UV Laser Diagnostics for Studies of Finite-Rate Chemistry in PDEs

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Abstract

Time-resolved OH concentration and gas temperature are measured in the Stanford University pulse detonation tube facility using CW, UV laser absorption. OH is monitored by direct absorption of the $R_{21}(5)$ and $S_{21}(1)$ transitions in the 0, 0 band of the A-X system. Gas temperature is determined from UV CO_2 absorption. Results from these diagnostics are useful in determining the impact of finite rate chemistry assumptions on PDE performance characteristics, in verifying computational simulations, and in advancing PDE design and development.

Introduction

Pulse Detonation Engines (PDEs) have received much interest in recent years due to their potential advantages over conventional aero-propulsion systems. Researchers have performed both computational and experimental studies designed to characterize the performance, study feasibility, and investigate limitations of the device.

Assumptions regarding reactive chemistry employed in most computational simulations of PDE performance can be broken down into two main categories: 1) frozen chemical composition at the Chapman-Jouguet plane, and 2) full, finite-rate chemistry. Recent computational results for H_2/air show a 5-7% difference in overall performance for straight tubes (as determined by specific impulse, I_{sp}, and head end pressure calculations). Differences in temperature and species concentrations can be much larger and could become important in overall performance when additional characteristics such as heat transfer effects and thrust-enhancement devices such as nozzles are included in system calculations.

Diagnostics based on laser spectroscopy have been successfully demonstrated even in harsh measurement environments. Hence these diagnostics, capable of measuring several pertinent gas properties (T, P, $V_{\text{burned gas}}$), can play an important role in PDE advancement. In order to evaluate chemistry assumptions employed in computational simulations, transient measurements of species concentration are needed. In this paper, we describe the initial results from two newly applied diagnostics: an X_{OH} sensor and a T_{CO2} sensor based on UV absorption These two diagnostics and sample results are described below.

OH concentration

A novel, *in situ,* microsecond time-resolved, laser absorption measurement of OH concentration behind the detonation wave in the Stanford PDE facility is reported. A CW, frequency-doubled, Nd:YAG- pumped dye laser is used to probe OH absorption features near 306 nm for single-cycle PDE experiments.

The theoretical groundwork for extracting species concentration in high temperature combustion environments from laser absorption measurements of spectroscopic features has been described and detailed previously. In brief, a laser beam tuned to the line center of a resonant transition of the target species is pitched through a test gas of interest and its transmitted intensity is monitored using a photo-detector. The ratio of the transmitted (resonant) to the incident (baseline) beam intensity determined from the photo-detector signal provides absorbance through the Beer-Lambert relation. The absorbance quantity can be used to infer information on temperature, pressure and gas composition.

For this set of measurements, two transitions OH were chosen: the $R_{21}(5)$ and the $S_{21}(1)$. These transitions are well suited for measuring the OH concentration for the first 5 ms behind the detonation wave for two reasons. The transitions are well isolated from surrounding absorption features and have an appropriate absorption strength for the test conditions of interest.

The Stanford PDE facility and the laser utilized for this diagnostic are shown in Fig. 1. The PDE consists of a 3.8 cm diameter, 160 cm long tube closed at the head end and open at the tail end. For a typical experiment, premixed, stoichiometric ethylene-oxygen is injected into the head end of the tube. After the tube is filled, the flow valves are closed and a spark ignitor is fired at the head end causing a detonation wave to form and traverse the length of the tube. The optical measurement station is 144 cm from the head end of the PDE. For the OH concentration measurements, a 5W, 532 nm, solid-state laser pumps a tunable, intra-cavity-doubled ring dye laser to produce UV light near 306 nm.

A measurement cycle consists of three consecutive detonation experiments for which the dye laser is tuned to three different wavelengths. The raw laser transmission data is shown in Fig. 2. The gas mixture is ignited at time 0; the detonation wave reaches the measurement station at 0.6 ms. The first wavelength (off-line OH, 306.0457 nm) is used to track non-resonant extinction caused by soot and window effects and resonant absorption by other species (CO_2) providing the I_o signal for the OH concentration measurement. For the second and third wavelengths (306.3413 nm, $S_{21}(1)$, and 306.7004 nm, $R_{21}(5)$), absorption by OH further reduces the transmitted laser intensity values compared to the off-line extinction. Two absorbance values are determined from the ratio of the $S_{21}(1)$ to the off-line OH and the $R_{21}(5)$ to the off-line OH signals using the Beer-Lambert relation.

In order to determine OH concentration from the absorption measurements, the temperature and pressure of the gas need to be measured to determine the spectral absorption coefficient. The results of T and P from a previously developed diagnostic based on rapid lineshape and emission measurements of flow-seeded cesium are shown in Fig. 3. Using these traces in conjunction with the measured OH absorption, OH concentration is determined as shown in Fig. 4.

Fig. 4 contains one calculated and two measured traces (determined from these experiments) of OH concentration. The temperature and pressure values of Fig. 3 are used in conjunction with the predetonation gas composition to determine a temporally-resolved, equilibrium OH concentration using the STANJAN equilibrium code. The results of this sensor demonstrate that the reactive chemistry is a quasi-equilibrium process (on the sub-millisecond time scale) for times greater than 1 ms after detonation arrival in this PDE environment. For times less than 1 ms, chemical modeling indicates that the gases quickly equilibrate (<1µs); current work looks to extend measurement capabilities to this period.

CO_2-based temperature sensor

Absorption in the UV by carbon dioxide causes the transmission of the off-line OH wavelength to decrease. This UV absorption provides a strategy to determine product gas temperature in hydrocarbon combustion system where CO_2 is a prominent combustion product. This new sensor and sample results are described below.

For this set of measurements, two laser wavelengths are used. A 390 nm (TUI diode laser) offline beam is used to track extinction due to soot, beam steering, and window transmission variation. The 306 nm dye laser (offline OH wavelength) is used to measure CO_2 absorption, as shown in Fig. 2. The ratio of off-line OH (306.0457 nm) to off-line CO_2 (390 nm) provides absorbance through the Beer-Lambert relation.

For this sensor, two independent measurements are made: pressure and absorbance. These two quantities provide two of the three values needed to infer temperature; gas composition is constrained by enforcing equilibrium gas composition throughout the blow-down process. The results of the X_{OH} measurement indicate that this is a valid assumption for these test conditions. The measured temperature results are plotted in Fig. 5 compared to a previous temperature measurement performed using the cesium-based diagnostic. For time less than 1.2 ms, the temperature exceeds the present characterization range of the absorption coefficient. For time greater than 3.3 ms, the absorbance at this wavelength is too low to provide an accurate measurement.

The results obtained with this sensor demonstrate the potential for using UV absorption of CO_2 to determine temperature in harsh measurement environments using native combustion product species. Further calibration of the absorption coefficient to higher temperatures would facilitate temperature measurements up to the CJ temperature in hydrocarbon detonation systems. Also, by utilizing multiple UV wavelengths, the error bars shown in Fig. 5 could be reduced, measurement times could be extended past 3.2 ms, and the need for an equilibrium assumption could be eliminated.

Conclusions

Two UV laser absorption diagnostics were employed for measurements of combustion parameters in the Stanford PDE facility. The first sensor provides OH concentration behind the detonation wave with microsecond time response. The results of the initial demonstration of this diagnostic indicate that the reactive chemistry is a quasi-equilibrium process (on the sub-millisecond time scale) for times greater than 1 ms after detonation arrival in this PDE environment. The second sensor illustrates a new gas temperature measurement scheme using absorption of a native combustion product, CO_2. Both sensors should prove useful in studying the impact of PDE design changes, such as a nozzle, and in validating computational simulations.

Acknowledgements

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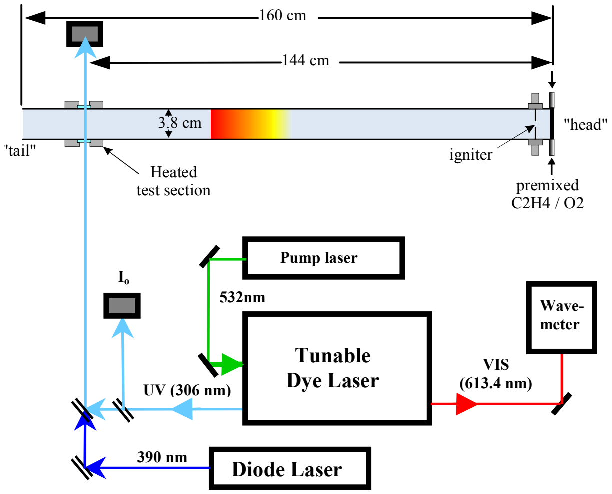

Fig 1: Schematic of Stanford University PDE facility with UV diagnostics laser sources.

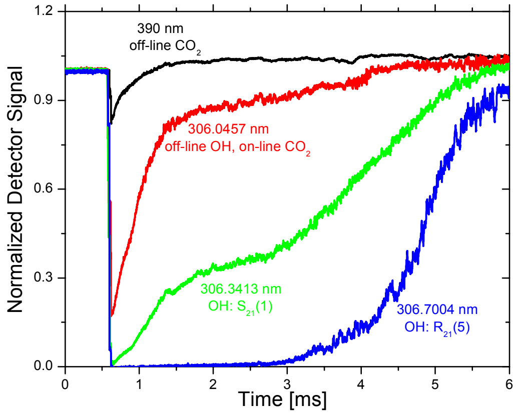

Fig. 2: Normalized detector signals at the measurement station for four distinct wavelengths for single-cycle PDE experiments.

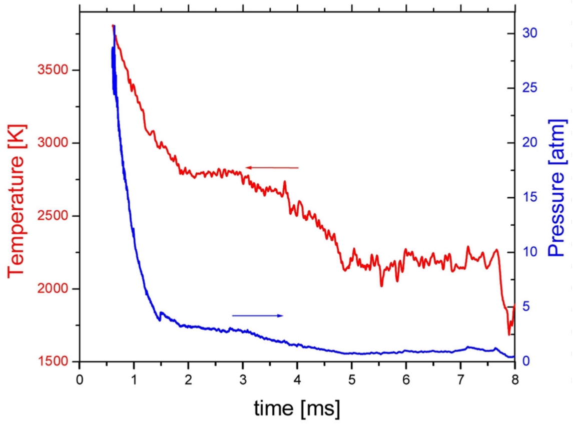

Fig 3: Previously measured temperature and pressure history at the measurement station. These data, determined from Cesium lineshape and emission measurements, are used for the OH data reduction process.

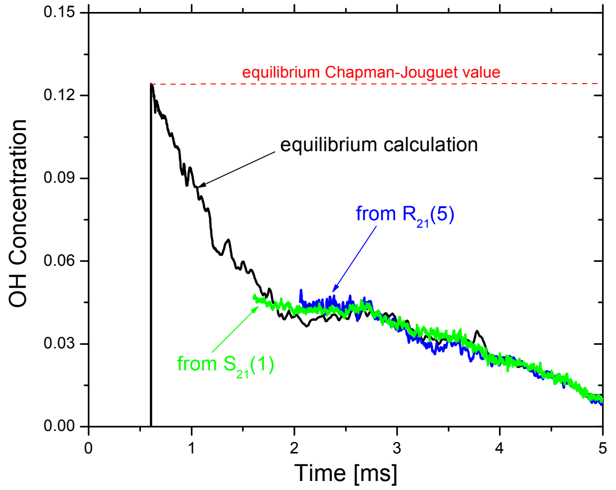

Fig 4: Measured and calculated OH concentration (mole-fraction) at the measurement station. The OH resonant transitions provide two independent measurements for times greater than 1.5 ms after detonation initiation. The equilibrium concentration is determined from the previously measured T and P along with the known reactant concentrations using the STANJAN equilibrium code. The dashed line represents the frozen, Chapman-Jouguet concentration.

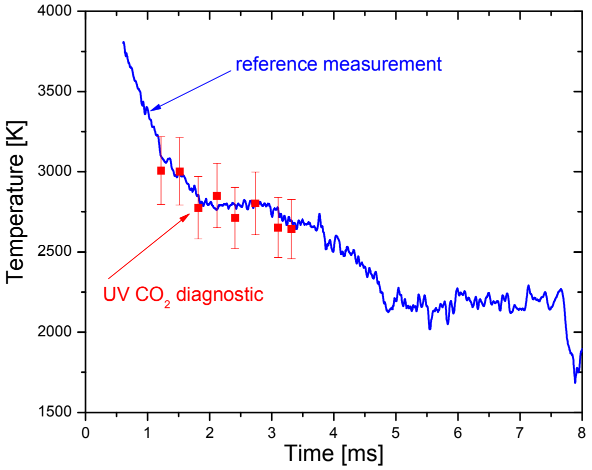

Fig 5: Temperature results from the new CO_2 diagnostic technique compared to the reference, Cesium-based measurement. A reduction in the error limit could be achieved by utilizing multiple CO_2 UV absorption wavelengths.