TDLAS for Sensing Pre-vaporized Jet A-1 in Liquid-fuel Pressure Gain Combustion

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1 Introduction

Detonation combustors have been increasingly gained in popularity due to the resulting pressure gain from reactants to products and less entropy productions. Among the detonative devices, the continuous pressure gain combustor (PGC) has recently received considerable attention and been considered as a viable combustion solution for future engine system owing to its compact size and high energy density [1-3]. In general, the PGC has an annular shape where fresh reactants are continuously fed into the annulus. The detonative mixture is initiated only once at start. Subsequently, the single/multiple detonation waves propagate circumferentially and continuously in the annular combustor. The typical operating frequency of PGC is 1-10 kHz.

Nearly all of experimental and numerical test programs to date that have investigated the PGC have focused on gaseous fuel such as hydrogen and ethylene. However, when it comes to practical applications, the liquid fuel is definitely more attractive because of much higher energy density and ease of storage. The time available between successive detonation waves is on hundred-microsecond scale, while the vaporization and mixing of liquid fuel is on millisecond scale. The short period between two successive detonation waves makes liquid fuels difficult to direct implement in PGC. To overcome this challenge, more reactive additives, such as hydrogen or oxygen, were added to the reactants when using liquid fuels [4-6]. Direct injection is another solution, where the liquid fuel is injected directly into combustor via atomizer or narrow slots [5, 7-8]. By doing so, the droplet size of fuel aerosol can be reduced significantly; however, the assistance of reactive additives or very high-temperature oxidizer is still necessary to obtain successful initiation. Without the assistance of reactive additives and very small fuel droplets via atomizer, the pre-vaporization of liquid fuel is absolutely expected solution to get detonation initiations. In our previous study, the pre-vaporization method has been demonstrated in the pulse detonation engine (PDE), and it is found that the vapor-phase equivalence ratio plays an important role in the two-phase detonation initiation [9].

In this study, the pre-vaporization method with non-premixed injection strategy was utilized, and the Jet A-1/air mixture was used as the reactants. The main objective of the resent study is to apply tunable diode laser spectroscopy (TDLAS) based technique to measure the concentration of Jet A-1 vapor/air and further investigate the detonability of liquid-fuel continuous pressure gain combustion, based on measured local equivalence ratio. For the pre-vaporization method, a small amount of elevated air was used to pre-vaporize Jet A-1 fuel and the concentration of Jet A-1/air mixture was controlled to higher than upper explosive limit (UEL) for minimizing the occurrence of flashback during combustion process. Another elevated air was delivered into the combustor as the main oxidizer for pressure gain combustion process. The global equivalence ratio was estimated by the total air flow rate and the liquid phase fuel amount from the injector. The TDLAS for sensing the vapor-phase local equivalence ratio was employed *prior to* the occurrence of detonation/combustion; meanwhile, the time of arrival of the reactants inside combustor also can be acquired via the TDLAS. The description of the experimental setups, TDLAS system and results will be shown in the following sections.

2 Experimental setups and methodology

The schematic drawings of the PGC facilities is shown in Figure 1. As can be seen that there are two independent air pipelines. One of the pipelines is used to pre-vaporize Jet A-1 fuel (henceforth it is denoted as pre-vaporization air). The other is meant for delivery majority of combustion air (henceforth it is denoted as main combustion air). Note that each of the air pipelines has its own controller and heating system. The main combustion air was altered via an electro pneumatic controller (TESCOM ER5000 Series) and one sonic nozzle (Flow Systems) with an uncertainty of 0.866% was used to quantify the flow rate. On the other hand, the digital flow meter (Alicat Scientific) was used to measure the flow rate of pre-vaporization air. Two electric air heaters with different power ratings were used to elevate the pre-vaporization air and main combustion air. A Denso injector designed for direct injection gasoline engine was utilized to inject Jet A-1 fuel. The highly rich concentration Jet A-1/air mixture, generated from pre-vaporization chamber, flows into the combustor through the fuel inject holes, while the main combustion air is fed into annular channel through the air inject slot. When the reactant temperature in the combustor was higher than 190 °C, the detonative mixture was initiated by using a pre-detonator, which ran on a nearly stoichiometric ethylene/oxygen mixture. The LabVIEW was used in conjunction with a National Instruments PXI system to control the test procedures, e.g., delivering transistor-transistor logic signals at desired durations, frequencies and delays to control the sequence of ignition. Dynamic pressure transducers (PCB 11B21) were flush-mounted on the combustor outer wall to characterize the detonation waves. Omega PX-5500 pressure transducers measured the fuel plenum pressure and the air plenum pressure. In addition, the *k*-type thermocouples (Omega HKMTSS-125U-6) were used to monitor the temperatures at the pre-vaporization chamber and PGC combustor.

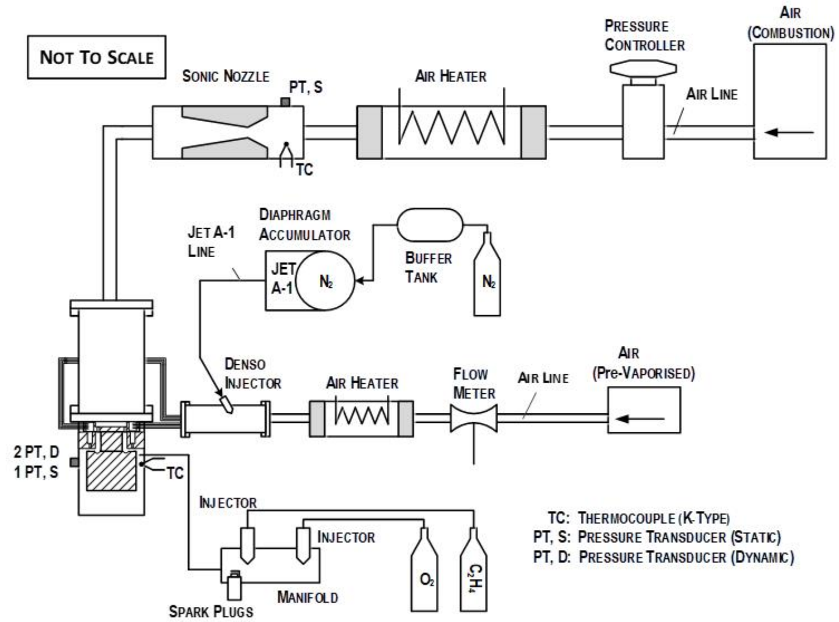

Figure 1: Schematic drawings of PGC facilities.

Figure 2 shows a schematic of the TDLAS optical configuration used for the single-ended approach, which is relied on the detection of back-reflection light from the inner wall of PGC combustor. Certain part of combustor outer wall was replaced with quartz window and the reflection surface at the combustor inner wall was polished, which makes PGC optically accessible. A DFB ICL laser operating near 3411 nm with approximately 3~6 mW of power output provided the light source for measurements of the concentration Jet A-1/air mixture. Beam from the laser was free-spaced redirected toward to PGC via the aluminum mirrors (Thorlabs, ME1-G01). Back-reflected radiation from the mirror-polished stainless steel PGC inner wall was transmitted back to the detection assembly to be focused on the photovoltaic detector via an f = 50 mm lens (Thorlabs). The bandpass filter (Thorlabs, FB3500-500) was used to suppress background noise and optical emission form the hot combustion gases. The laser beam path length between the entry and exit points on the quartz window and channel width was calculated via Pythagoras theorem. The scan rate of the TDLAS system is 5 kHz. The measured equivalence ratio via TDLAS fuel sensing diagnostics is denoted as local equivalence ratio, Φ_{local}. On the other hand, the measured equivalence ratio through the total airflow rate and fuel injection amount is denoted as Φ_{global}. In this study, the mass flow rate of pre-vaporization air was kept at a constant of 1000 slpm (~0.02kg/s). With changing the main combustion air mass flow rate and fuel injection pressure, the total air mass flow rate and Φ_{global} were varied from 0.158 to 0.2 kg/s and 0.725 to 1.021, respectively.

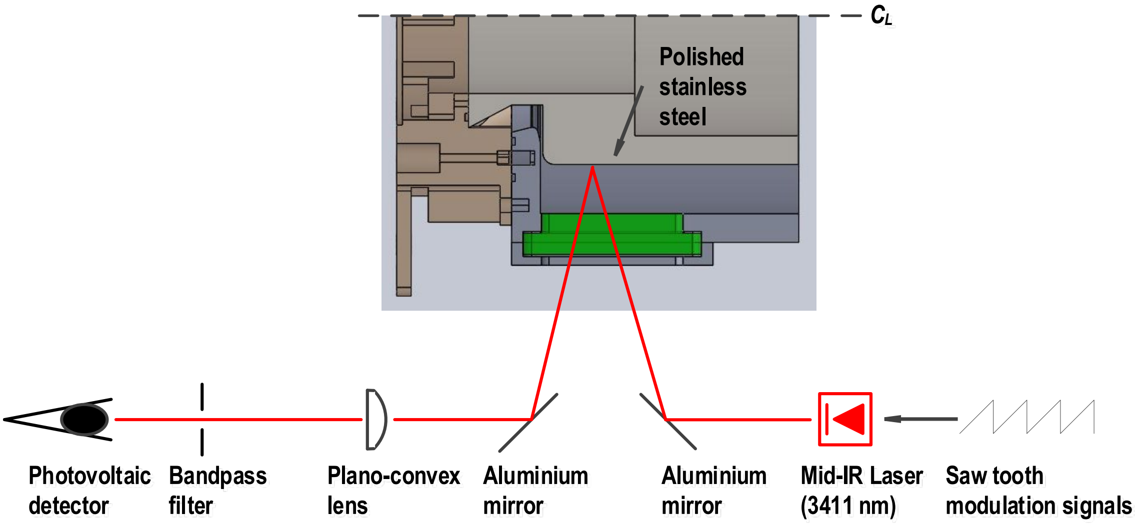

Figure 2: Schematic of single-ended optical setup for measurements of Jet A-1/air concentration.

3 Results and discussions

Time-resolved fuel/air concentration *prior to* combustion

Figure 3 shows the time-resolved Φ_{local} *prior to* combustion. The Jet A-1 fuel was injected in the upstream of the PGC at the time = 1.5 second. The amplitude of Φ_{local} starts to increases around the time = 1.6 second, which reveals that the reactants need 0.1 second to reach the TDLAS measurement location inside the combustor. Furthermore, the amplitude of Φ_{local} rises with time and at least 0.8 second is required to reach a plateau value. The amplitude of Φ_{local} during the period of 0.09 second *prior to* the ignition (at the time = 3 second) was averaged and compared with Φ_{global}. The comparisons of Φ_{global} and averaged Φ_{local} are tabulated in Table 1. As the expectation, the averaged Φ_{local} is lower than Φ_{global}, which can be attributed to the non-homogeneous Jet A-1/air mixture inside the pre-vaporization chamber and inside the PGC combustor. There is a discrepancy between the Φ_{global} and the averaged Φ_{local}. It means that liquid fuels were not fully pre-vaporized to the vapor phase even though the entire process during the experiment are controlled to above the full vaporization temperature of stoichiometric Jet A-1/air mixtures (around 150 °C). The phenomenon observed shows the importance of the time-resolved reactant distribution from the TDLAS fuel sensing diagnostics. With the high-scanning rate and *in situ* measurement provided by TDLAS techniques, one can temporarily and locally control the fuel/air mixture composition and further optimize the sequence timings of fuel injection, air supply, and spark ignition of the pre-detonator to achieve a better combustion performance.

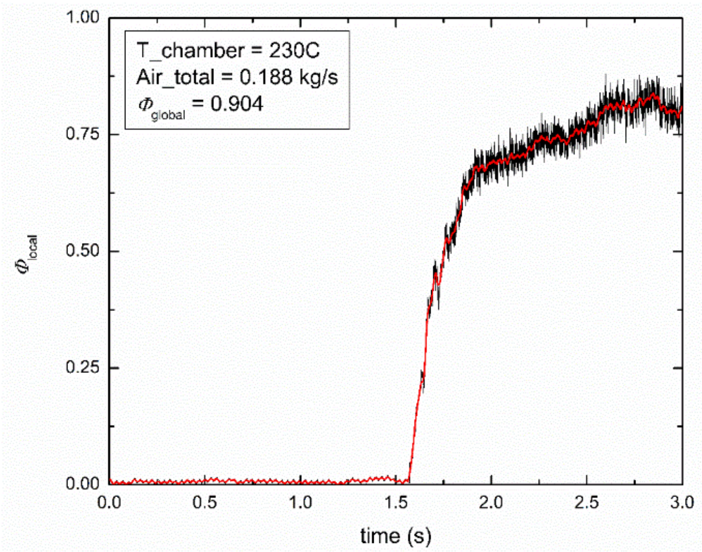

Figure 3: Time-resolved Φ_{local} *prior to* combustion.

Table 1: The comparison of Φ_{global} and averaged Φ_{local} in the selected testing cases.

Run #	Φ_{global}	Φ_{local} before ignition	total air mass flow rate (kg/s)
88	0.859±0.010	0.759±0.052	0.188±0.002
89	0.868±0.010	0.802±0.055	0.188±0.002
90	0.904±0.010	0.799±0.055	0.188±0.002
91	0.904±0.010	0.800±0.055	0.188±0.002
92	0.922±0.011	0.836±0.058	0.188±0.002
93	0.934±0.011	0.818±0.057	0.188±0.002
94	0.872±0.010	0.814±0.056	0.199±0.002
95	0.882±0.010	0.844±0.058	0.200±0.002
103	0.998±0.011	0.868±0.060	0.162±0.002
104	1.021±0.012	0.891±0.062	0.158±0.002

Pressure measurements and detonability

The equivalence ratio effect on the propagation characteristics of detonation waves was analyzed, wherein the total air mass flow rate remained approximately constant (~0.188kg/s), while the global equivalence ratio ranged from 0.759 to 0.904. The pressure traces recorded by PCB sensors are shown in Figure 4. General speaking, the pressure spikes are sharper and more clear with increasing the equivalence ratio. Furthermore, the averaged amplitude of pressure spikes also becomes higher in the higher equivalence ratio, implying the detonation combustion becomes stronger as more fuel is involved. The fast Fourier transform (FFT) with Welch's method and Hamming window were used to calculate power spectra for the five representative runs. In the cases of Φ_{global} = 0.759 and Φ_{global} = 0.764, two spikes located around 2.6 kHz and 4.5 kHz are observed. The spike around 2.6 kHz results from single wave, while the spike around 4.5 Hz is associated with two-pair of counter-waves [10]. In the rest three cases, the single wave component appears to diminish, and the spike locations of the two-pair of counter-waves are slightly increased. General speaking, the average propagation speed is about 0.55 V_{CJ}.

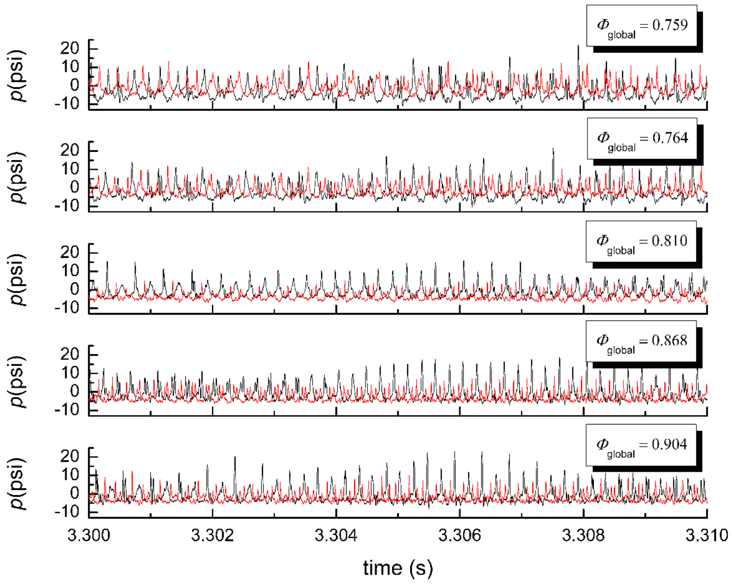

Figure 4: Pressure traces at approximately constant total airflow rate and various equivalence ratios.

As mentioned above, the vapor-phase equivalence ratio plays an important role in the two-phase detonation initiation. The global equivalence ratio and local equivalence ratio versus total air mass flow rate are plotted to investigate the detonability, as shown in Figures 5. The onset or not onset of detonation combustion is determined by the presence of pressure peaks, mentioned in the last paragraph. As seen from Figure 5(a), based on the global equivalence ratio, when the global equivalence ratio > 0.85, the air mass rate is required to > 0.16 kg/s to get the detonation onset. When the global equivalence ratio < 0.85, the air mass rate requirement is higher at the leaner mixtures. It is unclear why more amount of air is needed for the leaner reactants. As referred to the local equivalence, see Figure 5(b), to obtain the onset of detonation, the local equivalence ratio has to be richer than 0.66 and the total air mass flow rate has to be more than 0.156 kg/s. It is clear now that the critical conditions are directly correlated with the local equivalence ratio and the air mass flow rate. Apparently, there is no variation of the critical vapor-phase local equivalence ratio as varying the air mass flow rate. The critical local equivalence ratio would link with the properties of vaporized reactant reactivity, such as ignition delay, reaction time and detonation cell size. The critical airflow rate could be likely related to whether air plenum pressure level and/or refilling reactant height are sufficient to support the detonation onset and propagation.

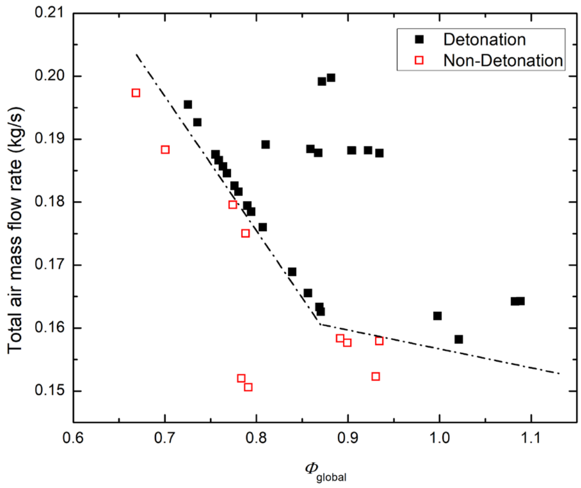

Figure 5(a) Detonability with global equivalence ratio.

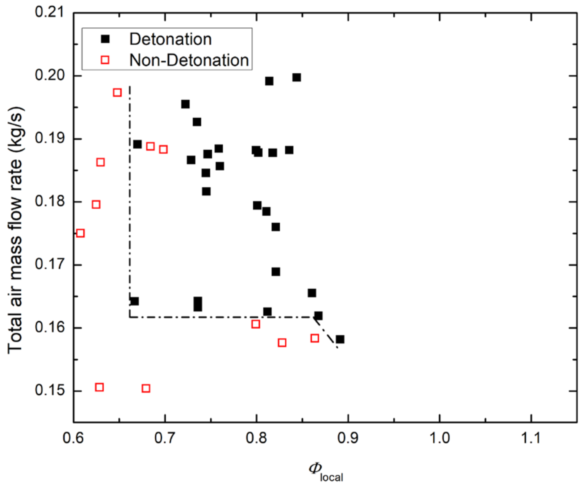

Figure 5(b) Detonability with local equivalence ratio.

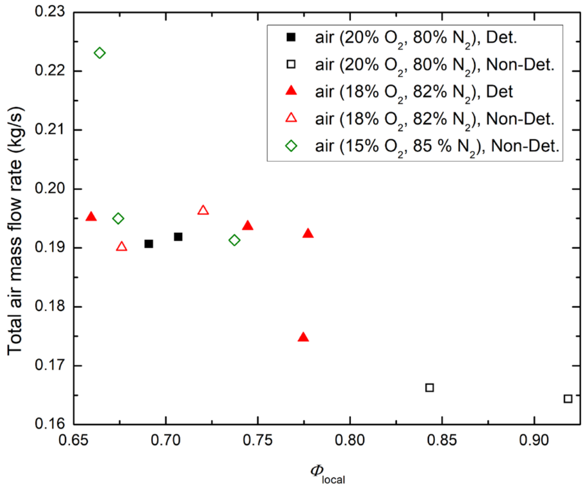

Figure 6: Detonability of artificial air with different O_2/N_2 composition.

In the pre-vaporization system, the high-temperature combustion gas could be utilized as the heat source to pre-vaporize the liquid fuels. The elevated artificial air with different oxygen and nitrogen concentrations (20%, 18%, 15% O_2) was used to simulate the use of combustion exhaust gas for the pre-vaporization process. As seen in Figure 6, the detonability is sensitive to the oxygen concentration, and it is difficult to obtain detonation onset when the oxygen concentration was reduced to 15%. Further investigation is required to address the effect of oxygen concentration on the detonability.

4 Summary

A liquid-fuel pressure gain combustion incorporated the pre-vaporization method has been successfully established. With the help of TDLAS techniques, the vapor-phase equivalence ratio and the airflow rate exceeding 0.66 and 0.156 kg/s, respectively, were found as the critical conditions for the onset of detonation. It is difficult to obtain the detonation combustion when the oxygen concentration in the oxidizer was reduced to 15%.

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