Experimental Study on Exhaust Nozzle Performance in H_2/Air PDE

Y. Kimura[1], S. Kitano[1], H.Sato[1], A.K.Hayashi[1], and N.Tsuboi[2]

[1]Aerospace Sytstem Laboratory, Aoyama Gakuin Univercity,
5-10-1 Fuchinobe, Sagamihara, Kanagawa 229-8558, Japan

[2]Institute of Space and Aeronautical Science, Japan Aerospacce Exploration Agency,
3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan

1 Introduction

Pulse detonation engine (PDE) is known as a new type thruster for the airplanes and rockets. PDE has been studied by many research groups since its thermal efficiency is theoretically estimated higher than the other conventional engines.

In general, the performance of PDE as a thruster is expressed by specific impulse. In order to improve PDE performance, it is important to investigate the effects of exhaust nozzle. Ma et al.[1] and Tangirala et al.[2] showed that the converging-diverging (C-D) nozzle with a certain level of small throat diameter produced higher specific impulse in their numerical analysis. Harris et al.[3] reported that PDE's chamber pressure must be maintained above the fill pressure and nozzle expansion ratio of C-D nozzle must be important for thrust performance of PDE. On the other hand, a single-cycle parametric study and experimental measurement by Hanson et al. [4] revealed that the appropriately optimized diverging nozzle produces the largest specific impulse. Cooper's single-cycle experiments using a ballistic pendulum method and analysis[5] also showed the similar result with Hanson's group's one. However, accoding to the results of Allgood's experimental measurements for multi-cycle PDE using a damped thrust stand[6], about 15% thrust enhancement is obtained with a converging nozzle as the operating fill-fraction is close to or above 1. Numerical simulations of four different types of nozzle configurations (straight, converging, diverging, C-D) for multi-cycle PDE by Tsuboi et al.[7] indicated that the results of specific impulse for using straight and C-D nozzle were 10% higher than that with the other nozzles. On the other hand, in the case of single-cycle simulation, a good performance by diverging nozzle was obtained. The difference of nozzle perfomance between single-cycle and multi-cycle was also discussed by Harris et al.[3].

Accoding to the results of the single-cycle experiments and Numerical simulations, the thrust perfirmance of diverging nozzle is better than that of the other nozzles. However, in the case of the multi-cycle experiments and simulations for nozzle performance, the previous results showed the different tendency from the single-cycle results. In addition, there are no generalized conclusion that which type of the nozzle configuration can generate the best performance in the multi-cycle operation. Therefore, it is important to evaluate thrust performance of PDE with exhaust nozzzles on multi-cycle high-frequency operation.

In this study, we investigate the influences of nozzle configurations on multi-cycle PDE operation. For that purpose, we perform PDE experiments with various types of exhasut nozzles at the some operating conditions. First, we measured pressure histories in the detonation tube using wall-mounted pressure tranceducers to know variations of pressure in the detonation tube that nozzle configurations make. Secondly, we measured net thrust by ballistic pendulum method and using load cell to estimate thrust performance of each nozzles.

Correspondence to: hayashi@me.aoyama.ac.jp (A.K. Hayashi)

2 Experimental setup

To evaluate nozzle performance on high-frequency operation, a small-sized PDE is used in this study. Figure 1 shows the experimental setup and measurement systems. Features of the nozzle configurations are also indicated in Figure 2. As for the nozzle configurations, converging angle, diverging angle, and exit diameter are varied as parameters shown in Table 1.

The PDE system consists of detonation tube, injection system, ignition system, Shchelkin spiral, and exhaust nozzle. The total length of detonation tube including exhaust nozzle is 646mm and the inner diameter is 15mm. Air is injected continuously from the closed-end as oxidizer and purge gas. In this case, the air flow rate is 12.8 l/s. As for the fuel, hydrogen is injected by automotive injectors. To accelerate deflagration to detonation transition (DDT), a Shchelkin spiral is installed in the detonation tube. The feature of the spiral is 300mm in length, 2mm in diameter, and 15mm in pitch. Burned gas is exhausted to dump tank. Pressure of the dump tank is maintained about 1atm. Therefore, the fill pressire and the ambient pressure are maintained about 1atm in the operations. Control devices and measurement systems are organized using LabVIEW7.0. This PDE can operate successfully up to 80Hz.

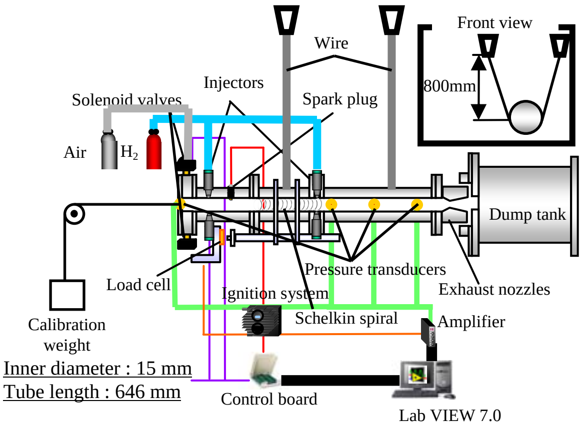

Figure 1 Experimental setup

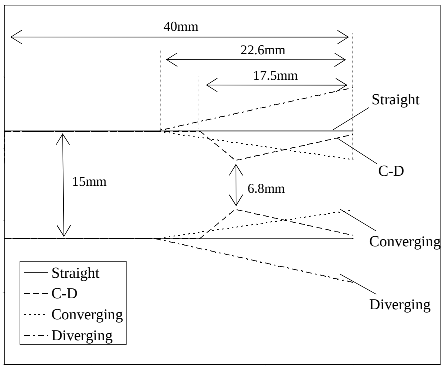

Figure 2 Nozzle configurations

Table 1 Nozzle parameters

No.	Nozzle configuration	Converging angle (degree)	Diverging angle, (degree)	Exit diameter, (mm)
1	Baseline Straight	0	0	15
2	45-15 C-D	45	15	14
3	10-0 Converging	10	0	7
4	0-15 Diverging	0	15	27.1

As for the measurement system, four pressure tranceducers (PCB113A24) are used to measure pressure and velocity, where one of them is mounted on the closed end-wall of the tube. Measurement points are 342mm, 422mm and 502mm from the ignition point. Propagating velocity of the pressure wave in the tube is calculated from the pressure spikes of two sensors. To estimate the nozzle performance, thrust measurements by ballistic pendulum and load cell method are similar to that by the pressure transducers.

3 Results and discussion

3.1 Pressure history analysis

Figure 3 shows the pressure histories obtained by a certain cycle in multi-cycle operation using the baseline straight nozzle. As for the experimetal conditions, the operating frequency is 50Hz and equivalence ratio is 1.45. Figure 4 indicates the result of 45-15 C-D nozzle case in the same operating conditions as that of straight nozzle case. In both results, a rapid rising waves are observed as the Neumann spike. In addition, each of the values of peak pressure are about 2MPa, and their propagating velocities are about 2000m/s. These values are close to the C-J properties. Therefore, these propagating waves are practically detonation waves. In the case of using the 45-15 C-D nozzle, a reflected wave propagating to the counter direction to the detonation wave and long blowdown time are observed as shown in Fig.4. In this study, the blowdown time is defined the time pressure is forced to closed end of the detonation tube. The reflected wave and long blowdown time are produced by the converging section of the exhaust nozzle. Since the similar result is obtained by the 10-0 converging nozzle. These influences of the converging section of the nozzles have been mentioned by previous reports [4][6][7].

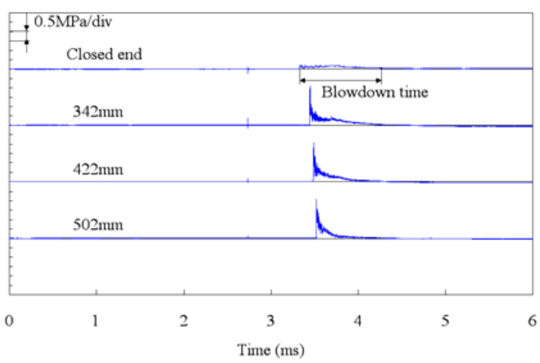

Figure.3 Pressure history of using the baseline straight nozzle

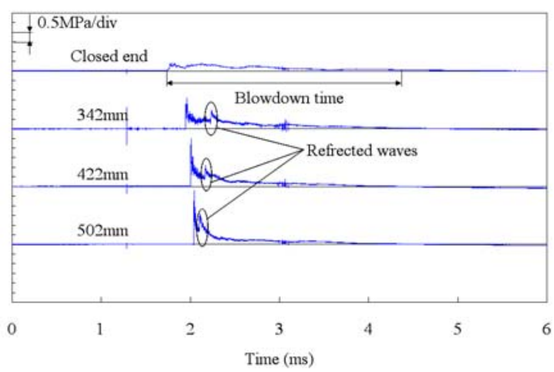

Figure.4 Pressure history of using the 45-15 C-D nozzle

3.2 Nozzle performance measurements

Net thrusts of using each type of nozzles were measured and shown in Figure 5. The x-axis is the operating frequency and y-axis is obtained thrust. Figure 6 shows the fuel based specific impulse (I_{spf}) of each type of nozzles. In these experiments, the operating frequencies were varied from 40Hz to 80Hz. Then the values of I_{spf} are less than the other studies, especialy these of numerical analyses [1][2][7]. This is considered that problem of mixing and influences of heat and viscous loss because the small tube diameter was used. And these experiments were carried out in large equivalence ratio conditions.

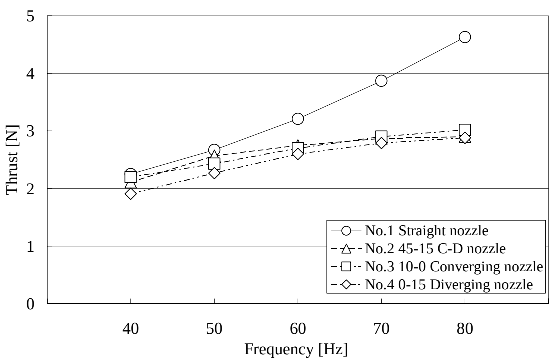

Figure.5 Net thrust of each type of nozzles

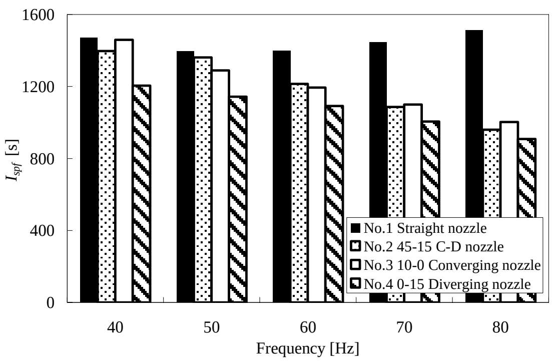

Figure.6 Fuel based specific impulse of each type of nozzles

In Fig.5, as the frequency gets higher, the thrust becomes larger when the straight nozzle is used. In theory, if the obtained thrust per cycle doesn't vary, the thrust is propotional to frequency. However, Thrusts using three other types of nozzle are convergent to 3N. Thus, these nozzles reduce the thrust performance per cycle. This tendency is also shown in Fig.6. Incresing frequency, the values of I_{spf} using the straight nozzle are constant at about 1500s. However, the values of I_{spf} using the other type of nozzles decrese as the frequency increses. It is considered that these performance decresements of using C-D nozzle and converging nozzle are influences of long blowdown time. At the high frequency operations, because of a long blowdown time, the next cycle starts before the blowdown has completely finished. Therefore, the part of the thrust per cycle is lost. In the case of using diverging nozzle, it is considered that the diverging section acts as a diffuser instead of a nozzle. This behavior of diverging nozzle in multi-cycle was reported by Allgood et al [6]. It is summurized these experiments, the straight nozzle shows the best thrust performance in four types of nozzle.

5 Conclusion

In this study, we analyzed the influence and estimated thrust performance of four different types of nozzle for varied operating frequencies from 40Hz to 80Hz. First, we measured pressure histories by the wall-mounted pressure transducers. As the result, the nozzles that have a converging section made long blowdown time. Secondly, we measured the net thrust by the load cell. As the result, the straight nozzle showed the best thrust performance.

References

[1] Ma, F., Choi, J.Y., Yang, V. (2006). Propulsive Performance of Airbreathing Pulse Detonation Engines. Journal of Propulsion and Power Vol.22, No.6, November-December 2006, pp. 1188-1203

[2] Tangirala, V.E., Dean, A.J. (2006). Performance Estimations of a Pulse Detonation Engine with Exit Nozzle. AIAA Paper 2006-4792, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 9-12 July 2006, Sacramento, California

[3] Harris, P.G., Stowe, R.A., Ripley, R.C., Guzik, S.M. (2006). Pulse Detonation Engine as a Ramjet Replacement. Journal of Propulsion and Power Vol.22, No.2, March-April 2006, pp. 1188-1203

[4] Owens, Z.C., Hanson, R.K. (2005). Unsteady Nozzle Design for Pulse Detonation Engines. AIAA Paper 2005-3649, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 10-13 July 2005, Tucson Arizona

[5] Cooper, M., Shepherd, J.E. (2004). The Effect of Transient Nozzle Flow on Detonation Tube Impulse. AIAA Paper 2004-3914, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 11-14 July 2004, Fort Lauderdale,

[6] Allgood, D., Gutmark, E., Hoke, J., Bradley, R., Schauer, F. (2005). Performance Measurements of Multi-Cycle Pulse Detonation Engine Exhaust Nozzles. AIAA Paper 2005-222, 43rd AIAA Aerospace Sciences Meeting and Exhibit 10-13 January 2005, Reno, Nevada

[7] Tsuboi, N., Hayashi, A.K., Tangirala, V.E, Dean, A.J. (2005). Nozzle Performance Calculations on Multi-Cycle Pulse Detonation Engine with Nozzles. Proceedings of the Thirty-eighth Fluid Dynamics Conference (Japanese), pp. 365-368