Development of a Liquid-Purge Method for Valvelss Pulse Detonation Combustor using Liquid Fuel and Oxidizer

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1 Introduction

Toward the practical use of a pulse detonation engine, both long-time and high-frequency operation are required. A valveless pulse detonation combustor (PDC) was proposed by Endo et al. [1]. For the operating principle of a valveless PDC, see reference [1]. The valveless PDC is suited for high-frequency long-time operation because it is free from moving components and controlled only by the repetitive ignitions. Actually, they realized continuous operation of a small-scale PDC at 150 Hz for 15 minutes [1]. However, due to the way the Endo et al. system operates, the detonable mixture is unavoidably diluted by the purge gas. Therefore, their valveless PDC includes some disadvantages, such as a decrease in the specific heat released by combustion and increase of DDT time and distance.

To solve such disadvantages, Matsuoka et al. [2] developed a novel method of operation for a valveless PDC in which burned gas is purged by injecting liquid droplets into the PDC and gaseous fuel and oxidizer are supplied to the PDC in the valveless mode. The newly developed purge method is called the liquid-purge method (LIP method). A conceptual diagram of the valveless PDC with the LIP method is presented in Fig. 1.

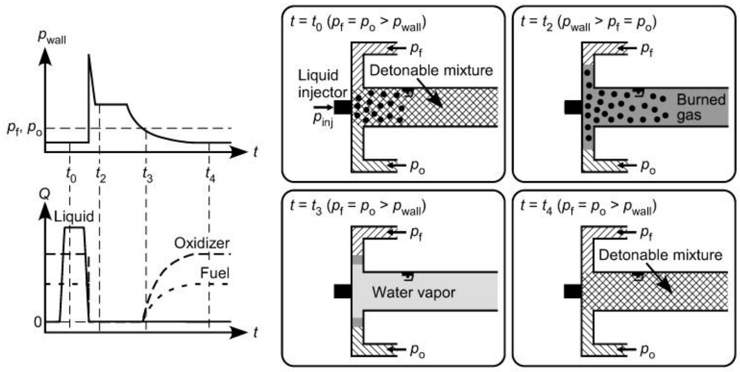

Fig. 1. Liquid-purge method in valveless PDC operation (Ref. 2).

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The left-side figures show the ideal pressure history at the closed end of a PDC (upper) and the flow-rate history of each gas corresponding to the pressure history (below); the right-side figures show the states inside the PDC at the same times as in the left figures. The pressures p_f and p_o shown in the pressure history are the supply pressures of the fuel and oxidizer, respectively. The injector of liquid droplets is installed at the closed end of the PDC instead of the purge-gas-feeding line. The injector can inject liquid droplets at any time specified, because of sufficiently high liquid-injection pressure (p_{inj}).

In the case of using a liquid droplet needed long droplet lifetime such as a water [2], the liquid droplets are injected before detonation initiation ($p_f = p_o > p_{wall}$ at $t = t_0$), and injection is stopped immediately before detonation initiation. After the ignition and subsequent detonation initiation, the high-pressure gas generated in the PDC interrupts the gas supply and the heating of the liquid droplets begins ($p_{wall} > p_f = p_o$ at $t = t_2$). Consequently, the liquid droplets are vaporized in the hot burned gas. The vaporization of liquid is an endothermic phase transition accompanied by a roughly thousand-fold volume expansion. Therefore, the hot burned gas is cooled and pushed outward—in other words, purged. This purge process should have progressed sufficiently by the time the gas pressure around the gas-feeding ports relaxes below the gas-supply pressure, i.e., by the beginning of the fuel-and-oxidizer supply ($p_f = p_o > p_{wall}$ at $t = t_3$). Once the gas pressure around the gas-feeding ports drops below the gas-supply pressure, fuel and oxidizer again flow into the PDC. When the gas pressure around the gas-feeding ports is much lower than the gas-supply pressure ($p_f = p_o > p_{wall}$ at $t = t_4$), the fuel and oxidizer flow into the PDC at a substantial flow rate. The liquid droplets for the next cycle are injected into the PDC in the final stage of the fuel-and-oxidizer-feeding phase. Finally, the PDC is filled with the detonable gas mixture, and the fine liquid droplets are suspended near the closed end.

With the LIP method, the dilution of detonable gas by purge gas does not occur. Matsuoka et al. [2] carried out the demonstration experiments where they used gaseous ethylene as fuel, gaseous pure oxygen as oxidizer, and liquid water as purging material. They found that a small-scale PDC operates at the frequency of up to 350 Hz and that the measured propagation speeds of detonations agreed well with the Chapman-Jouguet (CJ) detonation speed of the undiluted ethylene-oxygen mixture.

To apply a PDC to aerospace propulsion engine, it is required that a PDC operates by using only fuel and oxidizer. In present study, a liquid fuel (ethylene) and liquid oxidizer (nitrous oxide) were applied to the purging material instead of liquid water. We demonstrated the valveless PDC operation at 100 Hz and the measured propagation speeds of detonations agreed well with the Chapman-Jouguet (CJ) detonation speed of the undiluted ethylene-oxygen mixture.

2 Estimation of Droplet Lifetime

It is important to estimate the lifetime of the liquid droplets in the hot burned gas because the duration needed for the purge process is governed by the vaporization time of the liquid droplets in the hot burned gas. We carried out a crude estimation of droplet lifetime using the a simple evaporation model [3-5],. This model assumes the following: (1) quasi-steady evaporation of a single spherical droplet in static fluid; (2) the droplet is a pure liquid having a well-defined boiling point; (3) radiation heat transfer is negligible; (4) the distribution of temperature in the droplet is negligible; (5) the temperature of the surrounding gas far from the droplet is constant. The static fluid around a liquid droplet is assumed because the gas in the vicinity of the closed end must be at rest after the detonation initiation due to the boundary condition on the closed end at rest. Finally, we can achieve droplet lifetime, t_e, as follows [2].

$$t_e = \frac{\rho_L c_p D_0^{\,2}}{8k \ln\left[1 + \frac{c_p\left(T_\infty - T_{boil}\right)}{L}\right]}$$

We assumed environmental conditions for droplet evaporation as follows: pressure of p_∞ =1.24 MPa, temperature of T_∞ =3616 K, specific heat at constant pressure of c_p =2918 Jkg^{-1}K^{-1} [6], and heat conductivity of $k = 0.329\ \mathrm{W\,m^{-1}\,K^{-1}}$, which was evaluated using the method of Mason and Saxena [7].

Each liquid density of water, ethylene and nitrous oxide at environmental pressure were ρ_L = 876, 471 and 1044 kgm^{-3}, respectively. And each latent heat of water, ethylene and nitrous oxide at environmental pressure were L = 1979, 371 and 297 kJkg^{-1}, respectively.

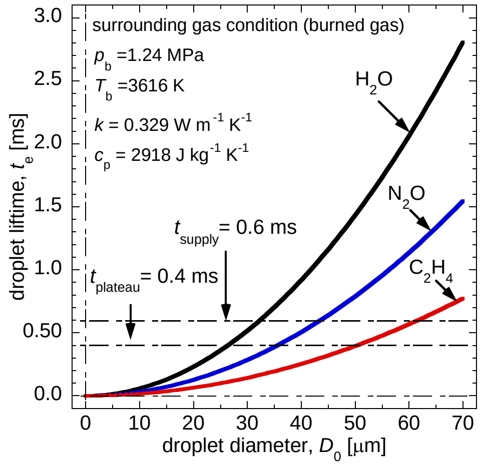

Fig. 2. Droplet lifetime at plateau region of burned gas.

Fig. 2 shows the droplet lifetime. $t_{plateau}$ = 0.4 ms and t_{supply} = 0.6 ms in Fig. 2 indicate the lifetime of the plateau region and start time of fuel-and-oxidizer-feeding phase where the length of the PDC is 300 mm (see Fig. 3). If the droplets are same diameter, the lifetime of ethylene and nitrous oxide are 28% and 55% of liquid water. Moreover, the endothermic energy ($1/6\pi D_0^3\rho_L L$) are 10% and 18% of liquid water.

3 Demonstration Experiment

Fig. 3 shows the PDC having inner diameters of 10 mm used in experiment. The inner diameter, total length, and inner volume were 10 mm, 300 mm, and 23.2 cm^3, respectively. In the following, the x coordinate is along the tube axis in the direction toward the exit whose origin corresponds to the exit of the droplet injector, namely the closed end of the tube. A spark plug (SP) was installed at x = 50 mm. Two ion probes (IP2 and IP3) were located at x = 230 and 260 mm on the side wall to measure flame propagation speed.

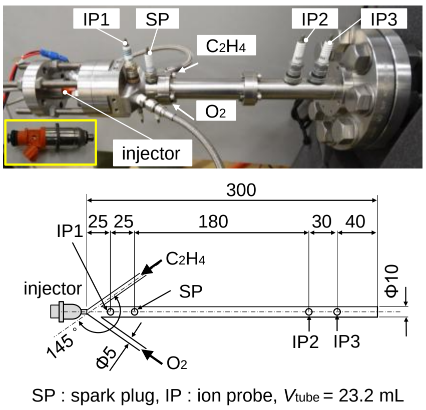

Fig. 3. Pulse detonation combuster used in present study.

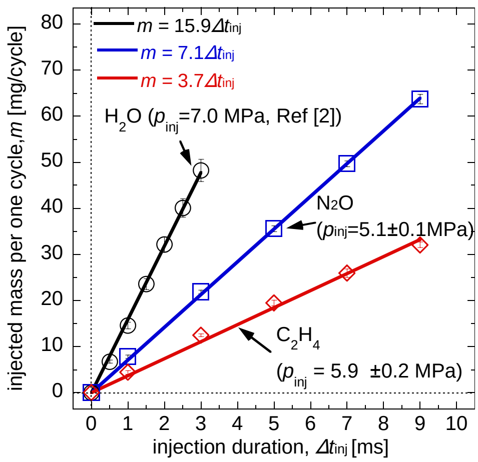

Fig. 4. Injected mass per one PDC cycle.

In all experiments, we used a commercially available automotive fuel injector for gasoline engines to inject liquid droplets into a combustor. A response delay of approximately 0.25-0.30 ms, and a spray angle of approximately 70° (total angle). Fig. 4 shows the mass per one PDC cycle m estimated in preliminary experiments. The droplets were injected into atmospheric air continually 300 times at operation frequency of 100 Hz, and the total quantity of the injected liquid was measured after each experiment. Because the liquid cylinder was inverted to push the liquid by the evaporation pressure, the injection pressure, p_{inj}, was same as the evaporation pressure as shown in Fig. 4.

Gaseous ethylene and oxygen were supplied to the combustor at an injection angle of 145° to the *x*-axis facing with each other through 5-mm-diameter ports. The supply pressures of fuel (ethylene) and oxidizer (oxygen) were $p_f = p_o = 0.5$ MPaA, and an orifice was installed in both feed lines in order to adjust the equivalence ratio (*ER*) so that $ER \approx 1$. The fill fraction of the mixture of fuel and oxidizer was more than unity in all conditions. The operation frequency was constant at 100 Hz and controlled by the spark interval.

Fig. 5 shows the operational sequence diagram. Time is defined such that spark input time is $t = 0$ ms. The injection duration before and after the spark were defined as t_1 and t_2, and the injection duration Δt_{inj} thus was expressed by $t_1 + t_2$. Fig. 6 shows the experimental condition. The injection pressure was constant at the evaporation pressure and the quantity of liquid injection (i.e. Δt_{inj}) was varied by changing t_1 and t_2. The number of cycles was 20 cycle under each condition and we repeated each experiment 10 times to assess the success rate of the intermittent combustion (α)—namely the success rate of the purge of the residual hot burned gas.

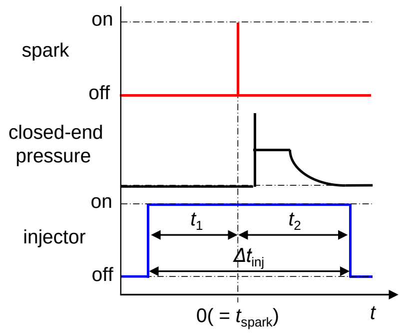

Fig. 5. Operational sequence diagram.

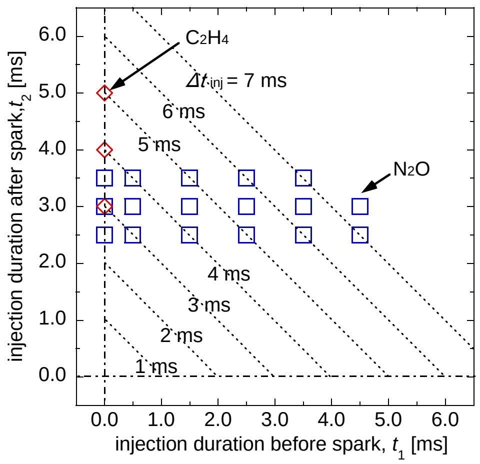

Fig. 6. Experimentcal condition.

4 Results and Discussion

We repeated experiments 10 times each, and defined the success rate (α) as the ratio of the number of experiments where intermittent combustion was successfully realized to the total number of the experiments for the same conditions (i.e., 10). In the failed experiments, we observed a continuous flame, like a stationary burner flame by ion probe. The speeds plotted in Fig. 7 are the average of the data (20 cycles) obtained in the successful experiments in which intermittent combustion was observed. The vertical error bars in the figure indicate the standard deviation. Measured propagation speeds were in the range of 109 ± 5 % (ethylene) and 102 ± 6 % (nitrous oxide) of the CJ detonation speed of the undiluted stoichiometric ethylene-oxygen mixture at the ambient conditions, showing that detonations were successfully initiated in the cases where intermittent combustion was observed. In other words, the residual hot burned gas was successfully purged.

Figure 8 shows the success rate for intermittent combustion (α). The horizontal axis indicates the hypothetical vapor thickness (L_{purge}), which is the superficial distance between the closed end of the PDC and the front boundary of the vapor layer, estimated as follows [2]. The pressure of the gas in the vicinity of the closed end of the PDC at the start time of fuel and oxidizer supply is almost the same as the supply pressure of the fuel and oxidizer (0.5 MPaA in the present experiments), because the gases are supplied to the PDC in the valveless mode. Assuming that all droplets injected into the PDC is saturated vapor at the gas-supply pressure. The volume of the vapor can be calculated from the total mass of the injected liquid into the PDC, and the hypothetical vapor thickness (L_{purge}) [2] can be calculated by dividing this volume by the cross-sectional area of the PDC. That is, L_{purge} is proportional to the injected liquid droplet mass per unit cross-sectional area of the PDC and depends on the supply pressure of the fuel and oxidizer.

As shown in Fig. 8, the quantity of injected liquid droplet per unit cross-sectional area of the PDC is an important parameter governing the stable operation of the PDC with the LIP method even if ethylene or nitrous oxide was used as a liquid droplet instead of a liquid water. Liquid water was injected before the spark time (t_2 = 0) [2]. However, in present study, it was found that the PDC cycle was successfully operated under the condition that the liquid droplet was injected for a while after the spark time. It was suggested that the success ratio depended not only the evaporation in the plateau region but also the injection during the fuel-and-oxidizer-feeding phase. From the viewpoint of fluid mechanics, hot burned gas is successfully purged when the gaseous-purging-material layer is thicker than the mixing layer between the gaseous purging material and the hot burned gas. Quantitative estimation of the effective thickness of a purge layer is very difficult because turbulent mixing between gaseous purging material and hot burned gas and turbulent boundary-layer flow on the side wall of a PDC may govern the phenomena in the purging process. The hypothetical vapor thickness calculated above (L_{purge}) is considered to be a scale length of the purge layer. This is why the success rate of the intermittent combustion (α) was plotted not against the injected water mass per unit cross-sectional area of the PDC but against L_{purge}.

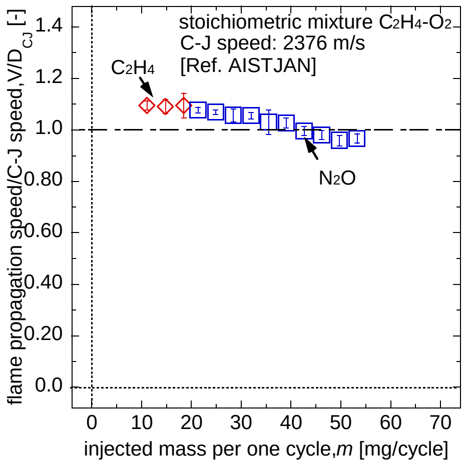

Fig. 7. Flame propagation speed

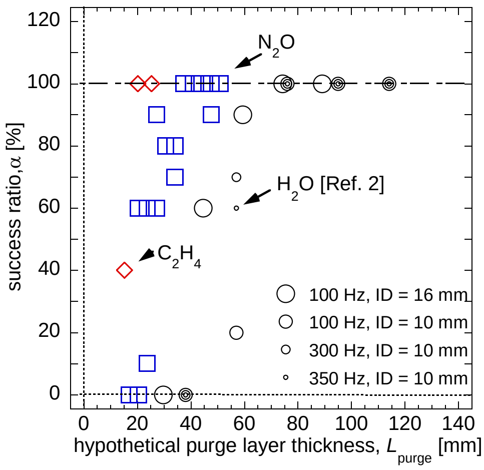

Fig. 8. Success rate

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