated by dividing one curve of S_f^+ by another.

measuring the mole fraction without simultaneous knowledge of temperature; and (2) the sensitivity of the fluorescence signal to temperature is strongest at short wavelengths. In anticipation of the need for ratio-based schemes, Fig. 8(b) provides a plot of the signal ratio for two attractive excitation wavelength pairs.

We have explored two different imaging strategies for acetone-seeded air flows. In cases where a constant mole fraction of acetone can be utilized, a simple single-excitation-wavelength scheme can be used. For reacting or mixing flows, a ratio of signals can be used, for example the wavelength pairs indicated in Fig. 8(b). Example results which demonstrate the single-wavelength scheme are shown in Fig. 9. This is a laminar (*Re* = 6) flow of air over a simple heated cylinder (approximately 485 K, 3 mm dia), with a constant seeding fraction of about 15%. Excitation is at 248 nm, provided by a KrF excimer laser with a pulse energy of about 40 mJ. The single-shot fluorescence image is recorded on an unintensified CCD array (512×512 pixels), and is shown after corrections for background luminosity and nonuniformities in the laser sheet profile and the collection optics. For this laminar flow, it is convenient to use a repeating intensity scale which illustrates the high sensitivity of the measurement.

The results obtained in this initial experiment suggest that acetone-based temperature imaging holds good

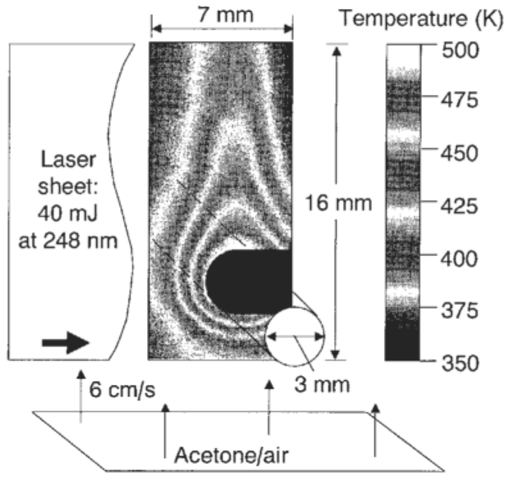


Fig. 9. Single-shot temperature image in a heated cylinder flow, generated with the single-wavelength technique using 248-nm excitation and the geometry shown.

promise for sensitive and accurate temperature measurements in air flows, with the potential to resolve temperature variations of a few degrees K or better. We have applied the method at temperatures up to 1000 K without signs of acetone decomposition (for the flow residence times employed), and of course the method should also be well-suited for measurements at low temperatures where the signal strengths are increased (per unit mole fraction). We have also demonstrated the dual-wavelength scheme, with similarly good results (see Thurber, 1996). Although further work is needed to characterize the combined temperature-pressure-wavelength dependence of acetone, it is clear that PLIF-based temperature imaging of acetone will provide useful new diagnostic capability for studies of heat transfer and combustion.

4. Conclusions

TDL absorption and PLIF imaging are laser-based diagnostics of growing impact and utility for gasdynamics and combustion research and development. TDL absorption offers viable and unique capability for monitoring and control of combustion (and other) processes through simple and quantitative measurements of species, temperature and velocity, where line-of-sight measurements are useful or preferred. These methods will surely grow in use as costs of laser sources and fiber-optic components drop and access improves to more wavelength regions. PLIF imaging continues to serve as a powerful tool for qualitative visualization of complex flows, but good progress is also being made toward development of quantitative PLIF imaging of some properties, such as temperature. In addition, there is an important trend toward combined imaging diagnostics, such as dual-PLIF imaging for simultaneous monitoring of multiple species or temperature and species. Such combined imaging strategies will increase the value of laser diagnostics in basic and applied future studies.

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References

Chou, S. I., Baer, D. S. and Hanson, R. K., "Diode-Laser Absorption Measurements of CH_3Cl and CH_4 near 1.65 μm," Applied Optics, 36-15, (1997), 3288.

Clemens. N. T. and Paul, P. H., "Effects of Heat Release on the Near Field Flow Structure of Hydrogen Jet Diffusion Flames," Combustion and Flame, 102-3 (1995), 271.

Furlong, E. R., Baer, D. S. and Hanson, R. K., "Combustion Control Using a Multiplexed Diode Laser Sensor System," 34th AIAA Aerospace Sciences Meeting, Reno, NV, January 16-20 (1996a), paper AIAA 96-0756.

Furlong, E. R., Baer, D. S. and Hanson, R. K., "Combustion Control Using a Multiplexed Diode Laser Sensor System," Twenty-Sixth Symposium (International) on Combustion (1996b), The Combustion Institute, Pittsburgh, 2851.

Furlong, E. R., Mihalcea, R. M., Webber, M. E., Baer, D.S. and Hanson, R. K., 1998, "Diode Laser Sensors for Real-Time Control of Pulsed Combustion Systems, "34th AIAA Joint Propulsion Conference, Cleveland, OH (1998), paper AIAA 98-3949.

Hanson, R. K., Kuntz, P. A. and Kruger, C. H., "High-Resolution Spectroscopy of Combustion Gases Using a Tunable Infrared Diode Laser," Applied Optics, 16-8 (1977), 2045.

Hertzberg, A., Bruckner, A. P. and Bogdanoff, D. W., "Ram Accelerator: A New Chemical Method for Accelerating Projectiles to Ultrahigh Velocities," AIAA Journal, 26-2 (1988), 195.

Kamel, M. R., Morris, C. I. and Hanson, R. K., "Simultaneous PLIF and Schlieren Imaging of Hypersonic Reactive Flows Around Blunted Cylinders," 35th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 6-9 (1996), paper AIAA 97-0914.

Lozano, A., Yip, B. and Hanson, R. K., "Acetone: a Tracer for Concentration Measurements in Gaseous Flows by Planar Laser-Induced Fluorescence," Experiments in Fluids, 13-6 (1992), 369.

Mihalcea, R. M., Webber, M. E., Baer, D. S. and Hanson, R. K., "Diode Laser Sensor for Combustion Emissions Monitoring," Proceedings of VSJ-SPIE98, December 6-9, 1998, Yokohama, Japan (1998), paper no. AB059,

Morris, C. I., Kamel, M. R. and Hanson, R. K., "Expansion Tube Investigation of Ram-Accelerator Projectile Flowfields," 32nd AIAA Joint Propulsion Conference, Orlando, FL, July 1-3 (1996), paper AIAA 96-2680.

Parr, T.P., Gutmark, E.J., Wilson, K.J., Hanson-Parr, D. M., Yu, K., Smith, R.A. and Schadow, K.C., 1996, "Compact Incinerator Afterburner Concept Based on Vortex Combustion," Twenty-Sixth Symposium (International) on Combustion (1996), The Combustion Institute, Pittsburgh, 2471.

Philippe, L. C. and Hanson, R. K., "Laser-Absorption Mass Flux Sensor for High-Speed Air Flows," Optics Letters, 16-24 (1992), 2002.

Rea, E. C., Jr., Salimian, S. and Hanson, R. K., "Rapid-Tuning, Frequency-Doubled Ring Dye Laser for High-Resolution Absorption Spectroscopy in Shock-Heated Gases," Applied Optics, 23-11 (1984), 1691.

Tait, N. P. and Greenhalgh, D. A., "2D Laser-Induced Fluorescence Imaging of Parent Fuel Fraction in Nonpremixed Combustion," Twenty-Fourth Symposium (International) on Combustion (1992), The Combustion Institute, Pittsburgh, 1621.

Thurber, M. C., Grisch, F. and Hanson, R. K., "Temperature Imaging with Single- and Dual-Wavelength Acetone Planar Laser-Induced Fluorescence," Optics Letters 22, 251-253.

Wehe, S. D., Baer, D. S. and Hanson, R.K., "Tunable Diode-Laser Absorption Measurements of Temperature, Velocity, and H_2O in Hypersonic Flows," 33rd AIAA Joint Propulsion Conference, Seattle, WA, July 6-9 (1997), paper AIAA-97-3267.

Wehe, S. D., Baer, D. S., Hanson, R. K. and Chadwick, K. M., "Measurements of Gas Temperature and Velocity in Hypervelocity Flows Using Diode-Laser Sensors," 20th AIAA Advanced Measurement and Ground Testing Technology Conference Albuquerque, NM, June 15-18 (1998a), paper AIAA-98-2699.

Wehe, S. D., Baer, D. S. and Hanson, R. K., "Diode-Laser Sensor for Velocity Measurements in Hypervelocity Flows," submitted for publication to Optics Letters (1998b).

Yuen, L. S., Peters, J. E. and Lucht, R. P., 1997, "Pressure Dependence of Laser-Induced Fluorescence from Acetone," Applied Optics 36-15 (1997), 3271.

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