Preliminary Studies on a Pulse Detonation Rocket Engine without Purging Process

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1 Introduction

The pulse detonation engine (PDE) has received considerable interest over the past few decades due to its potential for increased performance and hardware simplicity. There have been many studies on PDEs all over the world and several reviews have been published [1-6]. With oxidizer on board, a PDE works in rocket mode. Like traditional PDEs, PDRE operates by repeatedly producing detonation waves that propagate through fuel-oxidizer mixture and produce high chamber pressure intermittently which resulting in discrete impulses [7]. The basic structure of a PDE is a straight tube, also known as a detonation tube, with one end closed and the other open. A basic detonation cycle consists of the following processes: (a) filling process, i.e., the detonation tube is filled with fresh detonable fuel-oxidizer mixture; (b) the mixture is ignited near the closed end of the tube and detonation is initiated directly or indirectly through a deflagration to detonation transition (DDT) process; (c) a self-sustained detonation wave, which compresses the fuel-oxidizer mixture by shock waves and initiates combustion of reactants, propagates toward the tube open end; (d) the burned gas exhausts through a blow-down process; (e) purging process, i.e., the purge gas is injected into the tube to expel the burned gas and prevent pre-ignition of fresh detonable mixture in the next cycle.

The purging process was needed to ensure stable operation of the multi-cycle PDRE in previous studies. For example, Lu et al. [8] used air as purge gas, Li et al. [9] utilized nitrogen as purge gas, helium was adopted as purge gas by Kasahara et al. [10] and Matsuoka et al. [11, 12]. However, it takes some time to accomplish injection of purge gas into the detonation tube during purging process, which occupies considerable proportion of a single detonation cycle and. Therefore, it limits the overall cycle time together with injection process, DDT process, propagation and blow-down process putting a ceiling on the upper limit of operating frequency for a certain PDRE. In addition, it requires independent supply system which increases the hardware complexity. Thus, if the purging process is eliminated, great benefit can be derived, e.g., the complex valves and injection systems in Refs. [11-14] can be simplified.

This study presents a successful try to achieve stable operation of a PDRE without purging process. Oxygen-enriched air was utilized as oxidizer and liquid gasoline was used as fuel. Appropriate supply pressure for fuel and oxidizer was of great importance for such an operating mode. Different oxygen percentages were also tested to determine the upper and lower limits for stable operation without purging process. Additionally, different exhaust plumes were observed as operating frequency increasing in such an operating mode. Experimental results indicated that it was feasible for the PDRE to be operated without purging process.

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2 Method Description and Experimental Setup

In traditional PDREs, purge gas is mainly utilized to form a buffer zone to prevent pre-ignition of fresh fuel-oxidizer mixture by contact with hot combustion products in previous operation cycle. Similarly, there must be some measure to keep fresh fuel-oxidizer mixture from direct contact with hot combustion products if the purging process is eliminated. Figure 1 is the pressure trace measured at the position with a distance of 573.5 mm from the closed end of detonation tube. It was similar to the pressure history at the closed end in Ref. [15]. As illustrated in Figure 1, the detonation tube interior experiences a period of high pressure after detonation initiated. If supply pressure of fuel and oxidizer was appropriate, e.g., lower than 1 MPa as shown in Figure 1, fuel and oxidizer supply will be interrupted due to higher pressure inside the detonation tube; this interruption will continue, on condition that the pressure inside the tube is greater than the supply pressure, until an underpressure is created by the exhaust of combustion products. With a suitable equivalence ratio, flame, near the closed end, may quench after the DDT process and during the period without fuel and oxidizer injected, the combustion products will cool down; if appropriate fuel-oxidizer mixture were applied, pre-ignition by contact with residual combustion products can be avoided. Thus, the purging process may not be necessary for stable operation of multi-cycle PDREs. This supply method is similar to the idea of DeRoche [16] and the work of Baklanov et al. [17], where supply is controlled by the periodic pressure oscillations inside the detonation tube and combustion products are cooled in feeding lines to form a butter zone; however, liquid gasoline is used in the present study which means that forced cooling of combustion products will be introduced by the injection and vaporization of liquid gasoline leading to drop of the temperature of combustion products.

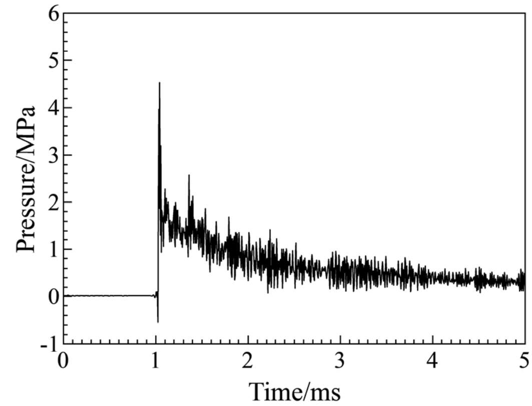

Figure 1. Pressure trace at some position of the detonation tube.

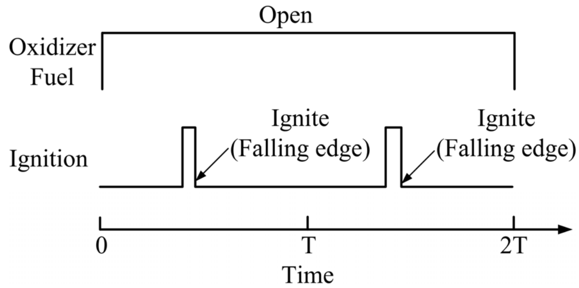

Figure 2. TTL control signals for supply and ignition.

To ensure implementation of this idea, fuel and oxidizer need not to be supplied intermittently by solenoid valves or rotary valves. Instead, only electrically operated valves are needed to control on/off before/after a run. Figure 2 shows the transistor-transistor logic (TTL) control signals for supply and ignition of this method. Note that ignition should be initiated by a phase delay than fuel and oxidizer.

To validate the feasibility of this method, experiments were carried out on a test rig. The detonation tube utilized was shown in Figure 3. It consisted of three sections, i.e., an injection and ignition section, a DDT section and a measurement section. An ordinary automobile spark plug with an ignition energy of about 50 mJ was used to initiate combustion. A typical Shchelkin spiral, which could accelerate the DDT process, was installed in the DDT section. Inner diameter and length of the detonation tube were 30 mm and 780 mm, respectively. The Shchelkin spiral had a length of 260 mm, and its pitch and wire diameter were 30 mm and 4 mm creating a blockage ratio of 0.46. Four pressure transducers were located 500 mm, 570 mm, 640 mm, and 690 mm axially away from the spark plug in sequence to record pressure history along the detonation tube. Oxygen-enriched air with a volume percentage of 45% oxygen and liquid gasoline were employed as oxidizer and fuel, respectively. To reduce the fuel depositing on tube-wall, liquid gasoline was sprayed into the detonation tube through a pressure swirl atomizer axially while oxidizer was injected through an annular gap surrounding the atomizer. Dynamic piezoelectric pressure transducers (SINOCERA CY-YD-205, natural frequency larger than 200 kHz, measurement precision ±3%) were employed in this study. The pressure transducers were connected to a multi-channel data acquisition system through a signal conditioner module. The pressure transducers were sampled at 200 kS/s. In addition, the pressure transducers were recessed in the mounting ports and water-cooled to prevent them from being damaged by extremely high temperature.

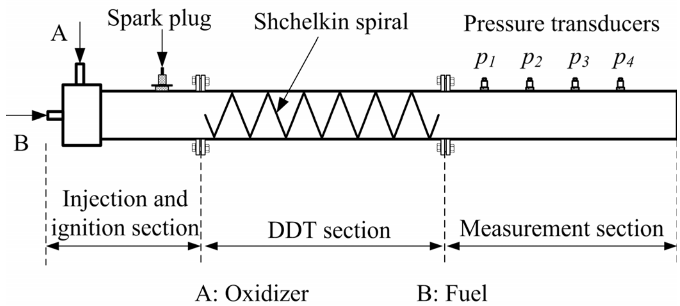

Figure 3. Schematic of detonation tube.

3 Results and Discussion

Experiments, without purging process, were conducted to validate whether the PDRE could operate stably or not. Supply pressure of fuel and oxidizer was set to be identical to ensure that fuel and oxidizer would stop supplying simultaneously during the period with a higher pressure inside the tube. It was observed that when supply pressure was lower than 0.7 MPa, stable operation could be obtained and a maximum operating frequency of 60 Hz was achieved in the present research.

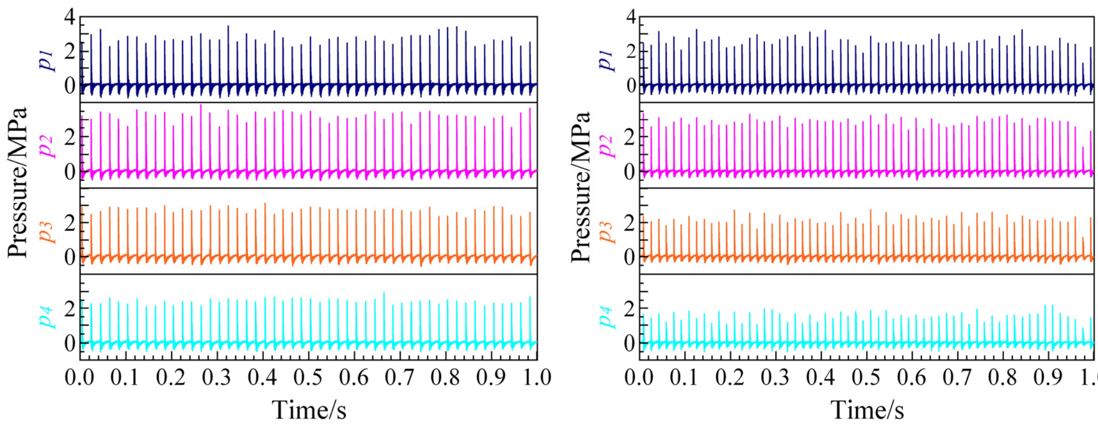

Figure 4. Pressure profiles. Left: Measured at an operating frequency of 50 Hz. Right: Measured at an operating frequency of 60 Hz.

Figure 4 were measured pressure profiles at operating frequencies of 50 Hz and 60 Hz while supply pressures of fuel and oxidizer were both 0.6 MPa. The fill fractions for 50 Hz and 60 Hz were 0.617 and 0.514, respectively. The Chapman-Jouguet (C-J) pressure and velocity calculated by Chemical Equilibrium with Applications (CEA) program [18, 19] were 2.69 MPa and 2034.1 m/s. The referenced pressure and temperature were 1 bar and 282 K in the calculation with an equivalence ratio of 1.71. Pressure measured, at the operating frequency of 50 Hz, by p_1, p_2, p_3, and p_4, were 2.8 MPa, 3.3 MPa, 2.8 MPa, and 2.6 MPa, respectively, approaching above 90% of the C-J value. The pressure measured by p_2 was evidently higher than C-J value and this might due to overdriven detonations formed around this location. Besides, detonation wave speed could be obtained by the time-of-flight method as in Ref. [14]. The calculated wave speed utilizing this method was between 1750 and 2000 m/s, about 86.0%~98.3% of C-J value. Considering liquid gasoline was used in this study and the assumptions on liquid-fuels in CEA program, fully-developed detonations were believed to be obtained. For the 60 Hz case, pressure measured by p_1 and p_2 were 2.6 MPa and 2.8 MPa, about 90% of C-J value; however, p_3 and p_4 only recorded pressure peaks of about 2.0 MPa and 1.5 MPa, respectively, which was evidently lower than C-J value. Additionally, wave speed between p_1 and p_2, p_2 and p_3, p_3 and p_4 was around 2000 m/s, 1750 m/s, and 1272 m/s, respectively, which indicated detonations attenuated along p_1~p_4 in sequence. Such a phenomenon was because the fill fraction at 60 Hz was too low to produce detonations strong enough to propagate through the tube length without attenuation. Higher operating frequencies were also tried but fully-developed detonations could not be produced at all with a lower fill fraction than that of 60 Hz. Yet, it was believed that, utilizing this method, higher-frequency detonations could be achieved in a detonation tube with smaller inner diameter or by employing electronically operated valves with larger flow rates for fuel and oxidizer which both produce a larger fill fraction.

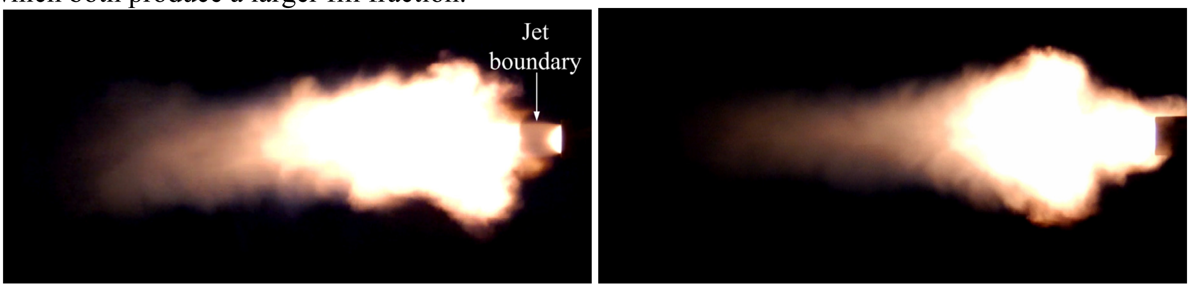

Figure 5. Exhaust plumes at an operating frequency of 46 Hz. Left: Initial stage of the operation. Right: Terminal stage of the operation.

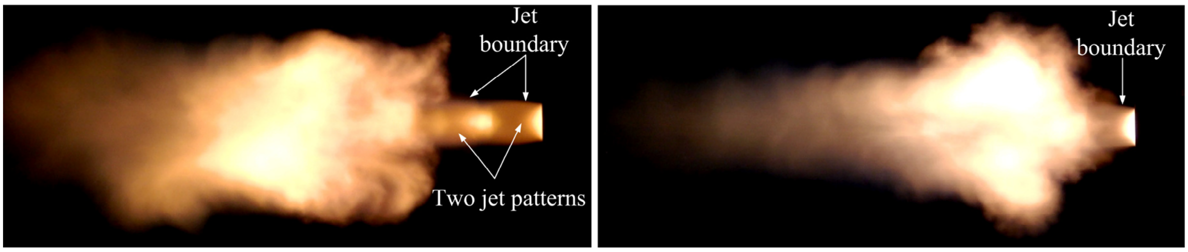

Figure 6. Exhaust plumes at an operating frequency of 56 Hz. Left: Initial stage of the operation. Right: Terminal stage of the operation.

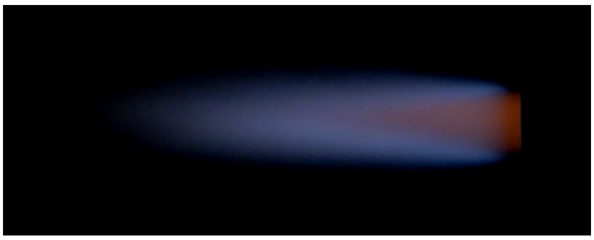

Figure 7. Exhaust plume at an operating frequency of 46 Hz but without detonation.

During the validation experiments, exhaust plumes were also captured while operations of the PDRE were carried out until tube ignition. Here tube ignition indicated that fresh detonable fuel-oxidizer mixture was ignited by hot tube-wall after a certain run time as no cooling measurement was adopted.

Figure 5 were exhaust plumes at an operating frequency of 46 Hz for initial and terminal stages. As shown in Figure 5, when combustion products were expelled from the tube, apparent jet boundary existed close to the tube and then the plume expanded suddenly at the initial stage and the whole plume was cone-shaped. When the burned gas arrived at the tube open end, it was under-expanded but with high velocity (more than 1500 m/s as previously discussed), thus a jet pattern, wave pattern or shock pattern similar to Ref. [20], was formed when it just emitted from the tube. Then the detonation waves expanded suddenly into the atmosphere unconstrainedly. Since the detonable mixture inside the tube was fuel-rich, unburned fuel, in the exhausted gas, reacted with oxidizer in the atmosphere which resulted in the suddenly expanded plume. Unlike at initial stage of the operation, only thicker plume without evident boundary was produced close to the tube at terminal stage (Figure 5 Right). Since after a period of time operation the tube-wall was heated and then the initial temperature of detonable mixture was increased by heat transfer from the tube inside wall, which would lead to lower detonation pressure and this was actually observed in this study, e.g., pressure recorded by p_2 decreased from about 3.0 MPa to 2.3 MPa after a run of 18 s. This would cause decrease of the time-averaged pressure inside the detonation tube, thus no evident boundary of exhaust jet was observed close to the tube open end.

As shown in Figure 6, exhaust plumes at an operating frequency of 56 Hz had some difference with that at 46 Hz. First, two jet patterns, instead of only one, were produced close to open end of the tube at initial stage of the operation. Second, one jet pattern with clear boundary still existed at terminal stage of the operation. Because with the increase of operating frequency, time-averaged pressure inside the detonation tube would increase due to higher-frequency detonations might combust more fuel-oxidizer mixture in detonation mode. Figure 7 was the exhaust plume at an operating frequency of 46 Hz when tube ignition induced deflagration happened. The exhaust plume was quite different from that produced by detonations as the exhaust plume was thinner.

In addition, different oxygen percentages were also tested to determine the upper and lower limits for stable operation in such an operating mode. Experimental results indicated that, when oxygen percentage varied from 25% to 45%, stable operation of the PDRE could be achieved.

4 Conclusions

To simplify hardware of the PDRE, purging process was tried to be eliminated as fuel and oxidizer supply would be stopped if higher pressure inside detonation tube than supply pressure were available. Oxygen-enriched air and liquid gasoline were utilized as oxidizer and fuel, respectively. Different supply pressures, for fuel and oxidizer, and oxygen percentages in oxidizer were tried to validate this method. Appropriate supply pressures for fuel and oxidizer were found to be important for stable operation of this operating mode. Experimental results indicated that stable operation of a PDRE without purging process could be achieved and a maximum operating frequency of 60 Hz was obtained. Oxygen percentage between 25% and 45% was observed workable in the present study. No other restrictions, except for flow rate, in increasing operating frequency were observed in this work, higher frequency was believed to be attainable if inner diameter was smaller or larger flow rates could be available in this work. Additionally, different exhaust plumes were observed as operating frequency varied. The results showed that it was feasible for the PDRE to be operated stably without purging process.

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