Advanced Laser Diagnostics for Reactive Flows

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Abstract

Laser-based diagnostics provide powerful and unique capabilities for non-intrusive measurements in reactive flows. This paper will overview recent progress in the evolution and application of two of the most important diagnostic concepts: tunable diode laser (TDL) absorption, which is a line-of-sight technique with continuous recording potential; and planar laser-induced fluorescence (PLIF) imaging, which yields instantaneous measurements at a large number of points in a plane illuminated by a pulsed laser. Techniques based on these measurement concepts can monitor multiple parameters including species concentrations, temperature, pressure and velocity. Example results will be shown for TDL measurements in a pulse detonation engine and for PLIF imaging in an expansion tube study of supersonic combustion.

Background

Several laser-based diagnostics have been investigated and employed for non-intrusive measurements in reactive flows, over a period of about thirty years. Interest in combustion and propulsion, in particular, has driven development of these advanced measurement techniques. Of the methods developed thus far, absorption and laser-induced fluorescence, both of which are linear methods, are especially attractive owing to high signal strength, species specificity, and relative simplicity of equipment and data interpretation. In addition, these methods have proven able to sense a variety of critical flowfield quantities including species, temperature, pressure and velocity. Absorption is a line-of-sight method, typically employing continuous wave (CW) laser sources, fixed or variable in wavelength, while fluorescence affords spatially resolved measurements at single or multiple points, and uses pulsed laser sources. When laser-induced fluorescence is conducted with a sheet of laser light and a 2-D detector array, the method is termed planar laser-induced fluorescence (PLIF). The underlying theory of both absorption and fluorescence is well understood, though quantitative applications require knowledge of various spectroscopic and collisional parameters which are known with varying uncertainty, depending on the species and the local thermodynamic state of the gas.

Laser absorption may be carried out using ultraviolet, visible, near-infrared (NIR) or infrared (IR) wavelength sources, and over the past thirty years there have been notable successes with laser absorption in all these spectral domains. Over the past decade, there has been particular emphasis on developing tunable diode laser (TDL) absorption diagnostics using NIR sources developed for use in the telecommunications industry. At the present time, laser sources can be produced over much of the spectral region from about 400 nm to 2.0 microns, but the cost of these lasers varies widely with wavelength owing to the influence of market size. In the section immediately below, we will illustrate the potential of NIR TDL absorption for reactive flows by presenting sample measurements obtained in a pulse detonation engine. In the following section, we will illustrate the power of PLIF diagnostics in reactive systems through an example application to supersonic combustion.

Tunable Diode Laser Absorption in Pulse Detonation Engine

Pulse detonation engines (PDEs) are of interest because they offer potential advantages over conventional propulsion concepts. We have applied diode laser sensors to PDE flows at Stanford University and at the Naval Postgraduate School (NPS) in Monterey, CA, with three primary goals: to demonstrate the utility of diode lasers in harsh reactive flow environments for flowfield sensing and combustion control; to improve understanding of performance-critical PDE processes, through measurements in realistic, developmental engines; and to obtain high-quality PDE data useful in developing and validating computational models of PDEs. See Ref. 1 for a recent summary of this work.

The flow in a pulse detonation engine is complex and features large and rapid variations in several key properties, which include: fuel and oxidizer concentration and temperature, detonation wave speed, concentration and temperature of combustion products, pressure, velocity, and soot loading. As an additional complexity, the flow properties and their time histories may vary with axial location in the PDE, though it is reasonable to assume that properties are relatively uniform transverse to the flow. Recognizing these challenges, we have pursued diode laser absorption techniques for multiple flow parameters, and we have developed diagnostic systems which allow multiple-parameter measurements to be conducted simultaneously and, if desired, at multiple axial locations in the PDE. A schematic of a typical TDL sensor system, as employed at Stanford and also in tests conducted collaboratively at the Naval Postgraduate School, is shown in Fig.1. The suite of lasers is mounted on a small optical breadboard (60x120 cm), located remotely from the PDE; the combined ("wavelength-multiplexed") light is sent by a single optical fiber to the test stand where it is directed through simple sapphire windows, de-multiplexed (separated into different-wavelength beams) and then recorded on separate detectors. This particular laser system utilizes five different wavelengths, chosen to match three selected water vapor transitions in the 1.3-1.8 micron region and two non-resonant wavelengths selected to be free of molecular absorption. These latter two wavelengths may be used to monitor particulate (soot) loading, droplet concentration, or simply to make baseline corrections to the signals acquired at resonant wavelengths. The number of laser wavelengths is somewhat arbitrary; as many as seven wavelengths have been used in any one experiment. In addition to water vapor measurements, which yield critical information on the products of combustion, we also employ TDL diagnostics routinely for oxygen concentration (and temperature) and fuel (hydrocarbon) concentration. We have found these latter two measurements to be critical in establishing desired fuel-oxidizer loading in the tube, prior to detonation wave formation, and in evaluating the effects of cycle-to-cycle interference effects when the PDE repetition frequency is increased.

The governing equation for absorption of narrow-linewidth laser light is the Lambert-Beer law

$$T_\nu = (I/I_0)_\nu = \exp(-S\,\phi(\nu)\,P_i\,L)$$

Here T_ν is the fractional transmission at frequency ν, I and I_0 are the transmitted and incident intensities at ν (these are the measured quantities), S is the integrated line intensity (a function of temperature), $\phi(\nu)$ is the lineshape function (dependent on temperature and pressure), P_i is the partial pressure of the absorbing species (often the desired quantity), and L is the known absorption pathlength (i.e., the tube diameter). The fundamental spectroscopic parameter S is typically known, either from tabulations or direct measurements in controlled experiments, while the lineshape function is either measured directly in the experiment (if the laser is rapidly scanned in wavelength) or modeled from known line broadening parameters (again, taken either from tabulations or controlled experiments). The justification for selecting multiple water vapor transitions is that the temperature can be inferred directly from the ratio of absorption at two of the wavelengths, with a third transition being selected either to be temperature-independent or as a check on the measurements recorded at the other wavelengths.

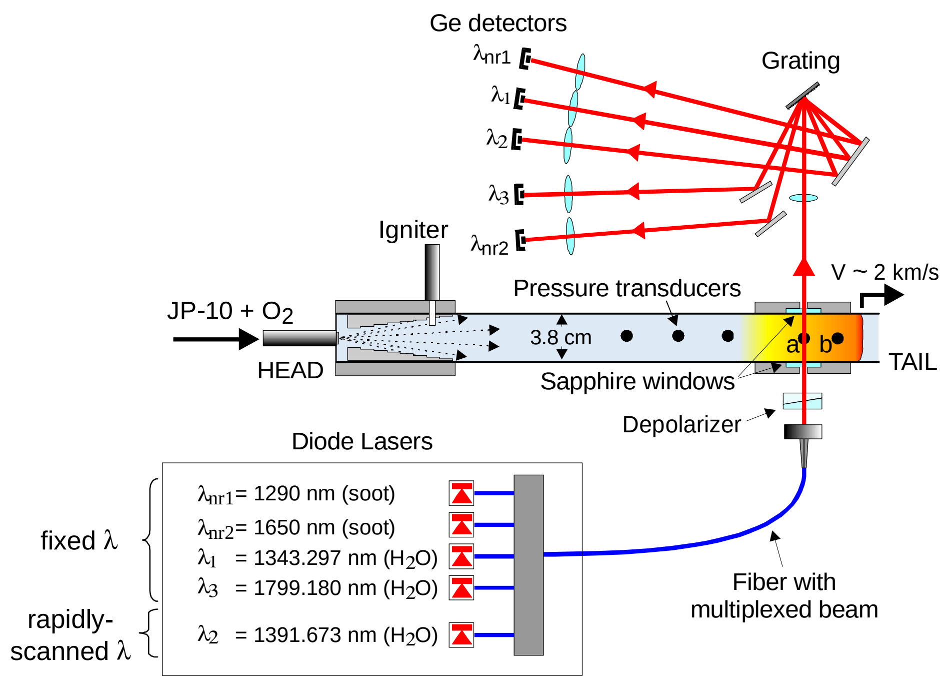

Figure 1. Schematic of 5-wavelength sensor for gas temperature and H_2O concentration, applied to the PDE at NPS. Overall tube length is 32 cm.

The absorption transitions in the near-infrared are typically vibration-rotation transitions, and generally correspond to overtone or combination bands of molecular species. For example, the water vapor transitions corresponding to the wavelengths indicated in Fig. 1 are part of the $\nu_1+\nu_3$, $2\nu_1$ and $2\nu_2+\nu_3 \leftarrow \nu_2$ bands of H_2O. Measurements of hydrocarbon fuel concentration are typically done either at 3.39 microns (infrared line of a helium-neon laser), corresponding to the C-H stretch of many hydrocarbons, or near 1.65 microns, which corresponds to the overtone of the fundamental band for C-H vibrations. Measurements of oxygen concentration and temperature are made near 760 nm, which is the center of the well-known atmospheric band of O_2. This is actually an electronic absorption band rather than a vibrational band.

Sample results of TDL absorption data, obtained in the Stanford PDE facility, are shown in Figs. 2 and 3. Figure 2 provides a record of the burned gas temperature history acquired near the exit plane of the PDE (fueled with stoichiometric ethylene and air at atmospheric pressure) and Fig. 3 provides the corresponding record of water vapor mole fraction. The detonation wave arrives at a time of about 1.1 milliseconds after the igniter is fired, producing a step change in temperature and water concentration to values corresponding closely to those calculated for the Chapman-Jouguet condition (combustion equilibrium). This rapid combustion behind the detonation wave is expected for the ethylene-air system, which has a small detonation cell size. The measurements are seen to agree well with simple (method-of-characteristics, with constant specific heats) modeling and also with a more realistic computation performed at the Naval Research Laboratory (NRL). The ability of the TDL sensor to make quantitative measurements in this hostile environment, with large variations in temperature and pressure, provides convincing evidence of the utility of this diagnostic tool for many reactive flows of fundamental and applied interest. It should be noted that this diagnostic has also been used with liquid fuels (JP-10), in the NPS PDE facility, including cases which produced heavy soot loading. Furthermore, we successfully employed other versions of the TDL system to characterize fuel droplet and fuel vapor fuel loading in the engine, and also to monitor the time-varying soot loading at the exit plane.

In the work thus far, measurements have typically been made at a single axial location, but it should be relatively straightforward to split the multiplexed beam and use these beams to make simultaneous measurements at multiple locations in the flow. In addition, other species or even other flow parameters may be sensed, such as velocity. In recent work, we have built a first-generation diagnostic for measuring the flow velocity at the exit plane of the Stanford PDE via absorption of a cesium chloride tracer. We have compared these measurements with computational results at NRL, and found excellent agreement. Such data are likely to be very useful in validation of computational codes for PDEs.

The good results obtained thus far with TDL diagnostics in PDEs provides convincing evidence that similar diagnostics could be used effectively in other reactive flow systems, both in fundamental laboratory experiments and also in larger-scale systems. Looking ahead, we believe that TDL sensors could be used in full-scale combustors and engines as sensors in control systems, and preliminary experiments to demonstrate fuel sensing and control are now underway.

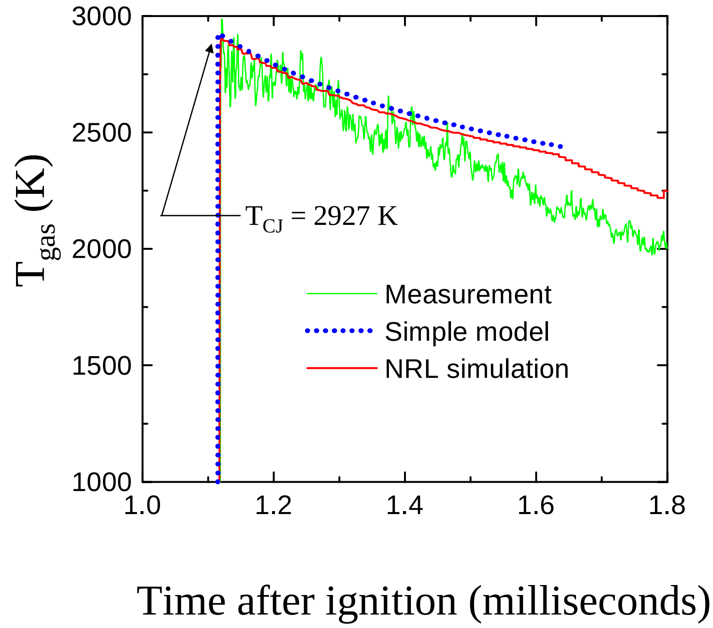

Figure 2. Measured burned gas temperature history recorded in the Stanford PDE using the 5-wavelength sensor shown in Fig. 1. The history agrees well with a simple (method of characteristics) model and a full numerical simulation (performed by NRL).

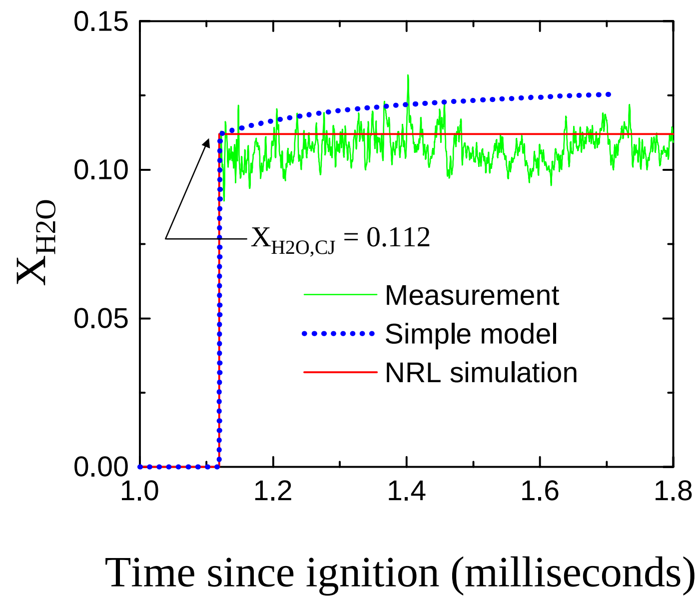

Figure 3. Measured burned gas H_2O concentration history recorded in the Stanford PDE using the 5-wavelength sensor shown in Fig. 1. The measurement again agrees well with both models. The simple model assumes equilibrium chemistry whereas the NRL simulation assumes frozen chemistry (at the CJ condition), accounting for the slight disagreement.

Planar Laser-Induced Fluorescence Imaging of Supersonic Combustion

Laser diagnostics capable of providing instantaneous 2-D images of key parameters are extremely valuable tools in both fundamental and applied studies of complex exothermic flows. An outstanding example of such complex flows is supersonic combustion, e.g. in connection with future hypersonic air-breathing propulsion systems. Such engines will depend on efficient injection, mixing, and combustion in a supersonic flow environment, and studies aimed at understanding and controlling these interconnected phenomena will clearly benefit from the use of advanced non-intrusive diagnostics such as PLIF which provide “image” data.

Due to the large enthalpies associated with supersonic and hypersonic flight, impulse flow facilities are often used to provide the required total temperature and high velocities. Expansion tubes and shock tunnels are the obvious choices for such facilities. At Stanford we have build and employed an expansion tube, which offers the advantage of less perturbation to the chemical composition of the high-speed air stream, and hence more accurate simulation of combustion chemistry, including ignition time delay. However, the test times possible in expansion tubes are shorter than those obtainable in reflected shock tunnels.

A schematic of the Stanford expansion tube and its key instrumentation is shown in Fig. 4. The facility allows single-shot PLIF imaging and simultaneous high-speed schlieren imaging (8 images at a framing rate up to 10^7 frames/sec)(See Ref. 2 for details). The laser system used for PLIF imaging is a conventional Nd:YAG-pumped dye laser, which is tuned to match an absorption line of the target species. The pulse of laser light (10-20 nsec in duration) is formed into a sheet which passes through a section of the flowfield, and the resulting fluorescence is collected with a time-gated image-intensified CCD camera (typically 578x384 pixels). The gatewidth of the camera is variable, and is typically set at 20-50 nsec, which is short enough to effectively freeze the motion of the hypersonic flows under study. The PLIF signal is linearly proportional to the population density in the absorbing quantum state; by proper selection of laser wavelength (and thus the quantum state excited), this signal may be rendered relatively insensitive to temperature and hence can be taken as proportional to the mole fraction of the target species. Different species may be excited, but OH is a common target in that it identifies the regions of combustion occurring in the flow. In work conducted previously in our laboratory, we used dual-line imaging of NO to measure the instantaneous temperature field in high-speed combustion flows.

The flow studied most extensively in our experiments has been a supersonic jet of fuel (hydrogen) in a supersonic crossflow of air; this has been done with and without the presence of a cavity flame holder. The objective was to simulate Mach 10-13 flight conditions (see Ref. 2 for details) and to investigate fundamental aspects of ignition limits, flameholding, and flowfield structure. An example PLIF image, for the case of normal injection of hydrogen without a cavity flameholder, is shown in Fig. 5. This image is obtained on the center-line axis of the hydrogen jet for the case of oxygen crossflow simulating Mach 10 flight. The horizontal axis is given in units of x/d, where d is the jet diameter, 2 mm. The freestream conditions are nominally M = 4.7, T = 1300K, P = 5 kPa, V = 3300 m/s. Note the ability of the PLIF imaging system to capture the presence of an upstream recirculation zone, which provides the needed flameholding, as well as to indicate the instantaneous flame zone, which is a thin filamentary region of complex structure that results from the mixing of jet and cross-stream fluid.

The PLIF data acquired in these experiments provides a helpful guide to understanding these flows as well enabling efficient study of combustion limits and how these can be modified with cavity flameholder schemes. In addition, these data are of critical value in the development and validation of computational codes for supersonic reacting flows.

Summary Comments

Laser-based diagnostics are now accepted tools in most modern laboratories engaged in research on reactive flows, and the impact of these tools on the pace of scientific and engineering research is apparent. Further progress is needed, however, to develop laser diagnostic systems which are more affordable, rugged and simpler to operate, which would lead to even greater use of such systems. The author is particularly optimistic about the future of TDL absorption diagnostics, which offer high potential as sensors in a wide range of applications, from basic research to industrial use, including a role in process control. The possibility of an expanded market for TDL sensors will likely lead to improved commercial availability of diagnostic systems of interest to scientists and engineers engaged in research and development of reactive flow systems.

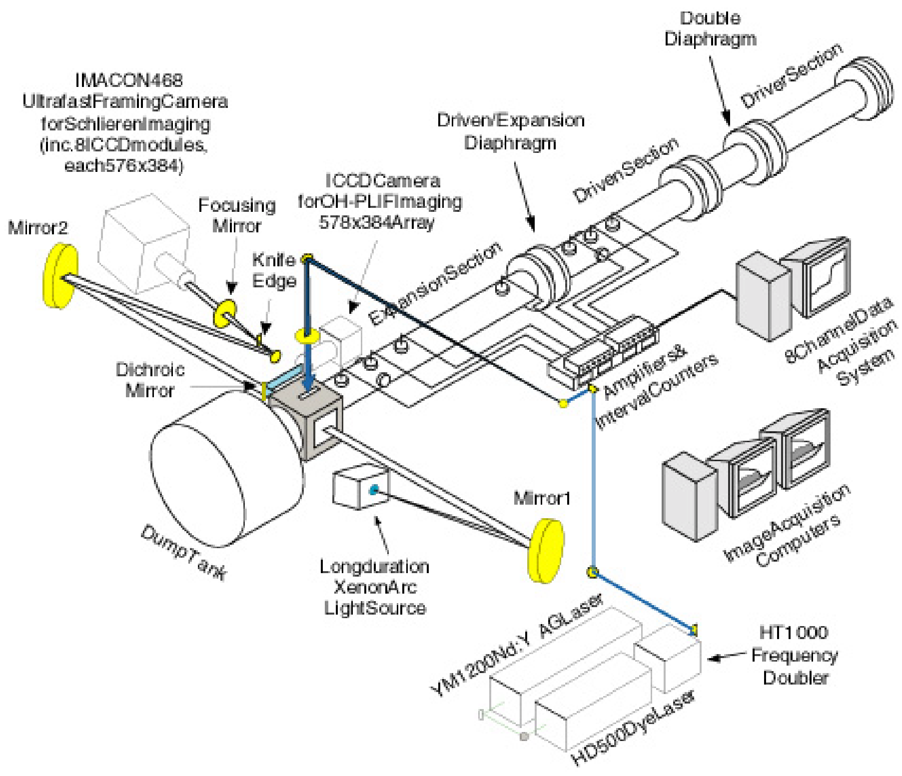

Figure 4. Expansion tube facility (12m in length) and imaging system.

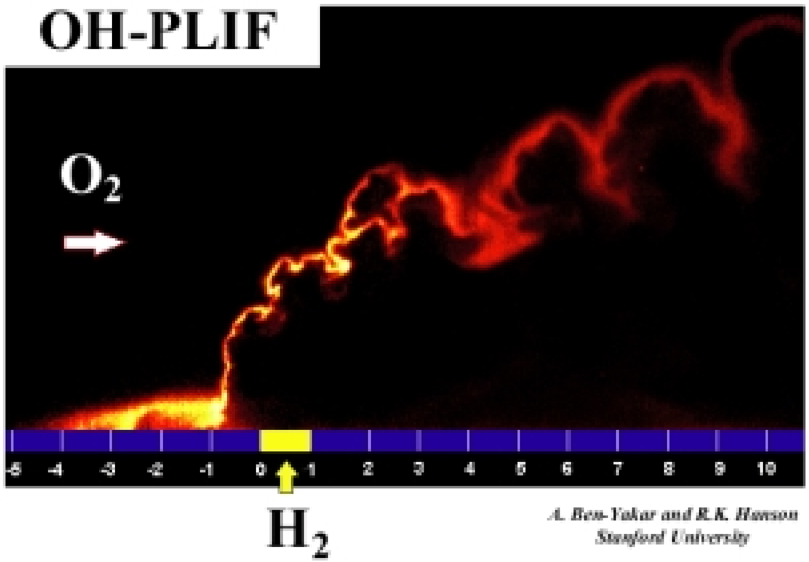

Figure 5. An instantaneous OH-PLIF image demonstrating the ignition and flameholding capability of jet-in-crossflow at high enthalpy condition. Free-stream conditions are nominally M = 4.7, T = 1300K, P = 5 kPa, V = 3300 m/s. The jet-to-freestream momentum flux ratio is J=5.

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