Experimental Study of Key Issues on Pulse Detonation Engine Development

By Feng-Yuan ZHANG,1) Toshitaka FUJIWARA,1) Takeshi MIYASAKA,1) Ei-ichi NAKAYAMA,1) Tsuyoshi HATTORI,1) Nobuyuki AZUMA,1) Satoru YOSHIDA1) and Azusa TAMUGI2)

1)Department of Aerospace Engineering, Nagoya University, Nagoya, Japan
2)Mitsubishi Heavy Industries, Ltd., Nagoya, Japan

(Received February 18th, 2002)

An experimental study on the 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 the PDE from opposite sidewall directions so as to be well mixed by collision of the two jets. A good agreement is obtained between the calculated and measured mixing ratios, indicating the occurrence of nearly instant mixing. Before the detonation velocity has reached the CJ value, it was found that the wave propagation velocity at the PDE exit increases with the increase in diameter, length and blockage ratio of the Shchelkin wire, and initial pressure. The PDE performance acquired was a specific impulse of about 2000 s, which was measured from the pressure history at the head end of the PDE.

Key Words: Pulse Detonation Engine, Propulsion, Hypersonic Flow, Chemical Reaction, Shock Wave

1. Introduction

The pulse detonation engine (PDE) has received considerable attention as a promising propulsion device for potential operation at speeds ranging from static to hypersonic, with competitive efficiencies. It is also more attractive in view of its fewer moving parts, high thrust density, low weight, low development/manufacturing cost and ease of scaling. In PDE operation, detonation waves are initiated repeatedly in a tube where a fresh combustible mixture is supplied as fuel for the next detonation. As shown in Fig. 1, a typical operation cycle mainly consists of (1) the injection and mixing of fuel-oxidizer, (2) ignition, (3) deflagration to detonation transition (DDT) and propagation, (4) evacuating the burned products. During this cycle, both the rarefaction waves trailing the detonation wave during propagation and the expansion waves generated after the detonation wave exit result in a periodic high-pressure plateau plus an ensuring decay at the head end (the thrust wall) of the detonation tube. In principle, the integrated effect of this high pressure over the head end produces the thrust.1,2)

A number of theoretical, computational and experimental studies on PDE have been made in past years.3–7) The premixed fuel-oxidizer mixture or oxygen was usually used to obtain detonation easily and simplify the research. For practical application, it is very important to study the key issues with the instant mixing of fuel and air. In this work, experimental research on PDE is conducted. The fuel and oxidizer are injected simultaneously into a PDE tube from opposite sidewall directions so as to be mixed by collision of the two jets. The PDE tube is 2200 mm long, with a 75 mm I. D., and is divided into three individual test sections connected by flange assemblies adjusted for different test conditions. Several key physical-chemical/engineering issues (i.e., solenoid valve operation, fuel injection, filling, mixing, detailed ignition characteristics, DDT and detonation propagation) are investigated using hydrogen-air as the combustible gas. The results of the experiment show that a stable detonation propagating with CJ velocity is obtained under our experimental conditions (i.e., a volumetric mixing ratio of 0.6 (equivalence ratio 1.43) between hydrogen and air). It was found out that transition to CJ velocity can be controlled by (1) the diameter, coil density and length of the Shchelkin wire, and (2) the initial pressure. The PDE performance is calculated from the measured pressure record, giving a specific impulse of about 2000 s.

2. Experimental Apparatus

The experimental setup consists of a detonation tube, fuel-oxidizer supply system, ignition system, evacuating system, exhausting system and diagnostics system as shown in Fig. 2. The PDE tube is 2200 mm long, with 75 mm I. D., consisting of three individual test sections connected by flange assemblies adjusted for different test conditions. Near the closed end (i.e., head end) of the detonation tube, the fuel and oxidizer are injected into the tube from the side-wall ports with the opposite lateral directions, and are mixed by the collision of the two jets. The distances of the pair of injection ports from the head end are 50 mm and 400 mm, respectively. The downstream open end of the PDE tube is connected to the exhaust system, which consists of a dump tank, a sub-evacuation system and a safety valve. The dump tank, which is a length of 1500 mm and has a 1000 mm I. D., is used to temporarily store the burned products and to re-
duce the noise during PDE operation, while the safety valve is for preventing the inner pressure of the tank to rise above a specified level. A thin Mylar diaphragm is set between the PDE tube and damp tank before operation.

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

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

Ionization probes and photodiodes are used to monitor the acceleration of the combustion wave to detonation. They are mounted in the sidewall of the PDE tube at intervals of 250 mm. Piezoelectric pressure transducers (TOYODA...
KOJI 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 agreement was observed among the velocity measurements by ionization probes, photodiodes and piezoelectric pressure transducers. A high-speed digital video imaging system (NAC HS-4540) is also utilized to record the physical phenomena occurring at PDE exit by visualization through a window in the dump tank. This camera system has a recording rate of 4,500 fps for full frames and 40,500 fps for split frames.

3. Results and Discussions

Air-fuel injection/mixing
First, fuel injection/mixing experiments are conducted to check the performance of the fuel-oxidizer injection system. Air, helium and oxygen are selected for their low cost, safety and similar weight considerations for expected fuel gases (hydrogen, ethylene). In experiments, the PDE and dump tank are initially separated by a thin Mylar diaphragm while the initial pressure of PDE is adjusted by the evacuating system. Figure 3 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 1 MPa. The upper solid lines in Fig. 3 are for the initial pressure of PDE at 0.1 MPa, while the lower dashed lines are for the case of initial pressure at 0 MPa. The symbols in Fig. 3 give the single-pulse operating time of solenoid valve; the circle corresponds to the operating time of 0.1 s, the diamond 0.3 s and the rectangle 0.5 s.

Throughout testing, it can be seen that the injection curve inclinations are not related to either the valve operating time or the initial pressures of the PDE tube and gas suppliers, but to the PDE charged pressure. For a specified fuel-supply system, therefore, the charged pressure can easily be estimated from knowing the 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 the PDE faster than air due to its higher sound speed.

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

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 35 mJ. The spark plug is placed at the center of the PDE head end. The hydrogen and air are simultaneously injected into PDE at a volume ratio of about 0.6 (equivalence ratio 1.43). The mixture is ignited when the pressure in the PDE reaches 50 kPa.

Figure 4 shows the simultaneous records of spark plug signal, two pressure transducer histories and two photodiode traces on an oscilloscope. Two pairs of pressure transducers and photodiodes are located at distances of 250 mm and 500 mm from the PDE exit. As shown in Fig. 4, there is a good agreement between the measurements by pressure

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>

Fig. 3. Charged pressure in PDE tube with injection.

Fig. 4. Typical experimental record in the digital oscilloscope.
transducers and photodiodes, both of which give the propagation velocity at detonation 2083 m/s; nearly the CJ detonation velocity of 2058 m/s for the present hydrogen-air mixture. The measured pressure peak of detonation is 0.91 MPa. Figure 5 gives the emission from high-temperature products behind the detonation wave, which has just come out of the PDE exit, at 8 ms after the ignition signal.

**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 the 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. The relation between the propagation velocity of combustion wave near the PDE exit and the orifice plate configuration is shown in Table 2, where the propagation velocity is derived from two pressure transducers located 250 mm and 500 mm upstream of the PDE exit. The orifice plate is placed 200 mm downstream of the PDE head end. Hydrogen and air are mixed by colliding injections at an equivalence ratio of about 2.33, where the ignition is done for the mixture gas pressure 50 kPa. It has been shown that the propagation velocity at the 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 a larger diameter seems to be more effective than the 89-hole plate.

![Fig. 5. Photograph of detonation wave exit.](image)

![Fig. 6. Relation of combustion wave velocity and geometry of Shchelkin wire.](image)

![Fig. 7. Effect of hydrogen-air equivalence ratio on combustion wave velocity.](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Configuration</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></td>
<td>454</td>
</tr>
<tr>
<td>2</td>
<td>0.57 × 10’</td>
<td>40</td>
<td>454</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>φ5 × 89</td>
<td>64</td>
<td>555</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>φ23.2 × 4</td>
<td>64</td>
<td>714</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6 shows the relation between the velocity and the geometry of the Shchelkin wire (SW). The initial condition was the same as stated in the experiment with the orifice. The symbols in the figure denote the diameter φ and pitch D of the wire. The closed circle gives the result without Shchelkin wire, and the closed rectangle is for a wire with a diameter of 10 mm and pitch of 50 mm, while the open circles are for a pitch of 10 mm with various diameters of 1, 2 and 3 mm, respectively. The detonation velocity of about 2066 m/s is obtained with Shchelkin wire E at a length of 1400 mm. Before the detonation velocity is reached, the velocity increases linearly with the length of wire E as shown by the solid line. A similar value can be given with wire C, but for the wires of A and B with a smaller diameter, not much velocity improvement can be derived compared with the results obtained without the wire.8–10)

**Propagation velocity and mixing ratio**

The effect of the mixing ratio of hydrogen-air on the propagation velocity of the combustion wave is studied, as shown in Fig. 7. The mixing ratio of hydrogen-air is controlled by adjusting the metering valve for hydrogen flow. During this experiment, a Shchelkin wire with a length 600 mm is utilized from the head end of PDE. In Fig. 7, circles denote the cases of initial pressure 50 kPa, while the open rectangles for 81 kPa. Their theoretical results are given with solid and dashed lines, respectively.

It has been shown that stabilized propagation of detonation wave at CJ velocity is obtained for the equivalence ratio of nearly 1.43 for 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 of around 1.43. This agreed well with the theoretical results also shown in Fig. 7. Before the detonation onset, the increase in initial pressure from 50 kPa to 81 kPa at the mixing ratio of 2.3 results in a higher propagation velocity. The re-
lation of propagation velocity and the initial pressure is also shown in Fig. 8. In the case of quasi-detonation, there exits a stable low velocity around 0.5 V_{cj} at the initial pressure from 50 kPa to 92 kPa. It can be inferred that the deflagration-to-detonation transition length can be shortened by increasing the initial pressure or increasing fuel-air ratio in a certain region.\[^{11-14}\]

**Estimation of performance**

Figure 9 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 the PDE is kept at 50 kPa, containing a hydrogen-air mixture at the equivalent mixing ratio of 1.43. The Shchelkin wire is 600 mm length, and implemented from the head end. A pressure transducer is placed 20 mm downstream from the head-end center, where a spark plug is mounted for ignition. As shown in Fig. 9, 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 350 kPa from the initial value of 50 kPa in less than 1 ms due to ignition. The second peak C of 380 kPa is observed 0.5 ms later, caused by detonation initiation in the PDE. Thereafter, the head-end pressure remains unchanged at 270 kPa for 2.5 ms until point D; the plateau. Then, the expansion waves generated by the detonation wave exhausted from the PDE reach the head end, giving the pressure relaxation from D down to the atmospheric level E in 1.5 ms. After the head-end pressure reaches the minimum value 20 kPa at F, it begins to increase again, oscillating in vicinity of the ambient level due to the occurrence of inverse flow at the 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 the pressure difference using the following equation:

$$I = \int_{0}^{t_{\text{final}}} (P(t) - P_a) dt.$$  \hspace{1cm} (1)

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

$$I_{sp} = I \cdot A / (m \cdot g).$$  \hspace{1cm} (2)

Figure 10 gives the impulse and specific impulse as functions of time. The head-end pressure is integrated from point A as shown in Fig. 9, where the pressure is equal to the ambient value. The symbols correspond to the lengths of Shchelkin wire utilized. For a SW length of 600 mm, the impulse and specific impulse reach the peaks 650 N s/m² and 1800 s at point E in 5 ms; prior to that, they increase almost linearly with time, and thereafter they keep oscillating until the end of the reverse-flow phenomenon at the PDE exit. The second peak occurs at the time of 25 ms. Similar results can be obtained for a SW length of 1400 mm, although higher values 860 N s/m² and 2380 s are acquired. These results clearly indicate that the instant when the head-end pressure becomes subambient at E should be a good time to refill the PDE and start the next cycle. Higher impulse and specific impulse can be expected by reducing the interval between B and C as shown in Fig. 9; it can eventually be realized by shortening the DDT distance.\[^{15-17}\]

4. Summary and Conclusion

A pulse detonation engine (PDE) is developed and studied in Nagoya University. The fuel and oxidizer are injected into the PDE at opposite directions from the sidewall and are mixed by collision of the two jets. Nearly instantaneous mixing is realized by jet collision between hydrogen and air judging from the gas chromatography measurements. The
detonation velocity of 2083 m/s is derived using a conventional automobile ignition system at a gas mixture equivalence ratio of 1.43 and the initial pressure of 50 kPa.

Several orifice plates and Shchelkin wires are tested to determine their optimal geometries in wave interaction with obstacles. The propagation velocity of detonation/quasi-detonation at the PDE exit increases with increases in blockage ratio, length and diameter of Shchelkin wire. Meanwhile, orifice plates having a larger hole diameter seem to be more effective for an identical BR. Throughout the experiment, a stable CJ detonation velocity is obtained around the gas mixture 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 ignition of the mixture, both impulse and specific impulse reach a maximum in 6 ms. The plateau region in the PDE head end pressure history plays an important role in generating impulse and specific impulse. The duration of this plateau region can be extended by shortening the DDT distance or increasing the PDE length.

Acknowledgments

The authors would like to thank Technician Akira SAITO for his enthusiastic preparation of experimental devices. Financial support from NEDO and Mitsutoyo Association for Science and Technology are gratefully acknowledged.

References