Pulse Detonation Operation at Kilohertz Frequency

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1 Introduction

A pulse detonation engine (PDE) is an internal combustion engine (ICE) in which fuel is intermittently burned by self-sustained detonations [1]. The burning temperature in a detonation is higher than that in an isobaric combustion and the thermal efficiency of a PDE is higher than that of a conventional ICE. Furthermore, a PDE can have more simple structure because detonable mixture is compressed by shock wave and the load to a precompressor decrease.

In a cylindrical pulse detonation combustor (PDC), the following processes are repeated: (1) filling of oxidizer and fuel (detonable mixture), (2) ignition and deflagration-to-detonation transition (DDT), (3) propagation of detonation wave, (4) blowdown of high-pressure burned gas (5) purging of the residual low-pressure burned gas. Of these processes, (3) and (4) are governed by gasdynamics [2]. The gasdynamics upper limit of operating frequency is govered by assuming pulse detonation (PD) cycle in which only this two processes are repeated. To achieve the PD operation at the upper limit frequency, it is essential to shorten process (1), (2) and (5). Many studies on shortening DDT process with Shchelkin spiral and/or obstacle have been carried out [3]. In addition, many valveless PD operation methods were proposed to shorten process (1) and (5) [4-7]. Matsuoka et al. proposed a liquid-purge method [8], in which gaseous oxidizer and fuel is supplied with valvelss mode and residual burned gas is purged by injecting water droplets. Recently, a semi-valveless PDC without purging material was proposed by Matsuoka et al. [9]. As shown in Fig. 1, this system has valveless oxidizer feed line, fuel injector and spark plug and the inner diameter of oxidizer feed line is equal to that of a combustor. The upper left figure in Fig. 1 shows the ideal pressure history in a combustor p_c measured at the same position as spark plug [10] and the horizontal dash line shows the total pressure of the supplying oxidizer $p_{t,o}$. The lower left figure shows the time history of

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fuel and oxidizer flow rate corresponding to the pressure history. The right figures show schematic illustrations of material distribution in a PDC at each specified time shown in the left figures.

At $t = t_1$, oxidizer and fuel are supplied and detonable mixture is filled up ($p_c < p_{t,o}$). At $t = t_2$, the detonable gas is ignited by a spark plug and DDT occurs. At this time, the injection of fuel is stopped and only the oxidizer is supplied to a combustor ($p_c < p_{t,o}$). At $t = t_3$, detonation wave propagetes and high-pressure burned gas is generated. The burned gas interrupts the oxidizer supply because the pressure in a combustor becomes higher than that of oxidizer ($p_c > p_{t,o}$) and a portion of the burned gas flows backward to the upstream of a combustor. At $t = t_4$, the pressure of burned gas is decreased by rarefied expansion waves from the open end of a combustor and the oxidizer is supplied again ($p_c < p_{t,o}$). Using the operation method, Matsuoka et al. demonstrated the PD operation at 800 Hz with ethylene-oxygen mixture [11].

In this paper, PD operation with a piezoelectric fuel injector instead of an automotive solenoid fuel injector was described. Consequently, the flame propagation speeds measured by ion probes were 2500 ± 100 m/s and 96 % of the PD operation cycles at 1000 Hz was demonstrated.

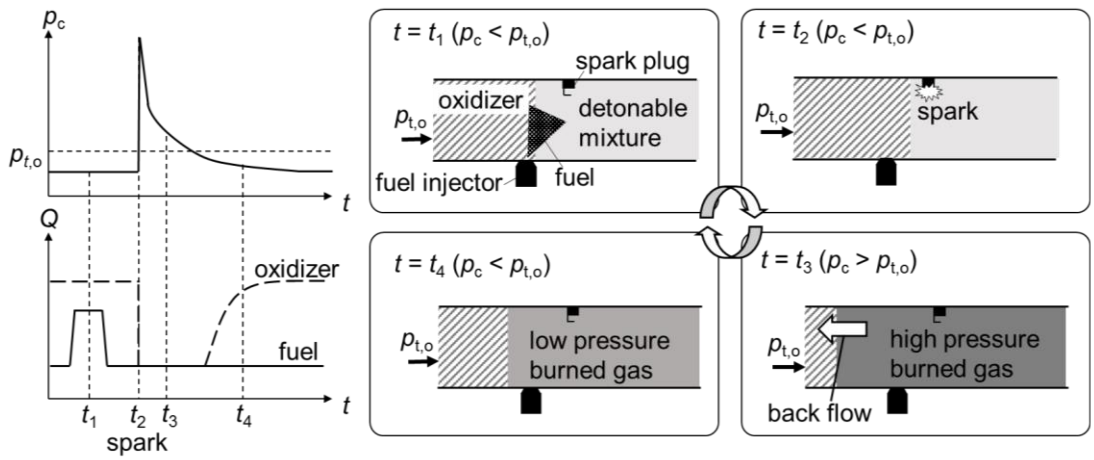

Figure 1. valveless pulse detonation cycle[9]

2 Evaluating Responsiveness of the Piezoelectric Fuel Injector and Ignitor

It is important to comprehend the responsiveness of a fuel injector and an ignitor for achieving high-frequency PD operation. Upon conducting a combustion test, visualization experiment of injection with a piezoelectric fuel injector (Bosch, HDEV4) and ignition was conducted and the responsiveness was investigated.

Fig. 2 shows input signal for an injector and an ignitor (solid line, subscript: set), real fuel injection and spark (dashed line, subscript: real) and the experimental pressure history in the combustor p_c. Time was defined so that the set time of spark was $t = t_{sp,set} = 0$ μs. As shown in Fig. 2, the response delay from the set injection start time $\Delta t_{on,delay}$ and from the set injection stop time $\Delta t_{off,delay}$ were measured using Schlieren method and a high-speed camera SA5 produced by Photron. Spark was also captured with a high-speed camera and the response delay $\Delta t_{sp,delay}$ in Fig. 2 was measured.

In the visualization experiment of fuel injection, the set value of operation frequency, injection duration and duty ratio (DR = injection duration/duration for one PD cycle) were fixed at $f_{ope,set}$ = 1000 Hz, $\Delta t_{inj,set}$ = 300 μs and DR_{set} = 30%, respectively and fuel injection was repeated 50 times. The frame rate and exposure time of the high-speed camera were 10 μs/frame and 1/236000 sec (4.24 μs), respectively. The fuel was ethylene and the fuel injection pressure was constant at p_{inj} = 5.99 ± 0.02 MPa. The error was the standard deviation of the pressure during 5 ms just before injection.

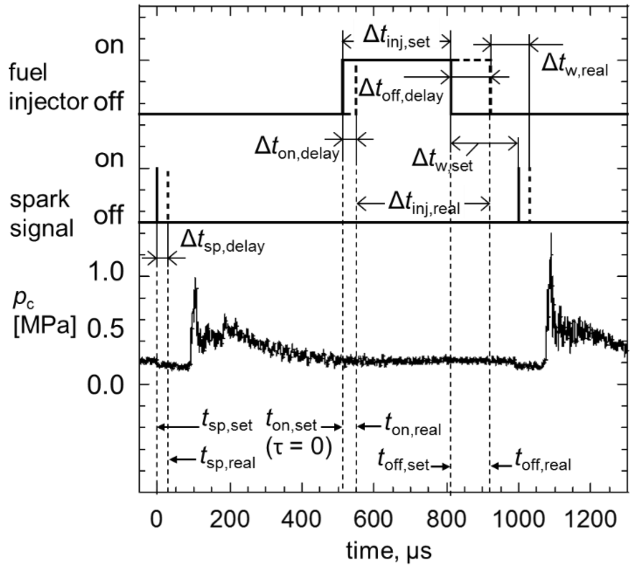

Figure 2. operating sequence and experimental pressure history in combustor

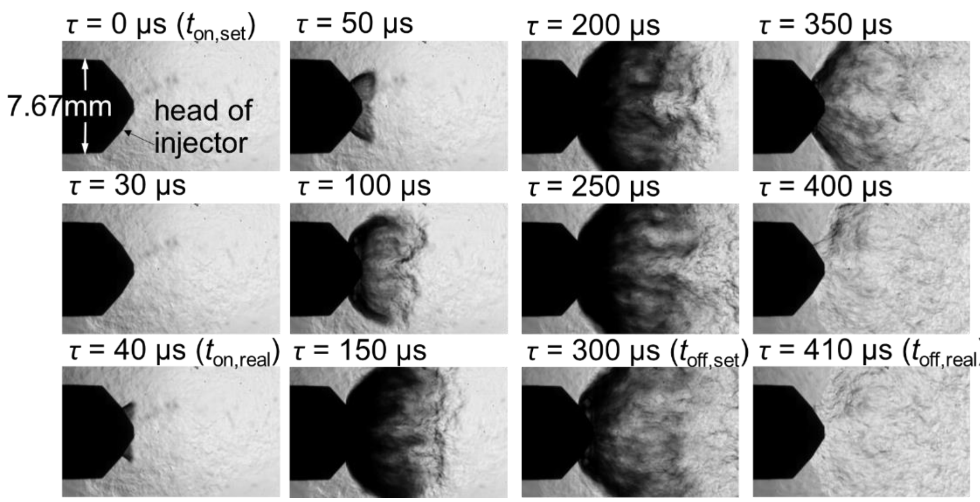

Figure 3. snapshots during fuel injection (30th cycle, fluid: C_2H_4)

As an example of visualization, snapshots during fuel injection in 30th cycle were shown in Fig. 3. Then, time τ was defined so that the set injection start time was τ = 0 µs ($\tau = t - t_{on,set}$). In Fig. 3, the first injection from the coaxial circular slit at the head of injector was observed at τ = 40 µs. At τ = 300 µs which is the set injection stop time, fuel injection was still observed. Then, the stop of injection was confirmed at τ = 410 µs. The average response delay from the injection start and stop time in 10, 20, 30 and 40th cycle was $\Delta t_{on,delay}$ = 36 ± 10 µs, $\Delta t_{off,delay}$ = 106 ± 10 µs, respectively. The duty ratio of the actual injection was DR_{real} = 37 ± 1% against DR_{set} = 30%. The error was duration of front and rear one frame. The response delay of the piezoelectric fuel injector was about 25% of that of the conventional solenoid fuel injector ($\Delta t_{on,delay} \approx$ 200 µs, $\Delta t_{off,delay} \approx$ 400 µs [9]).

In measuring the response delay of an ignitor, the set value of operation frequency was fixed at $f_{ope,set}$ = 1000 Hz and spark was repeated 50 times. The frame rate and exposure time of the high-speed camera were 1.90 µs/frame (525000 frame/s) and 1/frame sec (1.90 µs), respectively. The waiting duration from the set injection stop time $t_{off,set}$ to the set spark time $t_{sp,set}$ (see Fig. 2) was $\Delta t_{w,set}$ = 100, 200 and 300 μs and fuel injector was also operated. The average response delay of an ignitor in 10, 20, 30, 40th cycle in 4 conditions (total 12 cycles) was $\Delta t_{sp,delay}$ = 30 ± 3 μs. The standard deviation of 12 cycles was taken into account in the error.

3 Experimental Arrangement

Fig. 4 shows the combustor used in this experiment. The x coordinate is the central axis of the combustor along the flow, with the origin corresponding to the position of spark plug (SP, NGK, model number CR8HSA). The section between x = 0 mm and 100 mm was the combustor and the section between x = -230 mm and 0 mm was the oxidizer feed line. At x = -30 mm, the piezoelectric fuel injector (INJ) was installed. Four ion probes (IP1, IP2, IP3 and IP4), which were made of spark plugs (NGK, model number CR8HSA) [12], were installed at the side wall of combustor and the output voltage rapidly increased due to the passage of combustion wave. The flame popagation speed was measured by dividing difference of rise time by the interval of ion probes 20 mm. At x = 0 mm, a pressure transducer (PT, PCB Piezotronics,lnc, model number 113B24) was installed on the opposite side of a spark plug and used to measure the pressure in the combustor p_c. The inner diameter of -200 mm ≤ x ≤ 100 mm and -230 mm ≤ x ≤ -210 mm were id_c = 10 mm and 20 mm, respectively.

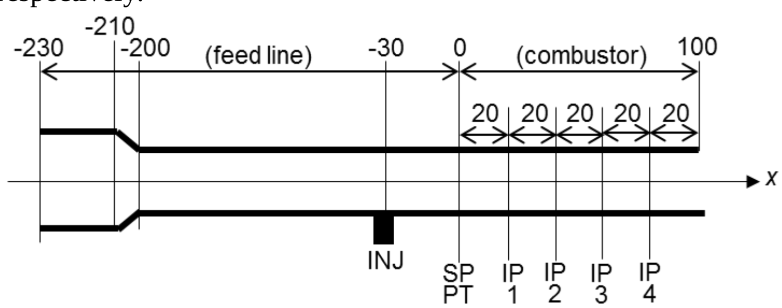

Figure 4. pulse detonation combustor used in experiment (unit: mm)

In this experiment, PD operation with ethylene-oxygen was carried out. The atmospheric pressure and temperature were p_a = 0.102 MPa and T_a = 290 K, respectively. The supply pressure of oxygen was set at $p_{t,o}$ = 0.3 MPa by the pressure regulator installed at the upstream of the combustor. The mass flow rate of oxygen in steady flow was $\dot{m}_o$ = 45.2 ± 0.5 g/s and the error was the standard deviation of 3-time measurement. 5000-cycle fuel injection was carried out and the mass flow rate of the fuel $\dot{m}_f$ was calculated using following equation.

$$\dot{m}_f = \frac{\Delta m}{5000 \times \Delta t_{inj,real}} \quad (1)$$

where Δm and $\Delta t_{inj,real}$ were the mass difference between before and after 5000-cycle injection and real injection duration (see Fig. 2), respectively. The fuel mass flow rate calculated with Eq. (1) was mass flow rate during real injection and $\dot{m}_f$ = 4.9 ± 0.3 g/s when the fuel injection pressure was p_{inj} = 5.84 ± 0.03 MPa. They were the average value of 3-time measurement and the error was the standard deviation. As a result, the equivalence ratio of ethylene and stesdy-flow oxygen was estimated to be ER = 0.38. As shown in Fig. 2, the injection duration, waiting duration and operation frequency were set at $\Delta t_{inj,set}$ = 300 μs (DR_{set} = 30%), $\Delta t_{w,set}$ = 186 μs and $f_{ope,set}$ = 1000 Hz, respectively and 71-cycle PD operation was carried out. Considering the response delay, real injection duration and real waiting duration were $\Delta t_{inj,real}$ = 370 ± 10 μs (DR_{real} = 37 ± 1%) and $\Delta t_{w,real}$ = 110 ± 8 μs, respectively and these values were set experimentally.

4 Result and Discussion

Fig. 5 shows the time history of the pressure p_c measured with PT installed at x = 0 mm. Time was defined so that the set spark time in the first cycle was set at t = 0 µs. The baselines of the pressure-transducer outputs during a PD operation gradually shift. The pressure history was corrected to cancel this characteristic so that the average pressure in 5 µs from the beginning of each cycle was equal to that between t = 0 µs and 50 µs. The estimated Chapman−Jouguet (C−J) detonation pressure was p_{CJ} = 2.35 MPa [13] under the condition that the initial temperature, pressure and equivalence ratio of the detonable mixture were T_d = 300 K, p_d = 102 kPa and ER = 0.38, respectively. The horizontal dash line in Fig. 5 shows the pressure p_{CJ} and the peak of the pressure in the combustor p_c was lower than p_{CJ} in most cycles. The possible reason was because the retonation wave was generated at the downstream of spark plug causing DDT and propagated into the upstream filled with burned gas and/or oxygen.

Fig. 6 shows the averaged flame propagation speed measured with ion probes in 7 cycles of 10, 20, 30, 40, 50, 60, 70th cycle (vertical dash line in Fig. 5). The vertical and horizontal error bar were the standard deviation and distance between two ion probes, respectively. The lower horizontal dashed line shows the estimated C−J detonation speed D_{CJ} = 1953 m/s (ER = 0.38, T_d = 300 K, p_d = 102 kPa) [13]. However, this speed was much lower than measured speed V_f = 2503 m/s. The detonable mixture flowed at high speed u_d, so detonation speed was estimated to be the sum of D_{CJ} and u_d. Assuming the detonable mixture flowed at sound speed, it was estimated at u_d = 329 m/s [13]. The flame propagation speed between x = 60 mm and 80 mm was 110 ± 6% of the estimated detonation speed $D_{CJ} + u_d$ = 2282 m/s (upper horizontal dashed line in Fig. 6) and the distance needed for DDT was estimated at 60% of length of a combustor. The time difference between real spark time $t_{sp,real}$ and time when the flame was detected at x = 60 mm was Δt_{DDT} = 110 ± 30 µs. The error was the standard deviation of 7 cycles. Assuming DDT occurred at x = 60 mm, the required duration for DDT was equal to Δt_{DDT} and 11 ± 3% of duration for one PD cycle. Increasing the equivalence ratio of detonable mixture is one of methods to shorten DDT and achieve higher-frequency PD operation. The other method is increasing the pressure of detonable mixture. Kuznetsov et al. proved the distance from ignition point to transition location was shortened with increasing initial pressure of static hydrogen-oxygen mixture [14]. Accordingly, increasing oxidizer supply pressure with constant ER leads to pressure increase of detonable mixture and shortening the DDT. In this experiment, PD operation at 1000

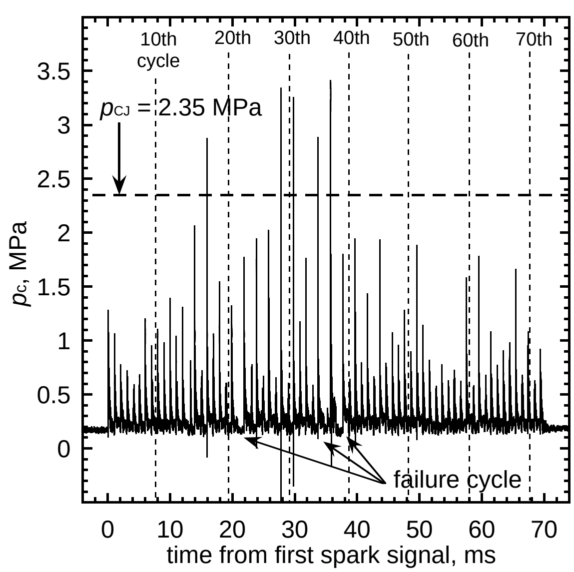

Figure 5. time history of the pressure

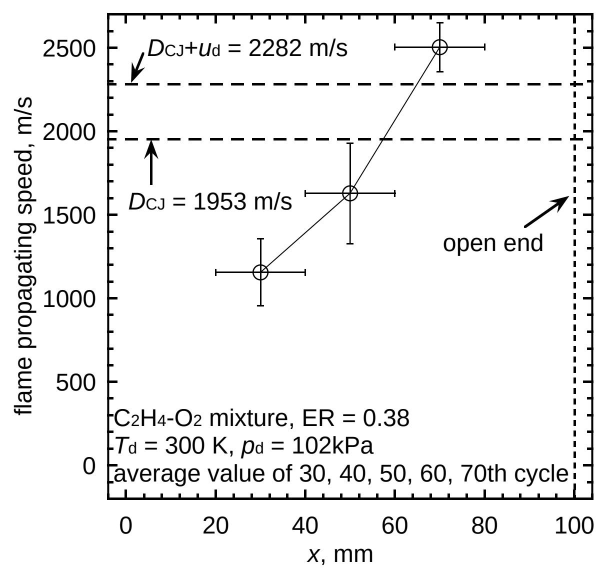

Figure. 6 flame propagating speed

Hz was demonstrated in 68 cycles of 71 cycles, namely, 96% of operation cycles. In three failure cycles, self-ignition or misfire was observed.

The thrust of a simplified PDE was clarify by the gasdynamics analysis [2]. The simplified PDE means single-pulse operation in a straight tube in which one side opens and another side is closed. However, because mixture in this study flows and combustor has no thrust wall, it is impossible to calculate thrust by the simplified model. It is necessary to investigate thrust mechanism by experiment and numerical calculation.

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