Detonation Studies of High-Frequency- Operation Pulse Detonation Engine with Air/Hydrogen

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ABSTRACT
An experimental study on pulse detonation engine (PDE) is conducted using hydrogen/air mixtures. Several key issues for PDE development, including valve operation, injection, mixing, filling, cycle repetition, ignition timing, DDT distance and propagation of detonation/quasi-detonation, are investigated. The fuel and oxidizer are injected into PDE from opposite sidewall directions to be well mixed by collision of two jets. The PDE performance is acquired to give the specific impulse about 2000 sec, which is measured from the pressure history on PDE head end. Operation at a maximum frequency 32 Hz is successfully performed. The deflagration-to-detonation transition (DDT) characteristics are measured in conjunction with operational frequency and ignition delay.

INTRODUCTION
The pulse detonation engine (PDE) has received considerable attention as a promising propulsion device for the operation potential at the speeds ranging from static to hypersonic, with competitive efficiencies. It also become more attractive for its fewer moving parts, high thrust density, low weight, low development/manufacturing cost, and ease of scaling. In the PDE operation, detonation waves are initiated repeatedly in a tube where a fresh combustible mixture is supplied to provide fuel accordingly to provide fuel for the next detonation. A typical operation cycle of PDE mainly consists of (1) the injection and mixing of fuel/oxidizer, (2) ignition, (3) deflagration to detonation transition (DDT) and propagation, evacuating the burned products. During this cycle, both the rarefaction waves trailing the detonation wave in the propagation and the expansion waves generated after the detonation wave exit result in a periodic high-pressure plateau plus an ensuring decay on the head end (the thrust wall) of detonation tube. In principle, the integrated effect of this high pressure over the head end produces the thrust.\textsuperscript{[1-2]}

A number of theoretical, computational and experimental researches on PDE have been made in the past years.\textsuperscript{[3-7]} The pre-mixed fuel/oxidizer mixture was usually used to get the detonation easily and to simplify the research.\textsuperscript{[8]} For the practical application, it is very important to study the key issues with the instant mixing of fuel and air. In this present work, an experiment research on PDE is conducted. The fuel and oxidizer are injected simultaneously into PDE tube from opposite sidewall directions to be mixed by collision between two jets. The results of experiment show that a stable detonation propagating with CJ velocity is obtained at our experimental condition, i.e. the volumetric mixing ratio 0.6 (equivalence ratio 1.43) between hydrogen and air. It is found out that transition to CJ velocity can be controlled by (1) the diameter, coil density and length of Shchelkin wire and (2) the initial pressure. The PDE performance is calculated from the measured pressure record, giving the specific impulse about 2000sec. High-frequency operation of hydrogen-air pulse detonation engine (PDE) is also experimentally studied. Operation at a maximum frequency 32 Hz is successfully performed. The deflagration-to-detonation transition (DDT) characteristics are measured in conjunction with operational frequency and ignition delay.

EXPERIMENTAL APPARATUS
The experimental setup consists of detonation tube, fuel/oxidizer supply system, ignition system, evacuating system, exhausting system and diagnostics system, as shown in Figure 1. The PDE tube is 2200mm long with I. D. 75mm, consisting of three individual test sections connected by flange assemblies adjusted for different test conditions. Near the closed end (head end) of the detonation tube, the fuel and oxidizer are injected into the tube with the opposite lateral directions from the sidewall ports, and are mixed by the collision of the two jets. The distances of the pair injection exits from the head end are 50 mm and 400 mm, respectively. The downstream open end of the PDE tube is connected with the exhaust system, which consists of a dump tank, a sub-evacuation system and a safety valve. The dump tank, which is at a length of 1500 mm and

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with internal diameter of 1000 mm, is used to store temporarily the burned products and to reduce the noise during the PDE operation, while the safety valve is for preventing the inner pressure of the tank to be above the specified level. A thin Mylar diaphragm is set between the PDE tube and dump tank before the operation.

![Experimental setup](image)

Figure 1 Experimental setup

The fuel/oxidizer injection system mainly consists of pressure regulator, mini-cylinder gas suppliers, solenoid/metering/check valves. The mass flow rates of fuel and oxidizer can be varied by changing the supply pressure and choking valve area. The gases can be fed at a rate giving the PDE tube pressure rise of up to 0.3MPa/s, using a gas cylinder pressure of 1MPa. The vacuum system is used to evacuate the existing air/burnt gas in PDE prior to initial filling of fuel/oxidizer.

A common used automobile ignition system is utilized to initiate the engine operation. The energy of the spark plug is around 35 mJ. The spark plug can be located at the center or near the center of the head end or in the side wall of the detonation tube to study the effects of the ignition location on the PDE performance. An ignition trigger pulse is generated and adjusted by a controller, which is coupled with the gas supply system controlled by solenoid valves for single-pulse-mode operation.

Ionization probes and photodiodes are used to monitor the acceleration of combustion wave into detonation. They are mounted in the sidewall of PDE tube at an interval of 250 mm. The piezoelectric pressure transducers (TOYODA MACHINE WORKS, LTD. PMS-5M) are used to record the pressure traces at certain locations of the detonation tube. All the signals are simultaneously recorded with an eight-channel digital oscilloscope (DL170, Yokogawa). Good agreements are observed among the velocity measurements by ionization probes, photodiodes and piezoelectric pressure transducers. A digital high-speed video imaging system (NAC HS-4540) is also utilized, to record the physical phenomena occurring at PDE exit by visualization through the window of dump tank. This camera system gives the recording rate 4,500fps for full frame and 40,500fps for split frame.

**FUNDAMENTAL RESULTS**

Air-Fuel Injection/ Mixing

First, fuel injection/mixing experiments are conducted to check the performance of fuel/oxidizer injection system. Air, Helium and oxygen are selected for their low cost, safety and similar weight consideration for expected fuel gases (hydrogen, ethylene). In experiments, PDE and dump tank are initially separated by a thin Mylar diaphragm, while the initial pressure of PDE is adjusted by the evacuating system. Fig.2 gives the relation between PDE charged pressure and initial pressures of air and oxygen in mini-cylinder gas suppliers, where the pressure of both suppliers for air and oxygen is initially set to 0.2, 0.6 and 1MPa. The upper solid lines in Fig.2 are for the initial pressure of PDE at 0.1MPa, while the lower dashed lines are for the case of initial pressure 0Mpa. The symbols in Fig. 2 give the single-pulse operating time of solenoid valve; the round one corresponds to the operating time 0.1s, the diamond one to 0.3s and the rectangular one to 0.5s.

Throughout testing, it has been shown that the injection curve inclinations are related not to either the valve operating time or the initial pressures of PDE tube and gas suppliers, but to the PDE charged pressure. For a specified fuel-supply system, therefore, the charged pressure could easily be estimated from the knowledge of injection curve inclination and initial gas pressure. Similar results are obtained in the injection experiment using Helium and air; note that Helium is injected into PDE faster than air due to its higher sound speed.

**Check of Mixing and Measurement of Mixture**

![Charged pressure in PDE tube with injection](image)

Figure 2 Charged pressure in PDE tube with injection

**Molar Ratio**
In the mixing experiment, oxygen and hydrogen are selected for convenience in measurement using the gas chromatography method. The initial pressure of gas suppliers of oxygen and hydrogen is kept at 1MPa. PDE is evacuated prior to injection of gases; two sampling packages are connected to PDE at the distances 50mm and 1350mm from head end. Sampling tests are performed when the supplied gas pressure has reached 0.104MPa. In the meantime, the ideal mixing ratio between hydrogen and oxygen mixture necessary for calibration can be given from the pressure reductions in mini-cylinder suppliers; it is compared with the results of jet mixing measured by the gas chromatography (SHIMAZU GC-8A) method, as shown in Table 1. Note here that a good agreement is seen between the estimated and measured ones, indicating an important result: direct collision of two jets inside PDE generates nearly instantaneous mixing and a uniform mixture.

**Table 1 Hydrogen/Oxygen Mole ratio**

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Measurement 1</th>
<th>Measurement 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.60/0.40</td>
<td>0.637/0.363</td>
<td>0.632/0.368</td>
</tr>
</tbody>
</table>

**Initiation of Detonation in PDE**

A conventional weak ignition system, using an automobile ignition coil and a spark plug, is employed with a supply of fixed ignition energy 35mJ. The spark plug is placed at the center of PDE head end. The hydrogen and air are simultaneously injected into PDE at a volume ratio about 0.6 (equivalence ratio 1.43). The mixture is ignited when the pressure in PDE has reached 50KPa.

![Figure 3 Typical experimental record in oscilloscope](image)

Figure 3 shows the simultaneous records of spark plug signal, two pressure transducer histories and two photodiode traces on oscilloscope. Two pairs of pressure transducers and photodiodes are located at the distances 250 and 500mm from PDE exit. As shown in Fig.3, there is a good agreement between the measurements by pressure transducers and photodiodes, both of which give the propagation velocity of detonation 2083m/s; nearly the CJ detonation velocity 2058 m/s for the present hydrogen/air mixture. The measured pressure peak of detonation is 0.91MPa. Fig.4 gives the emission from high-temperature products behind the detonation wave, which has just come out of PDE exit, at 8ms after the ignition signal.

![Figure 4 Photograph of detonation wave exit](image)

**Wave Propagation with Obstacles inside PDE**

Both an orifice plate and a Shchelkin wire are implemented to study their usefulness in shortening the DDT distance in PDE. Generally speaking, a turbulent mixing between hot combustion products and fresh reactants that can be promoted by placing an obstacle in the passage of combustion wave shortens the DDT distance. A relation between the propagation velocity of combustion wave near PDE exit and the orifice plate configuration is shown in Table 2, where the propagation velocity is derived from two pressure transducers located 250mm and 500mm upstream of PDE exit. The orifice plate is placed 200mm downstream of PDE head end. Hydrogen and air are mixed by colliding injections at an equivalence ratio about 2.33, where the ignition is done for the mixture gas pressure 50kPa. It has been shown that the propagation velocity at PDE exit increases by increasing the blockage ratio (BR), as seen in Table 2. For the same blockage ratio BR, the 4-hole orifice plate with larger diameter seems to be more effective than the 89-hole one.

**Table 2 Hydrogen/Oxygen Mole ratio**

<table>
<thead>
<tr>
<th>No</th>
<th>Size</th>
<th>Blockage ratio</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Without orifice</td>
<td></td>
<td>417</td>
</tr>
<tr>
<td>2</td>
<td>Ø5×10”</td>
<td>40%</td>
<td>454</td>
</tr>
<tr>
<td>3</td>
<td>Ø5×89</td>
<td>64%</td>
<td>555</td>
</tr>
<tr>
<td>4</td>
<td>Ø23.2×4</td>
<td>64%</td>
<td>714</td>
</tr>
</tbody>
</table>
Figure 5 shows the relation between the velocity and the geometry of Shchelkin wire (SW). The initial condition was the same as stated in the experiment with orifice. The symbols in the figure denote the diameter, \( \Theta \) and pitch, \( D \) of the wire. The closed round one gives the result without Shchelkin wire, and the closed rectangular one is for the wire at diameter of 10 mm with pitch of 50 mm, while the open symbols of round, rectangular, and diamond are for pitch of 10 mm with various diameter of 1, 2 and 3 mm, respectively. The detonation velocity of about 2066 m/s is obtained with Shchelkin wire E at length of 1400 mm. Before the detonation velocity is reached, the velocity increases linearly with the length of wire E as shown in the solid line. The similar value can be given with wire C, but for the wires of A and B with smaller diameter, no much velocity improvement can be derived compared with the results without the wire.\(^{[9-11]}\)

![Figure 5 Relation of velocity with geometry of Shchelkin wire](image1)

**Propagation Velocity and Mixing Ratio**

The effect of mixing ratio of hydrogen/air on the propagation velocity of combustion wave is studied, as shown in Fig. 6. The mixing ratio of hydrogen-air is controlled by adjusting the metering valve for hydrogen flow. During this experiment, a Shchelkin wire of length 600mm is utilized from the head end of PDE. In Fig. 6, the round symbols denote the cases of initial pressure 50kPa, while the open-rectangular ones for 81kPa. Their theoretical results are given with solid line and dashed one, respectively.

It has been shown that a stabilized propagation of detonation wave at CJ velocity is obtained for the equivalence ratio nearly 1.43 of hydrogen-air. The propagation velocity is observed to gradually decrease with increasing the hydrogen-air mixing ratios higher than 1.43, while it decreases more quickly for the hydrogen-air ratios lower than 1.43. Note here that the CJ velocity naturally changes little with the initial pressure for the hydrogen-air mixing ratio around 1.43. This agreed well with the theoretical results shown also in Fig. 6. Before the detonation onset, the increase of initial pressure from 50 KPa to 81 KPa at the mixing ratio of 2.3 results in a higher propagation velocity. The relation of propagation velocity with the initial pressure is also shown in Fig. 7. In the case of quasi-detonation, there exits a low velocity stable around 0.5 \( V_{cj} \) at the initial pressure from 50kPa to 92kPa. It can be inferred that the deflagration-to-detonation transition length can be shortened with the increasing of initial pressure or increasing fuel to air ratio in a certain region.\(^{[12-15]}\)

![Figure 7 Wave velocity versus initial pressure](image2)

**Estimation of performance**

Figure 8 shows the pressure history at the head end of PDE tube as a function of time, which is a very important physical quantity to generate thrust in such an unsteadily pulsating engine. The initial pressure in PDE is kept at 50kPa, containing a hydrogen-air mixture of equivalence mixing ratio 1.43. The Shchelkin wire is of length 600mm, implemented from the head end. A pressure transducer is placed 20mm downstream from the
head-end center, where a spark plug is mounted for ignition. As shown in Fig. 8, the head-end pressure history can be divided into the three regimes: X-detonation initiation, Y-plateau and Z-relaxation. The head-end pressure reaches a peak B of 350kPa from the initial value 50kPa in less than 1ms due to ignition. The second peak C of 380kPa is observed 0.5ms later caused by detonation initiation in PDE. Thereafter, the head-end pressure remains unchanged at 270kPa for 2.5msec till the point D; plateau. Then, the expansion waves generated by detonation wave exhausting from PDE reaches the head end, giving the pressure relaxation from D down to the atmospheric level E in 1.5ms. After the head-end pressure reaches the minimum value 20kPa at F, it gets back to increase, oscillating in the vicinity of ambient level due to occurrence of inverse flow at PDE exit.

The thrust of present PDE can be estimated from the difference between head-end pressure $P$ and ambient pressure $P_a$. The impulse $I$ can be obtained from the time integral of pressure difference using the following equation:

$$ I = \int_{t_0}^{t_f+\Delta t} (P(t) - P_a) \, dt $$

Using the impulse, the specific impulse $I_{sp}$, a more common performance in showing comparison among various propulsion devices, can be calculated through the knowledge of head-end area $A$ and propellant mass $m$, as follows:

$$ I_{sp} = I \cdot A (m \cdot g) $$

Pressure history at the head end

Fig.9 gives the impulse and specific impulse as functions of time. The head-end pressure is integrated from the point A, as shown in Fig.9, where the pressure is equal to the ambient value. The symbols correspond to the utilized lengths of Shchelkin wire (SW). For SW length 600mm, the impulse and specific impulse reach the peaks 650Nsm/m² and 1800s at point E in 5ms; prior to that, they increase almost linearly with time, and thereafter they keep oscillating until the end of reverse flow phenomenon at PDE exit. The second peak occurs at the time 25ms. The similar results can be obtained for SW length 1400mm, although higher values 860Nsm/m² and 2380s are acquired. These results clearly indicate that the instant when the head-end pressure becomes sub-ambient at E should be a good timing of refilling PDE and starting the next cycle. Higher impulse and specific impulse can be expected by reducing the interval between B and C, as shown in Fig. 8, it can eventually be realized by shortening DDT distance.[16-18]

RESULTS FROM HIGH-FREQUENCY OPERATION

Experimental setup

A high-frequency operation system of PDE is also developed. As stated in last chapter, the experimental system mainly consists of detonation tube, fuel/oxidizer supply system, ignition system, evacuating system, exhausting system and diagnostics system, while detonation tube is 800mm long with I. D. 30mm. The fuel and oxidizer are injected into the tube with the opposite lateral directions from the sidewall ports, located at the distance from the headend of 30 mm and are mixed by the collision of the two jets. The gas supply system is mainly controlled by the high-speed valves. Their injection time of fuel and oxidizer is set at 20 ms. The ignition plug is located at a distance of 60 mm from the head end. As shown in Figure 10, because the stable detonation is found at the equivalence ratio of hydrogen and air around 1.43, it is used in our high-frequency operation of PDE.
The PDE has been successfully operated at a frequency of 5Hz, 10Hz, 16Hz, 20Hz, 25Hz and 32Hz. The maximum operating frequency of the system is about 45 Hz. Figure 11 is a history record of spark plug, high-speed valve and ionization probes. As stated before, the injection time of the high-speed valve is around 20 ms, while the ignition signal is given less than 3 ms. The wave velocity of propagation for each cycle in the detonation tube is derived based on the signals of ionization probe as shown at the right part of the Figure. The similar results could be derived from signals of the ionization probe for the 1st and 2nd cycle. The output of the probes decreases from the 3rd cycle because of the increasing of partial pressure of burned gas due to the small size of the dump tank.

**DDT characteristics with operation frequency**

Figure 12 and Figure 13 give the relations of DDT distance and DDT time with operating frequency of PDE, respectively. The DDT distance is the distance from ignition location to the position where the propagation velocity of the wave reaches over 2000 m/s, while DDT time is given as the difference between the ignition time and the time when the propagation velocity of the wave reaches over 2000 m/s. It can be found that both the DDT distances and times do not change so much with the PDE operating frequency. It infers that the operating frequency could be increased by improving the fuel/gas supply system.

**SUMMARY AND CONCLUSION**

High-frequency operation of hydrogen-air pulse detonation engine (PDE) is experimentally studied, where mixing is carried out inside PDE, using collision of two impinging jets from PDE sidewall. Nearly instantaneous mixing is realized by jet collision between hydrogen and air, judging from the Gas Chromatography measurement. The detonation velocity 2083m/s is derived using the conventional automobile ignition system at the equivalence ratio of 1.43 and the initial pressure of 50kPa. Operation at a maximum frequency 32 Hz is successfully performed. The deflagration-to-detonation transition (DDT) characteristics are measured in conjunction with...
operational frequency and ignition delay.

Several orifice plates and Shchelkin wires (SW) are tested to find out their optimal geometries in wave interaction with obstacles. The propagation velocity of detonation/quasi-detonation at PDE exit increases with the increase of blockage ratio, length and diameter of SW. Meanwhile, orifice plates having larger hole diameter seem to be more effective for an identical BR. Throughout the experiment, the stable CJ detonation velocity is obtained around the equivalence ratio of 1.43. The propagation velocity decreases as the ratio moves away from 1.43, although the stable CJ velocity region is irrelevant to the initial pressure.

The pressure history on PDE head end is carefully monitored to give PDE performance. After the ignition of mixture, both impulse and specific impulse reach maximum in 6ms. The plateau region in PDE head end pressure history plays an important role to generate impulse and specific impulse. Duration of this plateau region can be extended by shortening DDT distance or increasing PDE length.

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REFERENCE