Tunable Mid-IR Sensing of a JP-10-Fueled Pulsed Detonation Engine

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1 Introduction

Pulsed detonation engines (PDE) have received widespread interest recently due to their potential advantages in hardware cost/complexity and performance (such as the incrase in specific impulse) over convential propulsive technologies. The accurate diagnosis of these engines has thus become critical. Fuel sensing is particularly important due to the need to validate predictions of specific impulse. The unsteady nature of pulsed detonation engines, along with their reputation for having extremely harsh flowfields, has motivated development of a new class of real-time, non-intrusive laser-based strategies.

This paper outlines the design and implementation of a sensor tailored to the PDE which was developed at the Naval Postgraduate School (NPS) in Monterey, California. The engine operates on air and JP-10. Fuel measurements provide information on equivalence ratio, injector/igniter scheduling, and fuel distribution within the engine. A two-wavelength scheme is also used to infer temperature.

The sensors make use of the mid-IR absorption of JP-10, located around 3.4 μm. A tunable mid-IR source is used in order to optimize the amount of absorption encountered in this particular PDE. Temperature is measured using two wavelengths, again chosen to optimize sensor accuracy for this engine. This represents the first such measurements in a PDE using a tunable mid-IR laser.

2 Fuel Sensor

Previous fuel sensing research carried out at Stanford University has been primarily motivated by PDEs fueled with C_2H_4. These sensors made use of overtone and combination band absorption of C_2H_4 near 1625 nm, thereby enabling the use of tunable near-IR fiber-coupled lasers [1]. Due to the need to understand the performance of PDEs operating on denser fuels (*viz*. JP-10), optical diagnostics which are optimized for these fuels have been developed and are presented herein. The major departure from past C_2H_4-sensing technology has been the shift from near-IR to mid-IR wavelengths. This is due to the fact that JP-10 (stoichiometrically mixed with air) absorbs less in the near-IR compared to C_2H_4 (also stoichiometrically mixed with air). For a PDE tube diameter of 7.3 cm (as used at NPS), a near-IR C_2H_4 sensor tuned to peak absorption will provide 3% attenuation. On the other hand, a near-IR JP-10 sensor tuned to peak absorption will provide only 1% attenuation.

By contrast, the mid-IR absorption of JP-10 is approximately 350 times stronger than in the near-IR. This makes a mid-IR strategy very attractive. The HeNe laser has been the traditional choice for mid-IR hydrocarbon spectroscopy. However, the wavelength of this laser (3.3912 μm) is not amenable to measuring JP-10 in the NPS PDE owing to excessive absorption: for a path length of 7.3 cm with stoichiometric JP-10/air at 420 K and 1 atm, 94% of the HeNe power is absorbed. This attenuation is further increased in practice because of elevated pressures inside the PDE (2 to 4 atm) which are typical operating conditions at high repetition rates (> 20 Hz). For example 99.7% of the laser power is attenuated for a pressure of 2 atm.

In order to achieve lower absorption levels, and thereby improve the sensor's SNR, a wavelength-tunable mid-IR laser is required. This was provided in a commercial product from Novawave Technologies, based on a form of Difference Frequency Generation (DFG), which uses two near-IR semi-conductor lasers (one of which is tunable) and non-linearly combines their frequencies to produce tunable radiation at the frequency difference of the two near-IR sources. A pair of DFGs were designed and built so that together the entire mid-IR spectrum of JP-10 can be accessed, in addition to those of many other hydrocarbons. The DFG used for the current JP-10 sensor has a maximum power of 200 μW and an SNR of 1250:1 (based on one standard deviation of laser noise). The fuel sensor wavelength selected was 3360.0 nm which optimizes accuracy for the conditions encountered in the NPS PDE. A 3.4 μm HeNe laser is also used to measure JP-10 in order to demonstrate the superiority of the DFG.

3 Temperature Sensor

In addition to providing flexibility in designing a wavelength-tuned fuel sensor, the DFG system also enables two-wavelength temperature sensing. This is achieved by incorporating a third laser into the two-laser DFG system described above. The first laser remains on, while the other two lasers (at different wavelengths) are sequentially turned on and off at a sufficiently high rate such that absorption at two wavelengths is measured essentially simultaneously. (The process is similar to that described by Klingbeil *et al*. [2] who used two wavelengths generated by the DFG system to reject interference from droplet scattering.) The two wavelengths chosen for the temperature sensor are 3367.9 nm and 3352.4 nm which give good temperature sensitivity.

4 PDE Facility and Sensor Setup

NPS has been making progress in developing a PDE fueled with JP-10 without the need for sensitizing fuels or oxidizers. In support of these efforts, a JP-10 sensor has been designed specifically for this particular engine. Fig. 1 shows a schematic of the engine and sensor setup. The engine is fed with vitiated air whose flow rate was varied between 0.11 and 0.25 kg/s. JP-10 is injected, vaporized, and convected downstream while it mixes with the air. A transient plasma igniter [3] is used to quickly generate a flame without the need for any sort of sensitizing fuel or oxidizer. A series of 24 ring obstacles along the tube promotes DDT. Static pressure and temperature gauges are installed near the laser sensor to provide the required information for extracting equivalence ratio (T = 477 K; P = 1.3 ~ 2.5 atm,abs). The diameter at the optical section is 7.3 cm. The engine was operated at repetition rates up to 30 Hz unfired and 20 Hz fired. (Herein, "fired" indicates that the ignition system was turned on.)

The DFG laser output is coupled into a multi-mode, fluoride-glass fiber (d = 160 μm, NA = 0.28) which is attached to the PDE. When shaken, the fiber produces an additional 0.5% noise on the power leaving the fiber. The light is pitched across the engine, and caught onto a second fiber (d = 480 μm, NA = 0.27). This fiber is fed to an optical table (located in a room adjacent to the test bay) and pitches the signal through two narrowband spectral filters, which are angled in order to optimize emission rejection [4]. Finally, the signal is focused onto a 1 MHz InSb liquid nitrogen-cooled detector. The laser is turned on and off with a 50% duty cycle at 100 kHz in order to fully reject any additional emission which passes through the filters. When used as a temperature sensor, two wavelengths are turned on and off (as described above) each with a 33% duty cycle. The laser is entirely turned off for the remaining 33% of the cycle. This enables power from the two wavelengths along with the emission level to be recorded at 100 kHz. For both the fuel and temperature sensors, the unabsorbed laser intensity is determined from signals taken before the arrival of fuel.

The HeNe radiation is coupled into its own fiber and pitched across the engine in the same way as the DFG. Rather than being caught on another fiber, the beam is focused directly onto a detector which is mounted on the engine (InAs, 100 kHz bandwidth, thermo-electrically cooled). A single narrow bandpass spectral filter rejects the emission. The HeNe sensor is located 6.35 cm downstream of the DFG sensor.

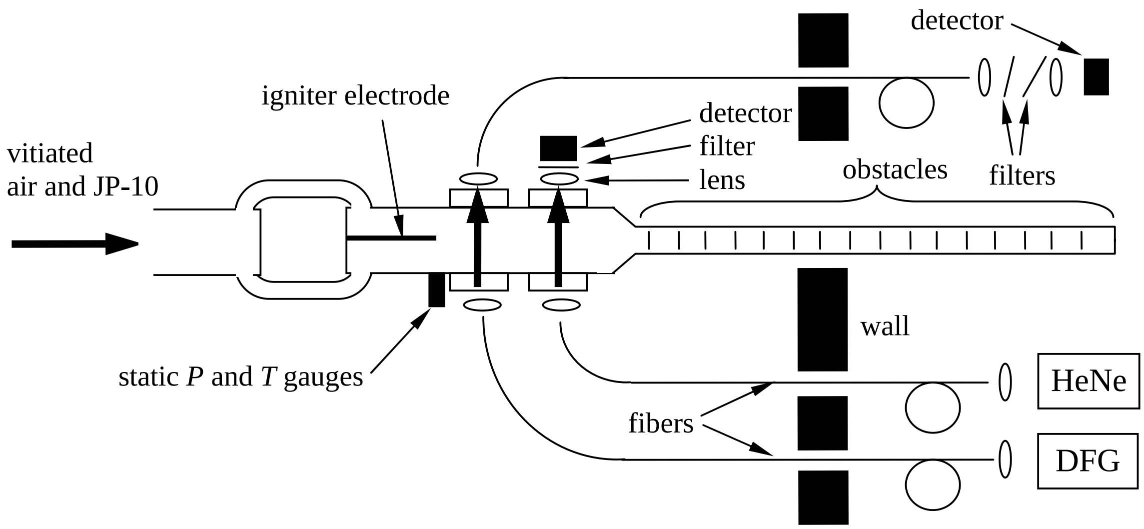

Figure 1 : Experimental setup. The length and diameter of the main detonator (i.e. which contains the obstacles) is 94 cm and 4.45 cm, respectively.

5 Results: Fuel

Fig. 2 shows a typical JP-10/air equivalence ratio profile in the NPS PDE as measured by the DFG. The engine repetition rate was 20 Hz, two injectors were opened simultaneously, and the engine was not fired. Knowing the air mass flow rate (using choked flow with a known orifice diameter and stagnation properties), the measured equivalence ratio can be converted to time-varying fuel mass flow rate, which can then be used to determine the mass of fuel released by each injector. The average injected mass per injector and per cycle was measured to be 121 mg, which matches the manufacturer's specification of 121 mg.

Along with the DFG data, the equivalence ratio as measured by the HeNe is included in Fig. 2. Because the absorption coefficient of the HeNe is 4.3 times greater than that of the DFG (tuned to 3360.0 nm), the HeNe-based sensor cannot accurately measured absorption levels at high equivalence ratios where the weak transmitted signal (since absorption is strong) is dominated by detector and bit noise. This clearly demonstrates the utility of a tunable mid-IR source.

These time-varying equivalence ratio data are next used to set the ignition timing (relative to the injector opening time), as well to evaluate how much time is required for an individual fuel plug to pass. For example, with an air flow of 0.25 kg/s as in Fig. 2, the fuel completely disappears in 52 ms which indicates an upper limit on repetition rate of 20 Hz. However, some fuel overlap between cycles may be tolerable and will depend on how much thrust can be gained by increasing repetition rate relative to how much fuel is wasted and at what point flame holding becomes a problem [5].

With equivalence ratio and engine filling time known, the ignition timing and repetition rates were set. The PDE was successfully fired (88% of cycles ignited) with a repetition rate of 20 Hz and an air mass flow rate of 0.20 kg/s.

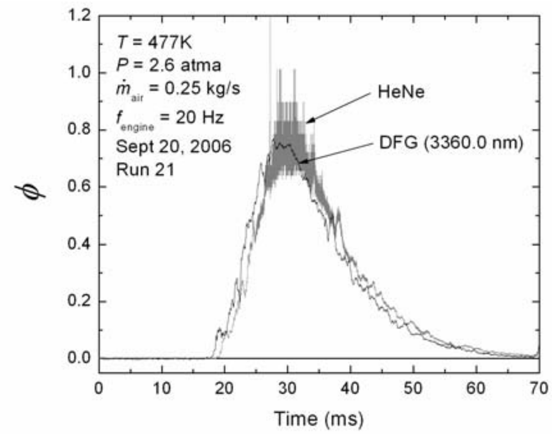

Figure 2 : Comparison of measured equivalence ratio by DFG and HeNe absorption.

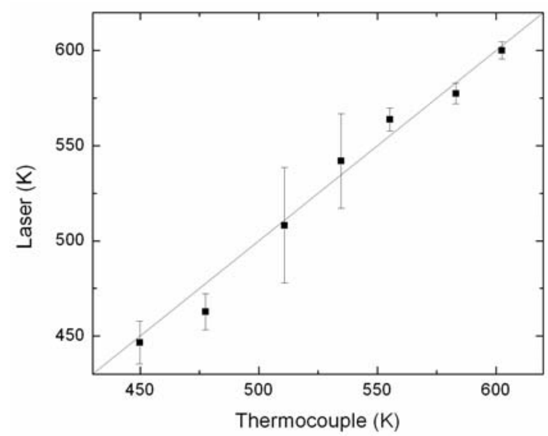

Figure 3 : Comparison of reactant temperature measured by thermocouple and DFG.

6 Results: Temperature

The static temperature of the unburned, vitiated reactants was measured using the two-wavelength strategy described above. Fig. 3 compares these results with those measured by the thermocouple. One standard deviation is used. No filtering or cycle-averaging has been performed. Although the accuracy of the laser-based sensor is somewhat lower than the thermocouple's, the time response is a factor of 10,000 greater than the thermocouple's. This increased bandwidth can be used to resolve high-frequency fluctuations, or to provide improved accuracy by filtering high-frequency fluctuations.

7 Conclusions

A high-bandwidth, non-intrusive optical sensor was developed for measuring fuel concentration in a fired PDE operating on air and JP-10. This represents the first case of tunable mid-IR fuel sensing in a PDE. With the help of the sensor, the engine was successfully fired at 20 Hz without the need to sensitize the fuel or to inject additional oxygen. Temperature of the reactants was measured with a bandwidth four orders of magnitude greater than that provided by a thermocouple.

References

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