Liquid-Purge Method in High Frequency Valveless Pulse Detonation Engine

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1 Introduction

Pulse Detonation Engine (PDE) [1] repeates the following cycle: 1) supplying of gaseous fuel and oxidizer into a combustor (detonation tube), 2) ignition and deflagration-to-detonation transition, 3) detonation propagation, 4) blowdown of high-pressure burned gas, 5) purge of low-pressure burned gas. The high frequency operation is required because the thrust density of a PDE is low. The high frequency operation by enhasment of DDT has been demonstrated [2]. Moreover, many PDE's valve systems were proposed [3, 4]. A rotary-valved PDE proposed by Matsuoka et al. [4] achieved a maximum operation frequency of 160 Hz.

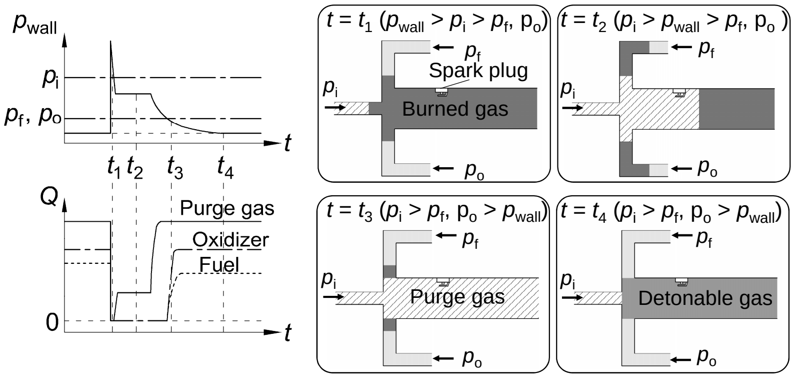

Fig. 1 Conventional purge method in valveless PDE operation (Ref. 5)

A valveless PDE was proposed by Endo et al [5]. Figure 1 shows the valveless PDE cycle. Left side of Fig. 1 shows the time histories of the end-wall pressure, p_{wall}, (above) and the volume flow of the each gas (below). The supply pressure of purge gas, p_i, was higher than the propellant supply pressure (p_o : oxidizer, p_f: fuel). Right side of Fig. 1 shows the each process of a PDE cycle. Supplying of all of the gas are interrupted when p_{wall} increase rapidly due to the detonation wave ($t = t_1$). While p_{wall} is maintained, the purge gas is supplied into the combustor and the burned gas is purged ($t = t_2$). When p_{wall} decreased by more than the propellant supply pressure, supplying of fuel and oxidizer are begun (t

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= t_3). Finally, all of gas is supplied into the combustor and diluted detonable mixture is filled ($t = t_4$). No moving part is required and the operation frequency is controlled by spark timing. The valveless PDE is suited for long-time operation and high frequency operation. Endo et al. [5] demonstrated a high-frequency operation of 200 Hz in the valveless PDE cycle.

In general, gas is used in the purge process (e.g., air or inert gas). The purge duration accounts for the relatively-high time fraction of one PDE cycle and this duration does not contribute to the work. Moreover, in Endo’s valveless PDE, the propellant is diluted by purge gas. The purge process must be optimized to obtain the higher thrust density.

This study proposed a novel purge method (Liquid-Purge method, LIP method) to increase the operation frequency of a PDE. We demonstrated the LIP method by using ethylence, oxygen and water under operation frequencies of 100-350 Hz in valveless PDE operation.

2 Liquid-Purge Method in Valveless PDE

Figure 2 shows the valveless PDE cycle with the LIP method. First, the liquid droplet is sprayed into the combustor by an automotive fuel injector while the propellant is supplied ($t = t_1$’). The evaporation of the droplet starts when the high-temperature burned gas is generated by the detonation wave ($t = t_2$’). While p_{wall} is maintained, the burned gas is cooled and purged by the phase transition ($t_2' \leq t \leq t_3'$). When p_{wall} decreased by more than the propellant supply pressure, supplying of fuel and oxidizer are begun ($t = t_3$’). Finally, the propellant is supplied into the combustor and pure detonable mixture is filled ($t = t_4$’).

LIP method is expected to improve the performance such as pure oxygen combustion, reduction of purge duration and volumetric flow rate (operating cost), efficient cooling in a detonation tube and enhancement of fuel vaporization.

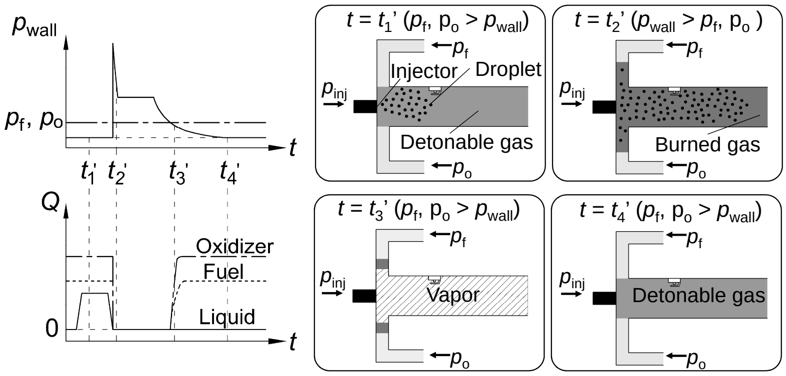

Fig. 2 Liquid-purge method in valveless PDE operation

3 Experimental Setup and Condition

Figure 3 shows the cross-section of detonation tubes (ϕ16, ϕ10). x axis is coaxial with central axis of detonation tube, and the end wall was origin. The inner volumes of each tube were 57.8 mL (ϕ16) and 23.2 mL (ϕ10), respectively. The ignition was made by the spark plug (SP) at x = 27.5 mm (ϕ16) and x = 25.0 mm (ϕ10). Fuel (ethylene) and oxidizer (oxygen) were supplied at an angle of ± 135 ˚ (ϕ16) or ± 35 ˚ (ϕ10) to x axis. As shown in Fig. 3, the propagation velocity of combustion wave and shock wave were measured by the two ion probes (IP1 and IP2 for ϕ16) or the two pressure transducers (PT2 and PT3 for ϕ10).

Figure 4 shows the operation sequence of a valveless PDE with LIP method. The timing of gas supplying and water injection were decided by the pressure history of the pressure transducer installed at the nearest to the end wall (PT1). As shown in Fig. 4, the rapid pressure increase of PT1 was confirmed after approximately 100 μsec of the spark ($t_{\mathrm{spark}} = 0$). This was due to the retonation wave from the DDT point. We decided that the stop time of water injection was constant at t_{stop} =

100 μsec. The injection duration, Δt_{inj}, was varied by changing the start time of water injection, t_{start}. Table 1 shows the experimental condition. Fuel and oxidizer supply pressure were constant at $p_{\mathrm{f}} = p_{\mathrm{o}} = 0.4$ MPa (gage). In addition, fill fraction of mixture was over 1 under all of condition. Liquid (water) supply pressure was constant at $p_{\mathrm{water}} = 7$ MPa (gage). We carried out 10 times for each condition and 20 or 25 cycles per one test.

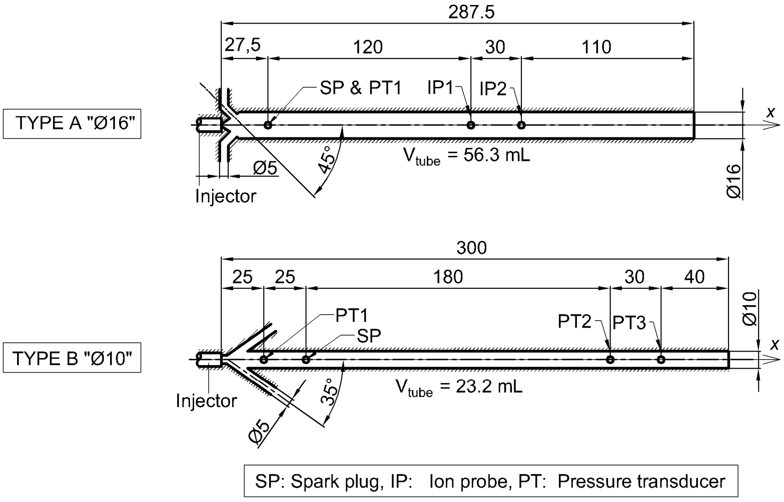

Fig. 3 Cross-section of detonation tubes

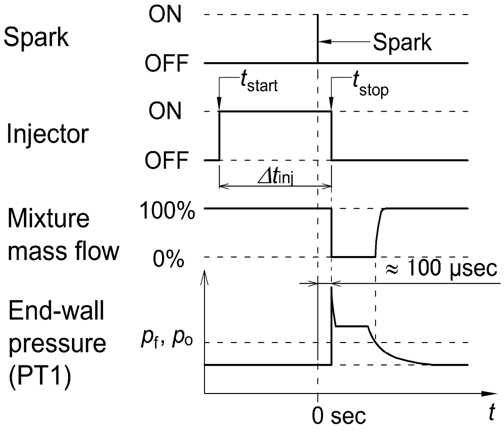

Fig. 4 Operation sequence of a valveless PDE with LIP method

Table 1 Experimental condition

Shot number	Tube Type	Frequency	Injection pressure	Injection duration	Cycles
		f_{ope}	p_{inj}	Δt_{inj}	-
		Hz	MPaG	0.5 msec/div	-
T-1	Φ16	100	7	1.5 - 3.5	20
T-2	Φ10	100	7	1.0 - 3.0	20
T-3	Φ10	300	7	1.0 - 3.0	20
T-4	Φ10	350	7	1.0 - 3.0	25

4 Results and Discussion

Figure 5 shows pressure histories at PT1, PT2 and PT3 under the condition of T-3 (Δt_{inj} = 1 msec). As shown in Fig.5, The pressure difference of the each cycle, Δp, and C-J pressure, p_{CJ}, were roughly same value. We confirmed the detonation wave from the propagation velocities of the combustion wave (T-1) and shock wave (T-2, 3, and 4). Figure 6 shows the propagation velocities under the all of the condition and normalized by C-J velocity (D_{CJ} = 2376 m/sec). The horizontal axis, m_{cycle}, was the mass of supplied water per one cycle. The propagation velocities were between 95- 110% of D_{CJ} and we confirmed the valveless PDE operation with LIP method under the all of the condition.

With decreasing the water injection duration, Δt_{inj}, burner flame due to lack of purge was confirmed. Figure 6 shows success rate, α, that means the number of tests in which cyclic detonation was confirmed. The horizontal axis was the purge thickness L_{purge} and defined as follows:

$$L_{\mathrm{purge}} = L_{\mathrm{taper}} + \frac{V_{\mathrm{vapor}} - V_{\mathrm{taper}}}{A_{\mathrm{tube}}} = L_{\mathrm{taper}} + \frac{\left(m_{\mathrm{cycle}} / \rho_{\mathrm{vapor}}\right) - V_{\mathrm{taper}}}{A_{\mathrm{tube}}} \tag{1}$$

where L_{taper} and V_{taper} were the length and the volume of end-wall taper of the detonation tube, respectively. A_{tube} was the cross-section area of the cylindrical segment of the detonation tube. V_{vapor} was the vapor volume. If the supplied water was evaporated completely, the vapor volume was calculated by m_{cycle} and vapor density, ρ_{vapor}. When supplying of fuel and oxygen were started, the vapor pressure was estimated to be same pressure of propellant supply pressure (0.4 MPa gage). We assumed that the vapor was the saturated water vapor under the pressure of 0.4 MPa and the density was 2.67 kg/m^3. Figure 6 indicated a similar tendency of the success rate even if the cross-section area was changed. The results suggest that the purge thickness L_{purge} was one of the critical parameters to achieve the stable PDE cycle.

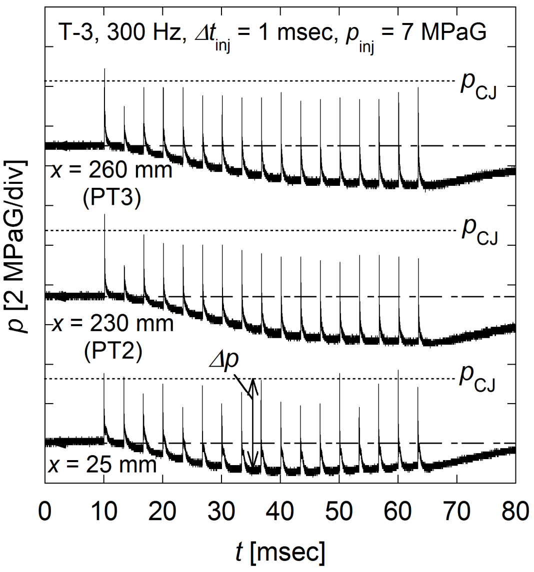

Fig. 5 Pressure histories at PT1, 2 and PT3 (T-3, Δt_{inj} = 1 msec)

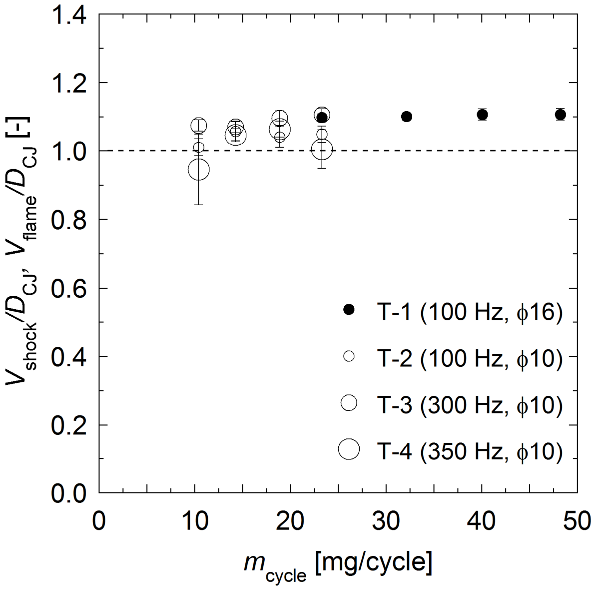

Fig. 6 Propagation velocities of combustion wave and shock wave

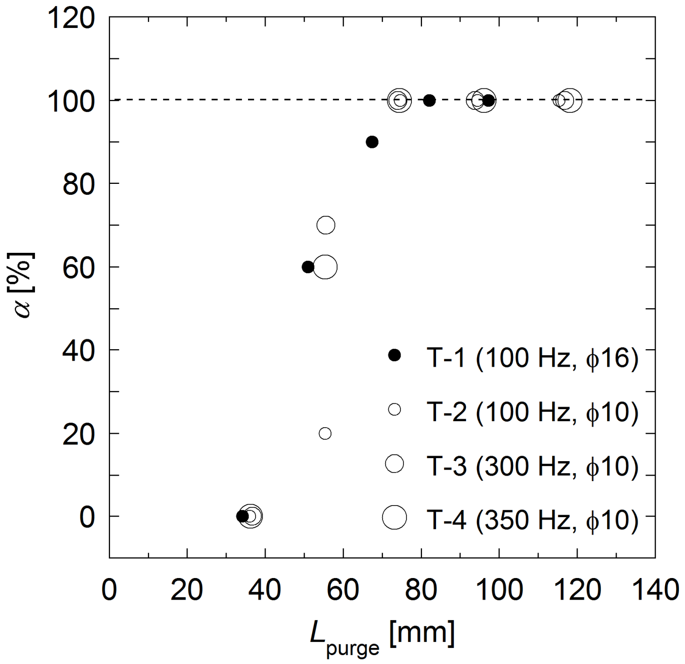

Fig. 7 Relationship between success rate and purge thickness

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