A Study of DDT Process and Performance for Pulse Detonation Engine

Takashi SAKURAI*, Shigeharu OHYAGI**, Tetsuro OBARA**
*Graduate School of Mechanical Engineering, Saitama University
**Department of Mechanical Engineering, Saitama University
255, Shimo-Ohkubo, Saitama, Saitama 338-8570 Japan
E-mail: sakurai@mech.saitama-u.ac.jp
Key words: Pulse detonation engine, DDT, Specific Impulse

A pulse detonation engine (PDE) is the propulsion systems that obtain thrust by the repetitive detonation. Because the detonation has a much greater propagation velocity than the deflagration wave, thermal efficiency of PDE is close to that of the constant volume cycle. Many researchers estimate that the PDE cycle exceeds the conventional Brayton cycle as well as Humphrey cycle [1].

A substantial effort in PDE research was done by Nicholls et al. [2]. They demonstrated cycle operation at 35 Hz with hydrogen-air mixtures and attained a fuel specific impulse of 2100 sec. From a practical perspective for volume limited propulsion applications, PDEs operating on liquid fuels need to be demonstrated. It is highly desirable that PDE use combustible fuels which have already been approved by the aviation industry (e.g., JP-10) [3]. Unfortunately, these fuels are insensitive to detonation so that we considered hydrogen-air PDE due to the increased detonability versus practical liquid hydrocarbon fuels. For hydrogen-air mixtures, Aarnio et al. [4] reported a fuel specific impulse ranged from 1116-1333 sec and cycle frequency up to 5 Hz and Schauer et al. [5] reported a fuel specific impulse of 4000 sec, which agrees well with that of the theory [6], and cycle frequency up to 40 Hz. But there are few examples that provide the pressure history and specific impulse beyond the cycle frequency of 20 Hz. Therefore, it is necessary to demonstrate the feasibility of multiple cycle operation of a PDE. One aspect of ensuing high cycle frequencies is to promote rapid deflagration to detonation transition (DDT).

The present study describes an experimental study of DDT behavior and performance in a pulse detonation engine fueled by hydrogen-air mixtures. Specific impulse and fuel specific impulse was investigated with the length of Shchelkin spiral and the length of the tube as parameters. A cycle frequency up to 50 Hz was attained in this study and the pressure history and the dependency of specific impulse on cycle frequency were obtained.

A schematic of the apparatus is shown in Fig.1. It consists of a stainless steel tube, which is closed at one end and open at the other, with 30 mm in-diameter and 850 or 1,450 mm length. In the tube, the Shchelkin spiral is inserted to enhance detonation transition. Two types of solenoid valve for the fuel gas and oxidizer gas were used. Details of solenoid valve are listed in Table 1. In the present experiment, four injectors for fuel (hydrogen) and air were situated in the opposite side for each other at the same axial location. Table 2 shows the present experimental condition.

The tube is evacuated at first to remove the residual gas of the previous experiment. Then it is filled with a fresh air at the atmospheric pressure. The fuel gas and air were injected into the tube through the solenoid valves mentioned above. In multiple cycle experiments, a purge air was injected at an appropriate timing between cycles to purge the combustion products of one cycle. Amounts of the injected gases were determined as they could fill the tube at an appropriate proportion in the closed tube, although it was not closed.

Figure 2 shows the pressure history on thrust wall and tube wall with an ionization current record. Because of a location of the spark plug, a combustion wave propagates to both upstream and downstream. A sharp pressure spike was observed at the thrust wall. Its peak is about 45 times the initial pressure so that it is believed that the overdriven detonation wave is formed due to the reflection of pressure wave near the thrust wall. On the other hand, a combustion wave that propagates downstream was observed to develop slowly to the detonation wave. When the detonation emerges from the tube, a blowdown process begins with the propagation of rarefaction waves, which are indicated dot lines, back into the tube. It is interesting to note that the detonations is initiated independently at the closed end and at 600 mm downstream.

The multiple cycle system was developed and was confirmed to operate up to 50 Hz. Figure 3 shows the thrust wall pressure record for 10 cycles, 50 Hz. A sharp pressure spike shows the overdriven detonation formed at the thrust wall. But in the downstream position at 700 mm, the detonation was extinguished to decay to a shock wave.

Figure 4 shows the dependency of specific impulse on the cycle frequency. It is revealed that the specific impulse depends on the frequency so that the combustion process per cycle may not be affected by the cycle frequency up to 50 Hz. This means that time averaged thrust linearly increases to the cycle frequency that is agree with the results of Schauer [5].

In summary, the DDT process and impulse performance were investigated in the experimental PDE. It was observed that the overdriven detonation was caused by the reflection of pressure wave in the vicinity of the thrust wall. A characteristic feature of this device was that two detonations were occurred independently at upstream and downstream of the location of ignition plug. Although it is doubtful that the fully developed detonation wave was formed, it was demonstrated that cycle frequency could be increased up to 50 Hz in this engine. It was revealed that the specific impulse did not depend on the cycle frequency so that the thrust should be linearly increased with the frequency in this range.

References

[1] Heiser,W.H., Pratt,D.T., "Thermodynamic Cycle Analysis of Pulse Detonation Engines," *Journal of Propulsion and Power*, Vol.18, No.1, 2002, pp.68-76

[2] Nicholls,J.A., Wilkinson,H.R. and Morrison,R.B., "Intermittent Detonation as a Thrust-Producing Mechanism," Jet Propulsion, Vol.27, 1957, pp.534-541

[3] Brophy,C.M., Netzer,D.W., "Effects of Ignition Characteristics and Geometry on the Performance of a JP-10/O_2 Fueled Pulse Detonation Engine," AIAA paper 99-2635, Jun.1999

[4] Aarnio,M.J., Hinkey,J.B. and Bussing,T.R.A., "Multiple Cycle Detonation Experiments during the Development of a Pulse Detonation Engine," AIAA paper 96-3263, Jul.1996

[5] Schauer,F., Stutrud,J. and Bradley,R., "Detonation Initiation Studies and Performance Results for Pulsed Detonation Engine Applications," AIAA paper 2001-3811, Jul.2001

[6] Cooper,M., Jackson,S., Austin,J., Wintenberger,E. and Shepherd,J.E., "Direct Experimental Impulse Measurements for Detonations and Deflagrations," Journal of Propulsion and Power, Vol.18, No.5, 2002, pp.1033-1041

[7] Wintenberger,E., Austin,J., Cooper,M., Jackson,S., and Shepherd,J.E., "An Analytical Model for the Impulse of a Single-Cycle Pulse Detonation Engine," AIAA paper, 2001-3811, Jul.2001

[8] Bratkovich,T.E., Aarnio,M.J., Williams,J.T. and Bussing,T.R.A., "An Introduction to Pulse Detonation Rocket Engines (PDREs)," AIAA paper 97-2742,Jul.1997

[9] Stanley,S., Burge,K. and Wilson,D., "Experimental Investigation of Pulse Detonation Wave Phenomenon as Related to Propulsion Application," AIAA paper 95-2580,Jul.1995

[10] Kailasanath,K., "Recent Developments in the Research on Pulse Detonation Engines," AIAA paper 2002-0470, Jan, 2002

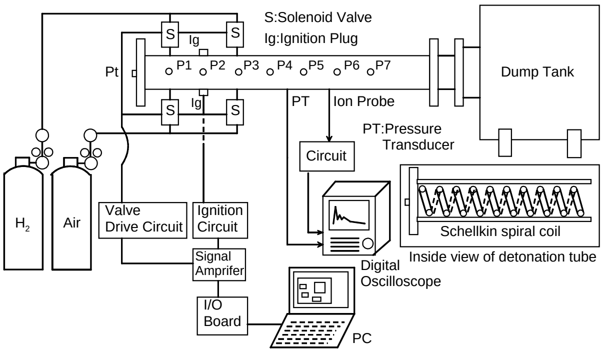

Fig.1 Schematic of experimental apparatus

Table.1 Details of injection

	Valve 1	Valve 2
Supplier	CKD	MAC
Diameter of orifice [mm]	2.0	2.0
Response time [ms]	15	8
Injection pressure of hydrogen [MPa]	0.8	0.5
Injection pressure of air [MPa]	2.0	1.5
Injection duration [ms]	12-60	13-60

Table.2 Experimental condition

Fuel / Oxidizer	H_2 / Air
Initial Pressure	Atmospheric
Equivalence Ratio of injected gases	1.00 – 2.19
Length of Shchelkin spiral, L_s [mm]	280, 850, 1,200
Length of tube, L_c [mm]	850, 1,450
Ignition timing, t_{ig} [ms]	0.1 - 40

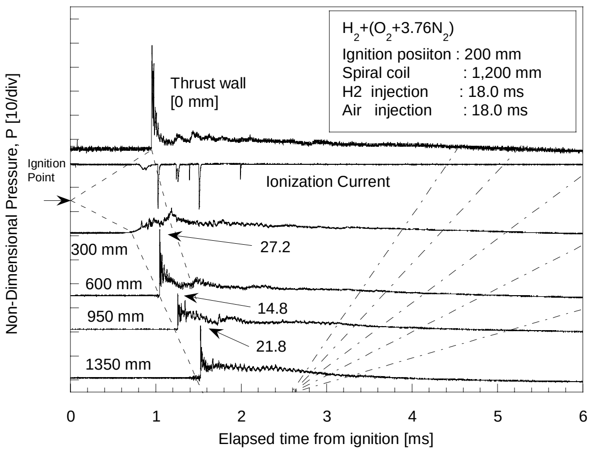

Fig.2 Thrust wall and tube wall pressure history and wave diagram: Valve 1, L_c=1,450 mm, t_{ig}=40 ms

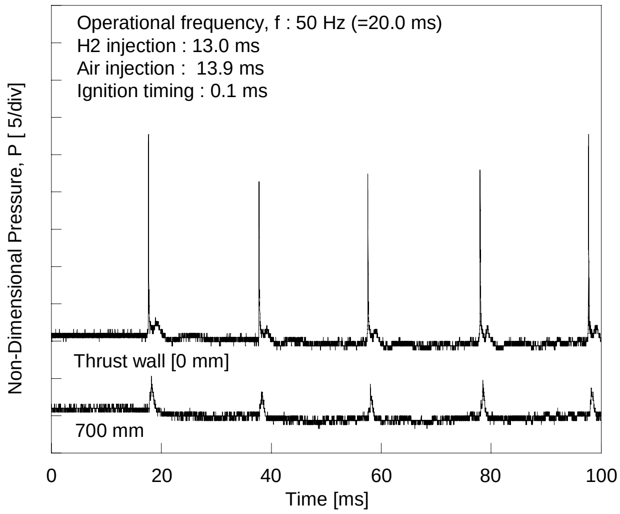

Fig.3 Thrust and tube wall pressure history in multiple cycle for a 5 cycles, 50 Hz: Valve 2, L_c=850 mm

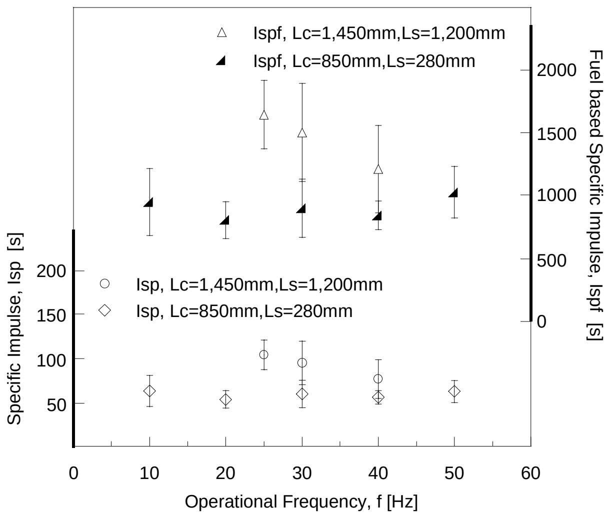

Fig.4 Dependency of specific impulse on cycle frequency: Valve 2