Thrust Performance Evaluation of a Rotating Detonation Engine with a Conical Plug

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Keyword：Propulsion, Detonation Wave, Detonation Engine, Rotating Detonation Engine

1 Introduction

Detonation engines are classified into two types of a pulse detonation engine (PDE) and a rotating detonation engine (RDE). RDE as shown in Figure 1 has the characteristic channel, composed of a double cylinder. Detonation waves in RDEs propagation in the circumferential direction to the channel and continue to propagate as long as the propellant is continuously supplied into the channel. Therefore, the ignition and the deflagration to detonation transition (DDT) in RDEs are only once. In view of thermal efficiency, PDEs have been known to have a higher thermal efficiency than that of the conventional engines using the Brayton cycle. [1] RDEs can be expected to obtain the thermal efficiency at same level as PDEs despite a more simple structure than a convenstional engine. Furthermore, RDE can be obtained the higher thrust density and be possible to the higher frequency operation as kHz order than PDEs. Therefore, RDEs have been studied worldwise for the purpose of application to next generation aircraft and spacecraft main engine.[2 - 19]

However, the combustion mode of RDEs still have many unclear part, and experimental approaches in relationship of the detonation wave state amount (propagation speed and wave number) and thrust, one of most important research issues, is little.

The final goal of this study is to prove that detonation engines, RDEs in particular is possible to use as the spacecraft main engines by performing an demonstration under space enviroment. Along with that, we evaluated the thrust performance of a RDE, the effect on the thrust performance of a conical plug with an apex angle of 30 degree. In addition, we worked on elucidation of the previous relationships.

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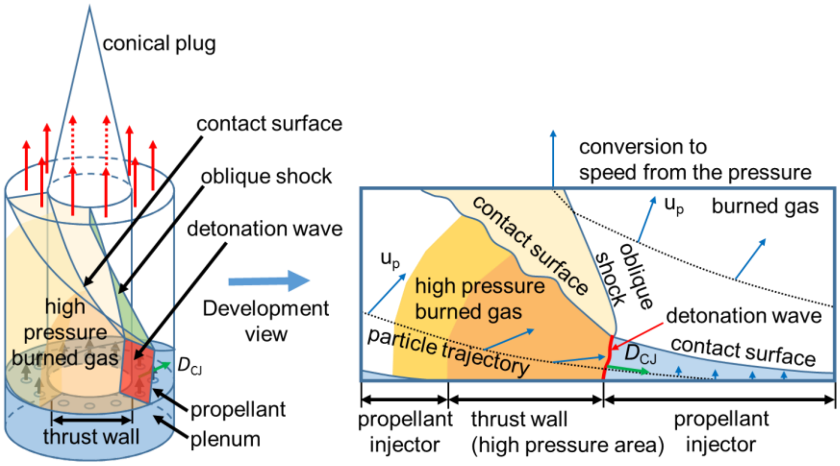

Figure 1. Schematic model of a rotatind detonation engine

2 Experimental apparatus

The schematic view of the RDE and the thrust measure measurement system in this study is shown in Figure 2 and Figure 3. We used gas ethylene and gas oxygen mixture as the propellant. The RDE was designed and producted with setting the target combusion pressure to 0.6 MPa, the target thrust at atmospheric pressure to 300 N, and the target specific impulse at atmospheric pressure to 219 sec. The specific impulse is the upper limit of the theoretical specific impulse of constant-pressure combustion rocket engine in the case of proper inflated at atmospheric pressure and combustion pressure of 0.6 MPa. Each parameter of the RDE is as follows: an inner diameter of the channel was 63.0 mm, a width of it was 3.0 mm, a length of it was 63.0 mm, and an apex angle of the conical plug was 30.0 degree. The diameter of the fuel injector was 0.5 mm, and that of oxidizer was 1.0 mm. This injectors were opened 100 holes each at equal intervals. We used the load cell and the linear slide to measure the thrust, and pressure sensors were attached to the fuel plenum, the oxidizer plenum, the pre-detonator and the channel. The RDE was pulled in advance by pre-load which was 1.4 kg to steady contact with the RDE and the load cell.

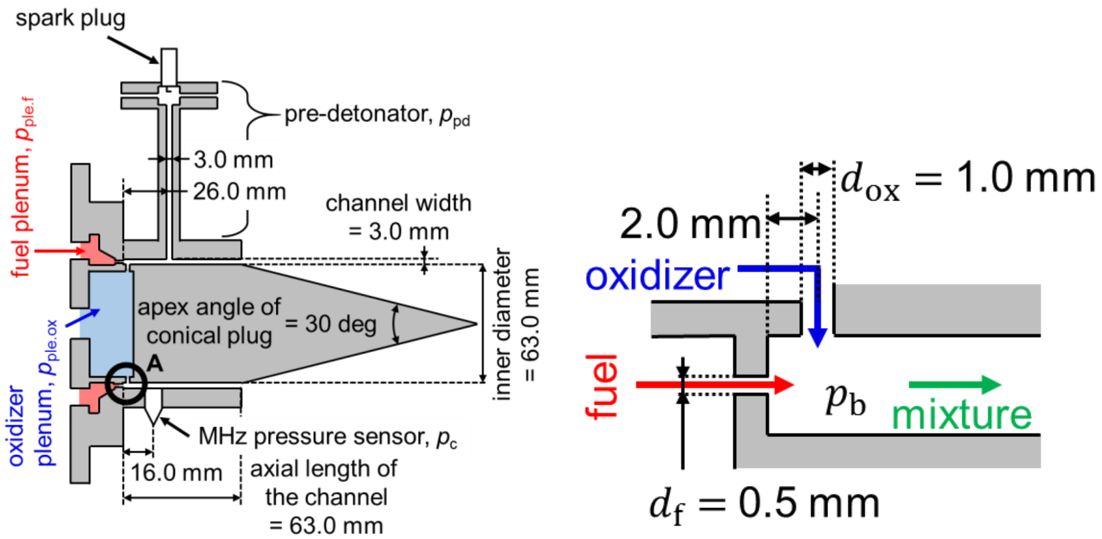

Figure 2. Schematic view of a rotating detonation engine (left) and an injector (right, the enlarged view of area A in the left figure)

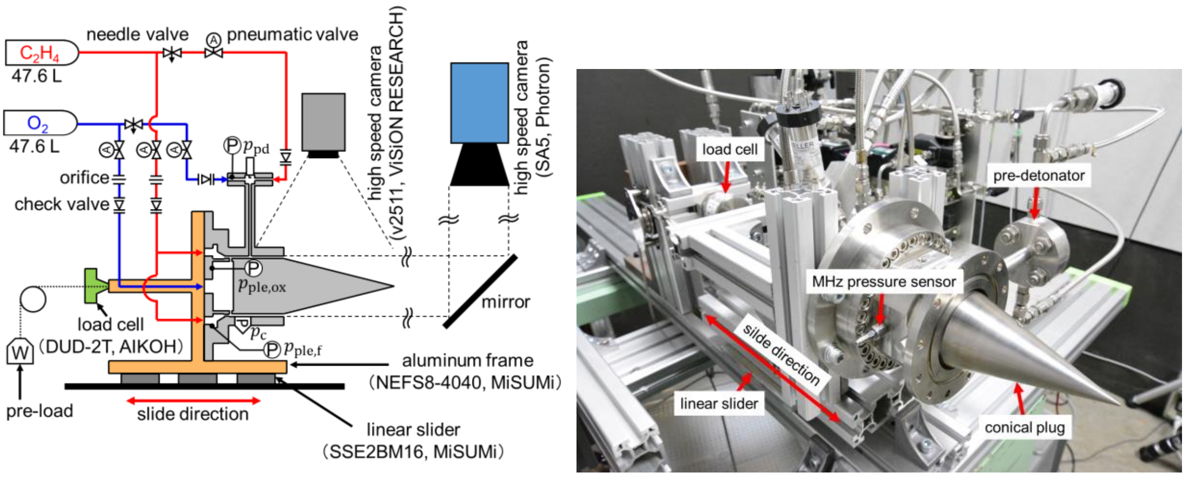

Figure 3. Schmetic view (left) and overview (right) of the thrust measurement system in this study

3 Experimental Results and Discussion

Figure 4 and Figure 5 show the experimental conditions and results. In this study, two of the combustion mode has been confirmed. One is a mode that the constant number of detonation waves continuously propagated in a constant direction, and the other is a mode that they continued to propagate but the number of them and the direction of propagation wasn't constant. In this study, the former and the latter were referred to continuous propagation mode and discontinuous propagation mode respectively. In RDE used in this study, the mode was switched to the boundary of equivalence ratio ≈ 0.9 as shown in Figure 4 (left).

The thrust achieved 99 – 239 N, and the specific impulse achieved 94 – 139 s without nozzles. With the conical plug with an apex angle of 30 degree, the thrust achieved 102 – 305 N, and the specific impulse achieved 99 – 149 s. The thrust was achieved the target value, however the specific impulse in this case was 68% of target value. The reason for this was considered that it's not properly inflated.

The specific impulse was improved 7.1 – 12.8% when changing the equivalence ratio at the same mass flow rate shown in Figure 5 (right). In addition, the thrust response was 0.9 – 1.7 ms, and we confirmed that detonation waves started continuous propagation in 4.9 – 9.1 ms. This was suggested to have an adequate response that the RDE performs pulse actuation, which it's considered to be one way to overcome the thermal problems in RDEs.

As shown in Figure 1, the Mach number of the axial direction at the channel exit should be 1 when the pressure energy changes to velocity energy by properly inflated in the flow path. Based on this assumption, the flow field after the channel exit could be plotted as shown in Figure 6 when calculating with the state quantity near the channel exit determined by C-J condition. In fact, Figure 7 shows the photos of the flow field after the channel outlet in the high speed camera. Form Figure 7, we could confirm the wave such as the mach disk and shock waves. We could probe that the mach number of the axial direction at the channel outlet reached 1 because the flow field of Figure 6 and Figure 7 was very similar. In the numerical calculation, the mach number near the channel outlet was not 1. In the numerical calculation, in view of the calculation load, the number of detonation waves was 1. However, in many experiments, multiple of detonation waves were observed, even in this experiment, we confirmed 4 – 5 detonation waves. The inverse relationship with the number and the height of detonation waves was confirmed. That the height of detonation waves is lowered with an increase of the number of detonation waves is that the area in which the combustion gas is expanded increased. Moreover, it's considered to contribute to the uniformity of the channel flow field. Above was considered the factor that the mach number became 1 at the channel exit.

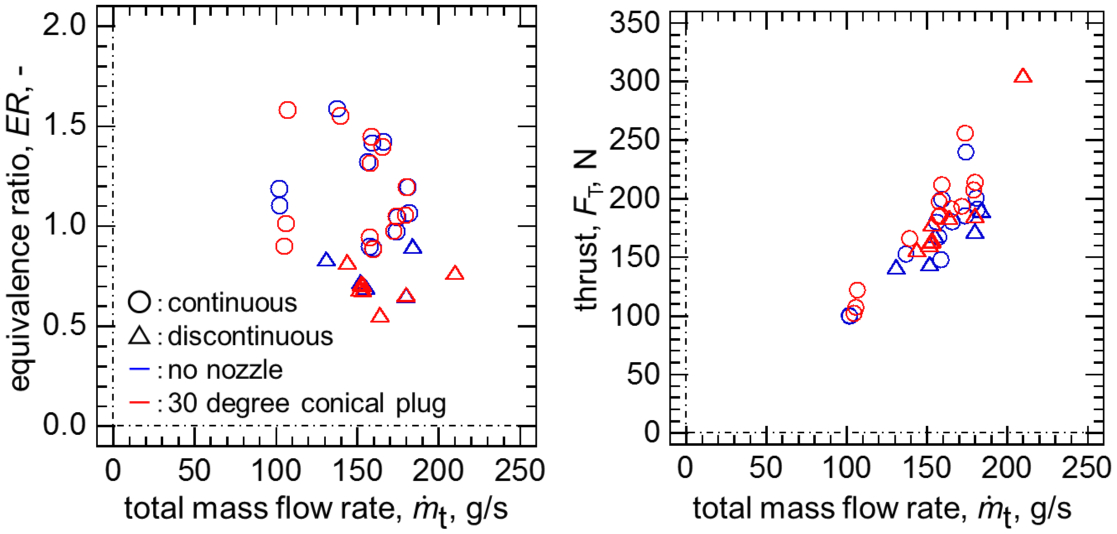

Figure 4. Equivalence ratio – total mass flow rate diagram (left), and thrust – total mass flow rate diagram (right)

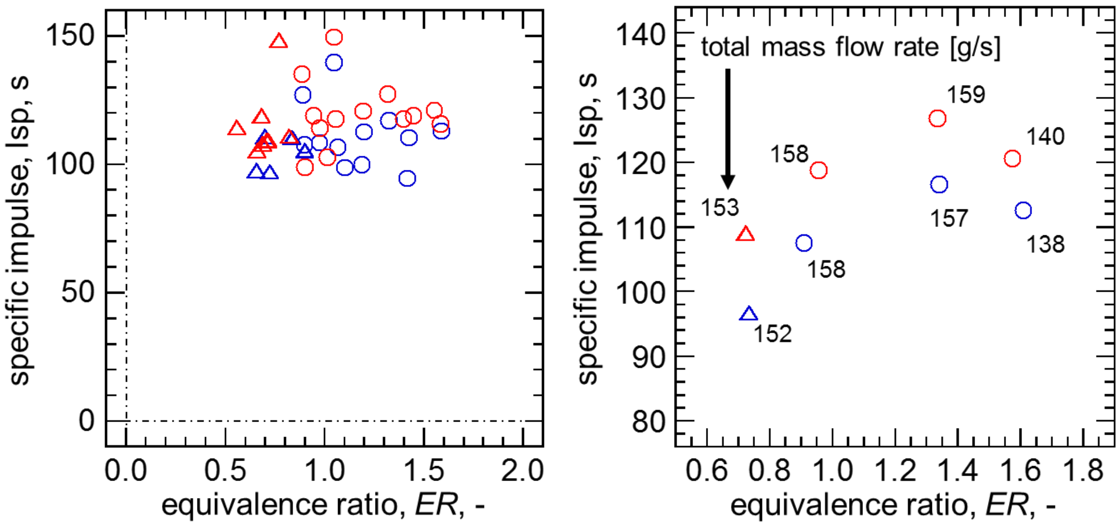

Figure 5. Specific impulse – equivalnce ratio diagram (left) and specfic impulse – equivalnce ratio diagram when total mass flow rate was 150 ± 22 g/s (right)

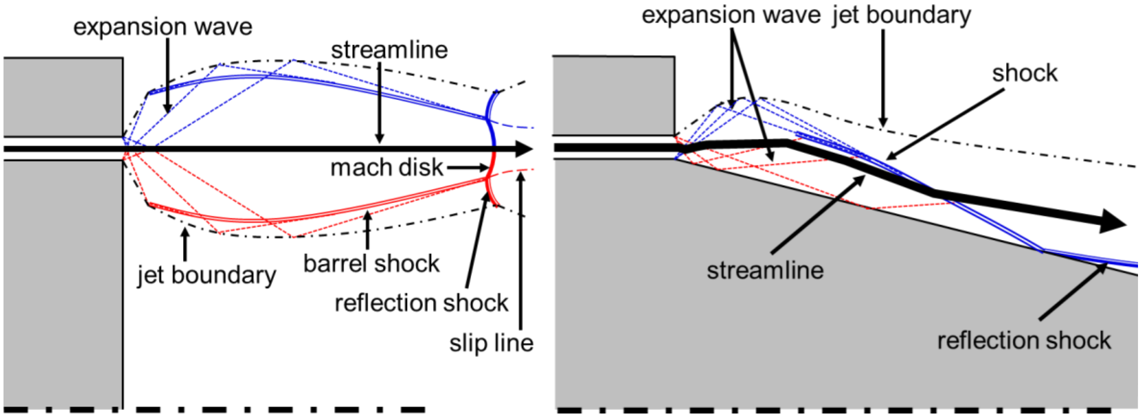

Figure 6. Calculation results of the flow field after combustion channel assuming that the mach number of axial direction of the combustion channel exit = 1 (left : RDE without nozzles, right : RDE with the conical plug with an apex angle of 30 degree)

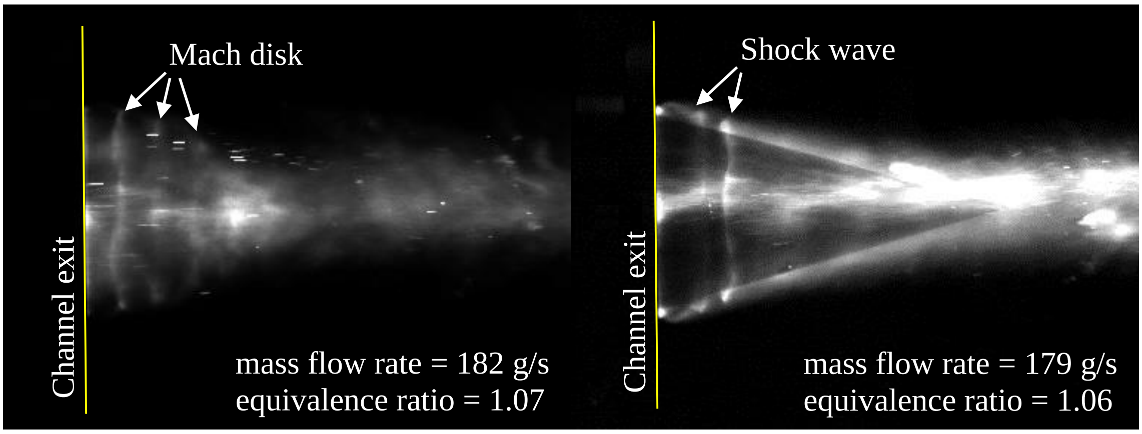

Figure 7. Photos taken the flame after the combustion channel exit from the side by high speed camera (v2511, ViSiON RESEACH) (left : RDE without nozzles, right : RDE with the conical plug with an apex angle of 30 degree)

4 Conclusion

We have developed the thrust measurement system of the rotating detonation engines, and the acquisition of the thrust of the rotating detonation engines in gas ethylene – gas oxygen mixture was carried out. As a result, the specific impulse of the rotating detonation engine was achieved 96 ~ 149 s, and it was confirmed that the thrust performance of the rotating detonation engine improved 6 ~ 11% by attaching a conical plug of which the apex angle was 30 degree. In addition, In addition, the thrust response was 0.9 – 1.7 ms, and we confirmed that detonation waves started continuous propagation in 4.9 – 9.1 ms. Furthermore, we considered that the mach number near the combustion channel exit became 1 since the number of detonation waves increased.

Acknowledgements

This study was subsidized by a Grant-in-Aid for Scientific Research (A), No. 24246137.

The main structure of the flight vehicle was designed and manufactured by NETS and Yamamoto Mechanical Design.

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