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Pulse Detonation Engine Characterization and Control Using Tunable Diode-Laser Sensors

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One of the phenomena limiting the performance of pulse detonation engines (PDEs) is detonation failure due to pulse-to-pulse interference. To better understand and control such interferences, two novel laser diagnostic techniques, based on absorption spectroscopy, have been developed and then used to demonstrate effective real-time control. The first technique utilizes a tunable diode-laser (TDL) sensor to measure H_2O temperature and concentration in the tube tail end at the Naval Postgraduate School's (NPS) PDE facility and in the tube head end at Stanford University's (SU) PDE facility. This sensor, capable of measuring temperatures from 300 to 1300 K at 3.33 kHz, reveals the temporal history of temperature for multipulse engines. In its application to the NPS facility, the sensor shows a distinct change in temperature profile when the engine pulse rate is changed from 5 Hz, where successful detonations are achieved, to 7 Hz, where interference produces undesirable flame holding and subsequent deflagrations on some pulses. We observed that the geometry evaluated possessed excess recirculation at the higher pulse rates resulting in flame holding at or near the point of injection. In its application to the SU PDE, this sensor reveals a temperature profile characteristic of detonation failure that could be used in future control schemes. The second diagnostic technique developed is used to monitor fuel and is employed in an active, real-time control scheme. For this sensor, we monitor the C_2H_4 (ethylene) concentration at the tail end of the NPS PDE initiator tube, which is operating at 20 Hz. When fuel is detected at the tail end, the sensor sends a signal to fire the ignitor. Compared to fixed-timing ignitor actuation, this control promotes more consistent detonation initiation and reduces misfire events. These two new laser diagnostic techniques provide useful tools for studying pulse-to-pulse interference and lay the groundwork for future, more advanced TDL-based PDE control strategies.

Introduction

PULSE detonation engines (PDEs) have received much interest in recent years due to their potential advantages compared to conventional aeropropulsion systems. These advantages include high thermal efficiency, high specific impulse, and mechanical simplicity.[1–4] Although these characteristics of the PDE show promise for applications in propulsion systems, practical problems of implementing high-pulse-rate detonation systems need to be characterized, understood, and overcome.

In its most basic form, the PDE consists of a tube that is closed on the head end and open on the tail end, as shown in Fig. 1. The PDE cycle begins by filling the tube with a mixture of fuel and oxidizer (either premixed or mixed in tube). After the charge has been injected, an ignition source at the head (closed) end ignites the mixture, and a detonation wave forms and propagates down the length of the tube. As the detonation wave reaches the tail end and exits the tube, rarefaction waves reflect from the open end and traverse toward the head end exhausting the high-pressure, high-temperature combustion products. During this crucial time between detonation formation and product gas removal by the rarefaction waves, high-pressure combustion products persist in the tube generating the desired thrust. During the next stage, the remaining high-temperature gases are either removed by an air purge or are cooled, and the cycle then repeats itself. Although different engine geometries and cycles have been developed and studied, most engine cycles contain the same basic fill–ignition/thrust–exhaust steps.

A common link between all PDE designs is the goal to optimize engine thrust by maximizing engine repetition rate. As the engine pulse rates increase, difficulties arise due to the coupling of the exhaust and fill stages of the PDE cycle. If high-temperature gases persist near the point of injection after the exhaust stage, for example, due to excess recirculation designed to increase mixing or due to insufficient purge airflow rates, the injection of a fresh fuel/oxidizer charge could result in autoignition at the point of injection. The resulting deflagration would prevent fuel charge filling of the tube and, thus, prevent detonation formation. Because the deflagration persists at nearly atmospheric pressure (unlike the high pressures produced by detonations), significant thrust degradation would result. This interference between consecutive cycles is one of the main factors limiting repetition rate in PDEs.

Tunable diode-laser (TDL) absorption sensors provide an ideal tool to measure important system properties, such as burned gas temperature and species concentration time histories, needed to advance PDE design and development. These systems can provide

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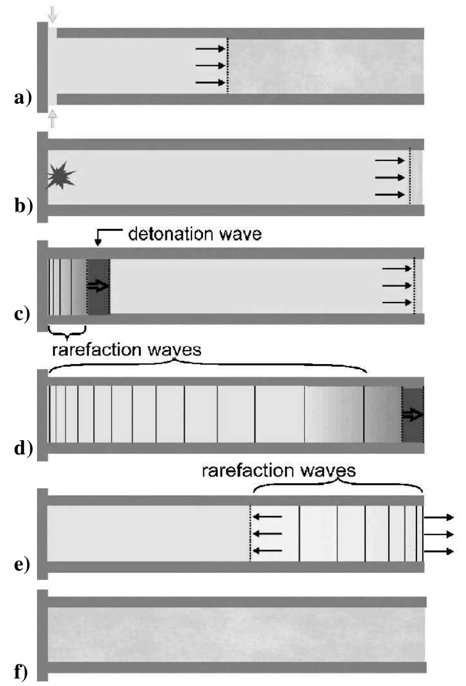

Fig. 1 Schematic of individual stages of basic PDE cycle: a) fill of fuel/oxidizer, b) ignition, c) detonation develops, d) detonation wave exits, e) burned gas exhausts, and f) delay/purge before next fill.

a wide variety of species concentration and temperature information with fast time response even in harsh combustion environments such as the PDE.[5] These same sensors also have good potential for characterizing and controlling PDE cycles. In this paper, we describe the design and application of TDL sensing and control schemes based on detection of fuel and a major combustion product, water vapor.

First, we demonstrate gas temperature and H_2O concentration measurements during multicycle engine operation to characterize pulse-to-pulse interference at the head and tail ends of two PDEs. This sensor, based on spectrally resolved absorption of near-infrared water vapor transitions, is used for measurements at the Naval Postgraduate School (NPS) in Monterey, California, and at Stanford University (SU) to map out temperature profiles characteristic of successful detonation and undesired deflagrations that could be useful in future, active-control schemes. The results of this sensor provide insight into the causes of the pulse-to-pulse interference phenomenon.

Next, we demonstrate the use of a fuel sensor, also based on near-infrared absorption, in an active, real-time PDE control system designed to reduce the duration of pulse-to-pulse interference effects that were characterized using the temperature sensor. This C_2H_4 (ethylene) concentration sensor and control scheme optimizes ignition timing and reduces pulse-to-pulse interference duration. The results obtained illustrate the potential for more extensive TDL-based control schemes.

Temperature and H_2O Concentration Sensor

The theoretical groundwork for extracting gas temperature and species concentration in high-temperature combustion environments from measurements of spectroscopic absorption features using tunable diode laser sources has been described previously.[6–9] In brief, a spectrally narrow diode-laser beam is pitched through a test gas of interest, and its wavelength is tuned across two or more absorption features. The laser is tuned rapidly enough that the timescale of flow fluctuations is much longer than the scan period of the laser. The ratio of the transmitted to the incident beam intensity is determined using established techniques, and from this ratio, the Beer–Lambert relationship provides the absorbance (see Refs. 10 and 11). Gas temperature is inferred from the ratio of peak absorbances from two distinct spectral absorption features.[5] When this measured temperature and an independently determined pressure are used, concentration of the target species is determined from the single absorbance of either feature. Although nonuniform temperature and gas composition profiles can potentially impact line-of-sight measurements, they render a small impact on PDE measurements due to uniform combustion across the tube diameter and thin boundary layers (compared to the tube diameter) produced by PDE flows.[5]

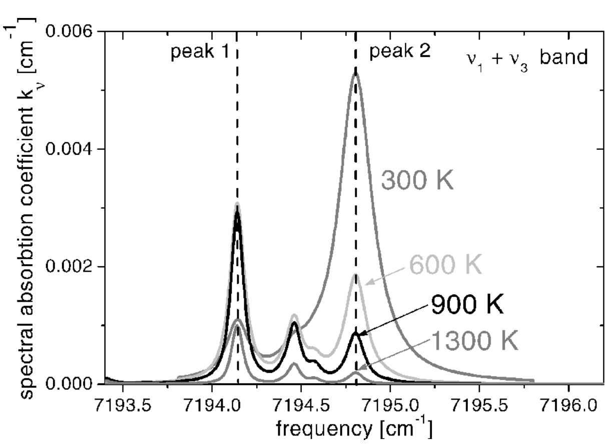

Fig. 2 Simulated (HITRAN) H_2O absorption features in the $\nu_1 + \nu_3$ band used to measure H_2O temperature and concentration in PDE flows.

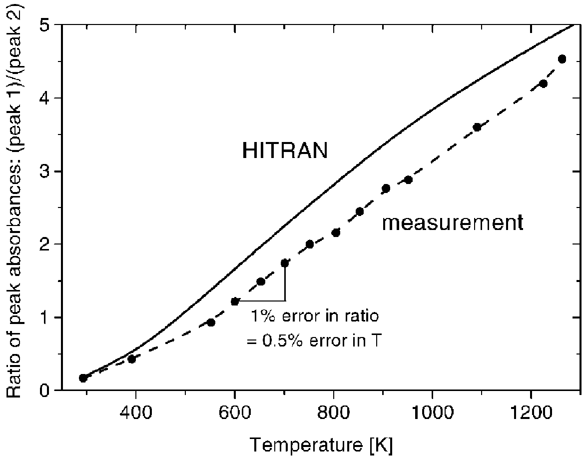

Fig. 3 Measured and simulated ratio of peak 1 to peak 2 absorbance (from Fig. 2) vs temperature.

Figure 2 shows the simulated (HITRAN)[12] near-infrared spectral absorption coefficient from a section of the $\nu_1 + \nu_3$ combination band of H_2O. The features labeled peak 1 ($\lambda = 7194.141$ cm^{-1}) and peak 2 ($\lambda = 7194.805$ cm^{-1}) are chosen for this measurement due to their strength and the high sensitivity of their ratio to temperature over the range of interest (300–1300 K). For this simulation, the pressure is 1 atm and $X_{\text{water}} = 0.015$. Figure 3 shows the simulated and measured ratio of these two peaks as a function of temperature. The total pressure for both the calculation and the measurement is 1 atm. For the HITRAN simulation, $X_{\text{water}} = 0.015$, and $X_{\text{nitrogen}} = 0.985$. For the measurement, $X_{\text{water}} = 0.015$, $X_{\text{nitrogen}} = 0.778$, and $X_{\text{oxygen}} = 0.207$. The accuracy of the HITRAN database was evaluated by performing controlled experiments in a heated cell. The temperature of the 20-cm quartz cell was varied from 300 to 1300 K, and the absorption features were detailed at 15 different temperatures. Thermocouple measurements are used to determine the temperature along the length of the heated cell. Although both the HITRAN simulation and the SU measurements show similar trends, discrepancies of up to 150 K at a peak ratio of 3.25 were large enough to encourage the use of our measured results over the HITRAN simulations.

Whereas the HITRAN database is useful for identifying potential absorption features and providing approximate spectroscopic

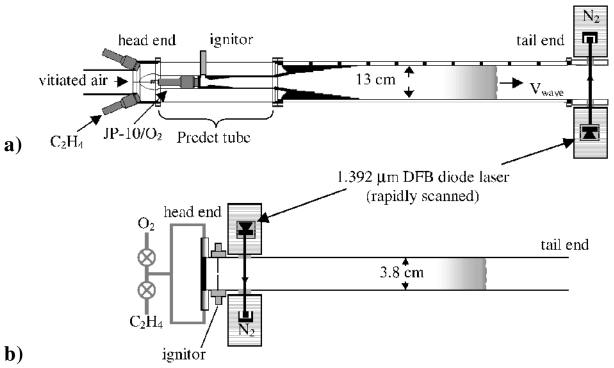

Fig. 4 Schematic of PDE facilities at the a) NPS and b) SU with the H_2O diagnostic applied to the tube head end (SU) and to the tube tail end (NPS).

quantities, it was primarily developed to predict and simulate light transmission and emission characteristics in the atmosphere where uncertainties in high-temperature spectroscopic parameters are unimportant. The discrepancies between the measured and calculated ratios are hypothesized to be due to errors in HITRAN broadening coefficients and temperature exponents for the line broadening. Errors of this magnitude have been previously identified for other absorption features and encourage the use of the cell calibration for these measurements.[5]

A spline fit to the measured ratio in Fig. 3 provides temperature from water absorption data measured in PDE flows. The architecture of the distributed feedback diode-laser (InGaAs DFB from AT&T®) ensures narrow-linewidth, single-mode operation as it is scanned across the absorption features shown in Fig. 2. An amplified InGaAs detector (PDA400 from Thorlabs®) is used to monitor the transmitted laser intensity. The 3.33-kHz scan rate provides a temperature and water concentration measurement every 300 μs. The sensor is relatively insensitive to errors in measured absorbance; a 1% error in measured ratio results in only a 0.5% error in temperature.

Previous diode-laser studies of PDE flows have concentrated on characterizing fundamental detonation properties by measuring temperature and pressure with microsecond time response for the first 10 ms following detonation arrival for single-pulse PDE operation.[13] The goal of this set of experiments is to characterize the tube blowdown, exhaust, and fuel filling stages of the PDE cycle by measuring temperature and water concentration during multicycle operation for time periods of 1 s. These stages of the PDE cycle are important in determining pulse-rate limiting performance characteristics.

The water sensor was applied to two different PDE facilities, as shown in Fig. 4. The NPS facility (Fig. 4a) consists of a 13-cm-diam main tube operating on vitiated air and ethylene and a 3.8-cm-diam initiator tube operating on JP-10 and O_2 (Ref. 14). Vitiated air continuously flows through the system; JP-10, ethylene, and O_2 (to replace that depleted by vitiation bringing air composition to 21% O_2) are intermittently injected into the system at the head end according to a predetermined valve schedule. The NPS PDE is 125 cm in length. A spark ignites the initiator tube, which then transmits the detonation wave to the main tube. For this set of experiments, the PDE operates at either a 5- or a 7-Hz repetition rate. Gas temperature and water concentration measurements are performed at the tail end of the main tube. As seen in Fig. 4, the sensor, consisting of a single laser and detector, is enclosed in an environment purged with N_2 to eliminate signal interference due to atmospheric humidity. The beam is pitched through optical access ports 2 in. (5 cm) upstream of the tube exit. Noise due to beam steering and flowfield emission was eliminated using established techniques. In brief, the laser and detector optics are mounted on a isolated stand to reduce noise from vibrations. A focusing mirror centering the transmitted beam on the detector further minimizes vibration noise. Irises minimize the solid angle of the collected light, reducing interference caused by emission from the high-temperature combustion products. A diffraction grating acts as a bandpass filter, further rejecting emission. These measures further improve signal quality in an inherently robust scanned-wavelength detection scheme.[13]

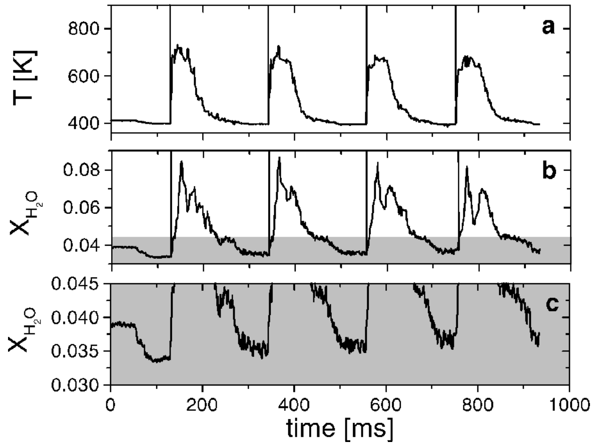

Fig. 5 Results for 5-Hz repetition rate of a) H_2O temperature b, c) concentration diagnostic applied to the tail end of the NPS PDE.

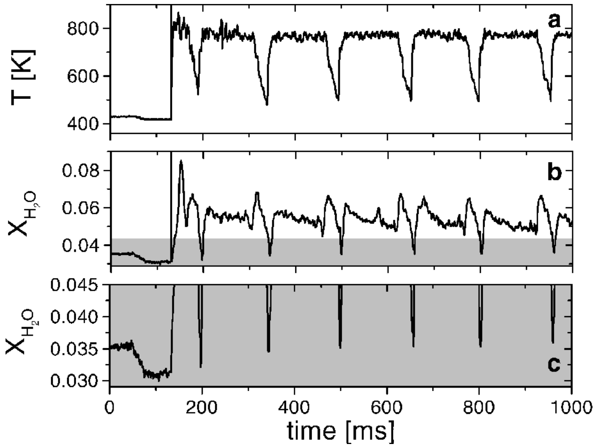

Fig. 6 Results of 7-Hz repetition rate a) H_2O temperature b, c) concentration diagnostic applied to the tail end of NPS PDE.

Sample results of gas temperature and water concentration for consecutive pulses at 5- and 7-Hz repetition are shown in Figs. 5 and 6, respectively. For both cases, before the arrival of the first detonation wave, the water concentration decreases at approximately 50 ms as highlighted in Figs. 5c and 6c. This reduction in water concentration at the measurement station is due to the dilution of the vitiated air with ethylene and marks the time when fuel arrives at the tail end of the tube. The finite rate of the reduction indicates that the fuel front diffuses as the charge flows down the tube. The delay between the reduction in concentration and the arrival of the first detonation wave (at approximately 120 ms) indicates that ethylene is filled beyond the end of the tube, resulting in wasted fuel. This demonstrates how the sensor could be used optimize the valve timing for more efficient operation.

For both repetition rates, the measurement trends are the same through the first detonation arrival until 200 ms. The differences in the traces after this time highlight the effect that pulse-to-pulse interference has on PDE performance. At this time, for the 5-Hz case, the temperature and water concentration continue to decrease until they reach the vitiated air values. The arrival of the second fuel charge is inferred from a similar decrease in water concentration at 275 ms. Then, the second detonation arrives at 340 ms, and the cycle repeats. This pattern is characteristic of successful detonation.

For 7-Hz operation, measurements after 200 ms show a distinctly different trend. After the first detonation passes, the temperature decreases to 530 K but does not reach the 400 K vitiated air temperature as occurs in the 5-Hz case before it rapidly increases again. The rapid increase in temperature is due to the autoignition of the fresh charge that is injected into the head end of the tube. The sustained plateau in temperature observed after the fuel injection indicates that a deflagration has formed at the head end of the engine. This combustion of the fuel as it is injected at the head end prevents filling of the detonation tube with a fresh fuel charge mixture. For each of the consecutive fuel injection events after this initial plateau in temperature, the same temperature plateau occurs indicating that the deflagration interference has persisted. This pulse-to-pulse interference caused by the deflagration interference significantly reduces the thrust of the PDE. The atmospheric pressure field created by the deflagration produces negligible thrust compared to the high-pressure combustion products produced by detonations.

At 5 Hz, there is sufficient time for the engine to cool and for the residual combustion products to be purged out of the system. At the higher repetition rate, some of the residual hot gases from the previous cycle remain in the head end of the tube due to excess recirculation created by the engine geometry evaluated. The residual gases cause the fresh fuel charge to auto-ignite, interfering with normal PDE operation and forcing the engine into a "flame-holding" pulse-to-pulse interference mode.

This TDL sensor reveals how pulse-to-pulse interference changes PDE cycle characteristics resulting in performance degradation. The sensor could be used to tailor a new injection strategy to eliminate interference. More important, measurements at varying engine geometry and injection times can be used to understand why hot gases remain in the tube after each pulse for times over 70 ms. A better understanding of the geometry effects and required engine purge rates would enable higher repetition rates, thus increasing engine thrust.

The results of the NPS measurements demonstrate the importance of understanding the reaction gasdynamics at the head end of the engine, where the injection of fresh charge occurs. Hence, for its next application, the sensor was used to monitor temperature in the head end of the SU PDE facility, as shown in Fig. 4b. This facility consists of a 3.8-cm-diam (160 cm long) tube that is charged with an ethylene–O_2 mixture. Ethylene and O_2 are premixed just upstream of the head end and are injected into the tube according to a predetermined valve schedule. A scheduled electric discharge ignites the mixture at the head end; the detonation wave forms rapidly and propagates down the tube.

The results from a successful detonation cycle and a flame-holding cycle are shown in Fig. 7a and Fig. 7b, respectively. For both cases, the detonation is formed at $\sim$10 ms and is followed by a $\sim$50 ms blowdown period in which most, but not all, of the residual hot gases are exhausted. In Fig. 7b, a fresh charge is injected into the tube at 100 ms. The resulting increase and sustained plateau of temperature reveals flame holding at the head end of the tube. Mixing between the fresh charge and residual hot gases causes autoignition, which is similar to the 7-Hz operation of the NPS tube.

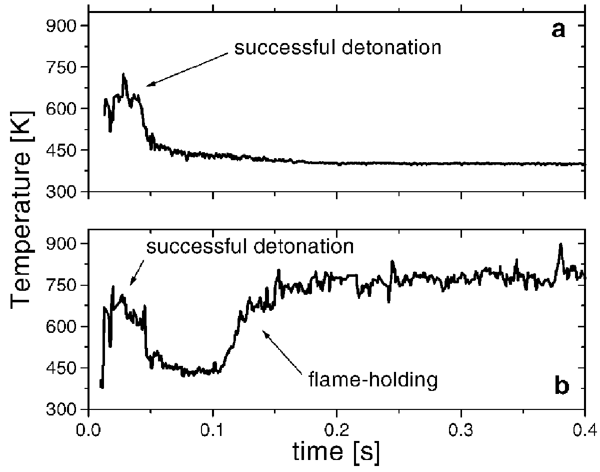

Fig. 7 **Temperature results for multi-pulse engine measurements near the head end of the SU PDE for a case of a) successful detonation and b) detonation failure due to flame holding.**

The autoignition results in engine failure and a substantial decrease in thrust.

The results of this experiment demonstrate that the flame-holding phenomenon is governed by the environment at the head end of the PDE. This sensor has proven useful for measuring a temperature profile that is characteristic of detonation failure. Similar applications of this sensor could be used to evaluate variations in head end geometry and ignition systems designed to reduce pulse-to-pulse interference.

Future iterations of this sensor could be employed in PDE control schemes. For example, head end temperature measurements could be coupled to valve and ignition timing to reduce and eliminate pulse-to-pulse interference. If pulse-to-pulse interference occurs, the sensor would observe the characteristic temperature profile. The fuel injection time could then be delayed until the measured temperature drops below the autoignition threshold, thus minimizing the interference period. Pulse-to-pulse interference can be prevented if the sensor is combined with a control system to delay the fuel valve opening until the temperature has dropped below the flame-holding threshold, thus eliminating autoignition. Both strategies would improve engine thrust by reducing interference effects.

Fuel-Based Control

Application of the temperature sensor to the NPS facility reveals that fuel overfill and pulse-to-pulse interference are two of the problems reducing PDE performance. Fuel that exits the tube before detonation arrival does not contribute to thrust generation and, therefore, reduces fuel economy. Pulse-to-pulse interference drastically reduces thrust by causing detonation failure. Controlling the ignition timing with a fuel sensor can reduce or eliminate both of these problems. This concept was realized in a fuel-based control demonstration at the NPS PDE facility.

For this experiment, a DFB diode-laser designed to detect C_2H_4 was pitched across the combustor exit at the tail end of a 3.8-cm initiator tube, as shown in Fig. 8. Vitiated air continuously flows through the predetonator tube, and an ethylene–oxygen mixture is intermittently injected at a repetition rate of 20 Hz. When the ethylene concentration detected at the tail end reaches a preset threshold value, a signal is sent to the ignitor and the PDE is fired.

The laser diagnostic used in this active control scheme has been previously detailed.[15] In brief, the laser wavelength is modulated across a spectrally varying absorption feature in the Q-branch of C_2H_4 near 1.62 μm. The modulated intensity of the transmitted signal was monitored using a detector, and the output voltage was processed using lock-in amplifier. Analog detection was used rather than digital data acquisition to maximize the time response of the detection and control system. When C_2H_4 concentration is low, the modulation in the transmitted laser intensity is weak, and thus, the output of the lock-in amplifier is low. As the C_2H_4 concentration increases, the amplitude of modulation increases; the output of the lock-in amplifier simultaneously increases. The output of the lock-in amplifier provides a control signal for the ignition source. For the case of active control, when the concentration of C_2H_4 at the tail end of the tube reaches a fuel-based equivalence ratio of 0.2, the ignitor is triggered. The fast time response of this control scheme ($\sim$10 μs) enables optimization of the ignitor timing even in high-pulse-rate PDEs.

The results of fuel-based control for 100 consecutive detonations are shown in Fig. 9a; three of these cycles are expanded in

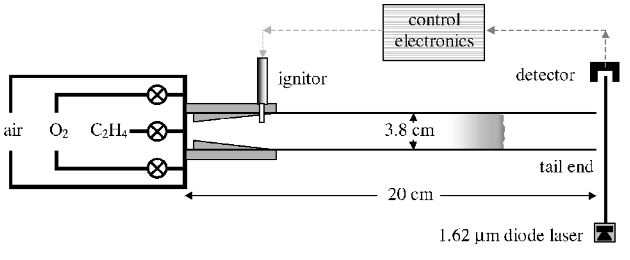

Fig. 8 **Schematic of diode-laser-based control experiment applied to the predet tube at NPS PDE.**

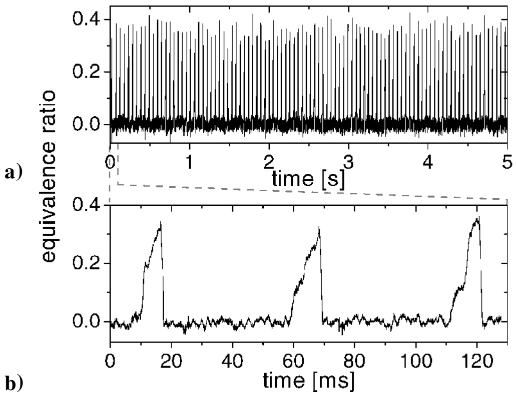

Fig. 9 Results of 20-Hz repetition rate of fuel-based control experiment. a) 100 consecutive pulses and b) 3 pulses.

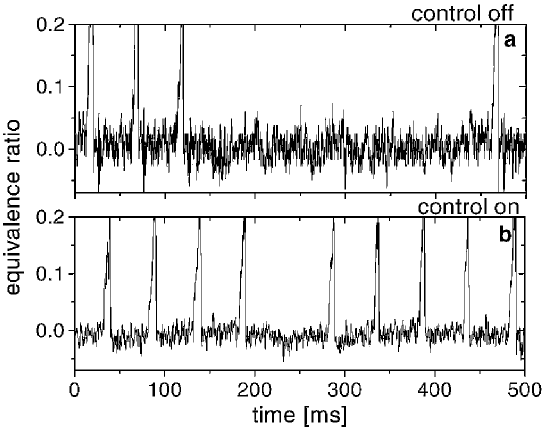

Fig. 10 Results of 20-Hz repetition rate using a) fixed spark timing and b) fuel-based control of spark timing.

Fig. 9b. After fuel is injected into the head end of the PDE, it diffuses slightly as the gases flow down the tube. This contributes to the observed ramp in equivalence ratio vs time at the measurement station. After the equivalence ratio at the tail end reaches the preset threshold value, a signal is sent to fire the ignitor. The sharp decrease in equivalence ratio is caused by the arrival of the detonation at the measurement station. After the detonation passes, the fuel and oxygen valves are opened again according to a preset schedule, and the cycle repeats itself. These results demonstrate that diode-laser-based ignition control reliably controls spark timing even in harsh combustion environments. It also prevents excess fuel from exiting the tube.

This sensor is capable of diagnosing engine failure modes such as ignition failure and pulse-to-pulse interference effects. In the case of ignition failure, the equivalence ratio would reach a sustained plateau at a signal level above the ignition set point. At the onset of flame holding, the fuel at the tail end of the tube remains low (due to combustion at the head end) and does not reach the level required to trigger the ignitor. Thus, the reignition cycle is suppressed and only a single cycle is missed. Figures 10a and 10b show a comparison of the measured fuel signal at the tail end for a case of predetermined, fixed spark timing (control off), and adaptive, diode-laser-controlled spark timing (control on), respectively. The absent peaks in each case indicate detonation failure due to flame holding at the head end of the tube. With the control off, even after a detonation failure, the ignitor fires at the beginning of the next cycle, helping to sustain the failure mode as indicated by the six consecutive absent peaks. With control on, the spark is suppressed until fuel has reached the tail end of the tube, and only a single pulse is missed. These results demonstrate that this control scheme aids in PDE recovery after the engine lapses into a flame-holding mode.

Summary

Two different TDL absorption sensors, one for fuel and one for water vapor concentration and temperature, have been developed and used to characterize and control multi-pulse PDE operation cycles. These sensors provide important new tools to help diagnose and understand engine failure modes. With this information, a variety of intelligent gas injection schemes and engine geometry modifications can be developed to improve engine performance. The fuel-based active PDE control scheme optimizes ignition timing and reduces the persistence of flame holding. In future iterations, both of these sensors could be used simultaneously in control schemes to optimize ignition and valve timing and substantially reduce the occurrence of engine failure.

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