Experimental Study on a Rotating Detonation Turbine Engine with an Axial Turbine

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1 Introduction

A jet engine is one of the most widely used main power sources of aircrafts. Utilization of the detonation combustion in jet engines can provide high thrust densities and high combustion efficiencies. Thus, the detonation combustion attracts attentions widely. In addition, the utilization of the detonation combustion can simplify the engine structure [1].

As for the studies of gas turbines with detonation combustors, various trials have been done. A hybrid system gas turbine that adopts a pulse detonation engine (PDE) for a combustor was developed by Rasheed *et al.* [2]. In addition, Endo *et al.* And Maeda *et al.* investigated a small turbine driven by pulse detonation combustors (PDCs). In the investigation, self-sustained operation of the pulse detonation turbine engine (PDTE) system was aimed [3,4]. Studies associated with rotating-detonation-engine (RDE) driven turbines are also very active. In a study by Higashi *et al.* [5-7], a novel turbine engine which has a compressor, combustion, turbine on a single rotor plate has been attempted. Also, Naples *et al.* succeeded in the operation of an open-loop gas turbine engine in which a turbine of a turboshaft engine was connected to an RDE [8]. However, the open-loop system has a limitation that cannot measure a effect of operating turbine to

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compressor. Thus, a closed-loop engine with turbine and compressor is necessary for the self-sustained operation.

In this study, for the first step of developing a rotating detonation turbine engine (RDTE), we designed, fubricated, and tested a prototype RDTE. We have confirmed that the rotational speed of the engine increases by the operation, and we have obtained a prospect for the self-sustained operation.

2 Experimental Apparatus and Experimental Condition

Upon the fabrication of the new RDTE, we replaced the combustor of a commercial jet engine by a newly designed rotating detonation combustor, which fits the other parts of the engine. Figure 1 shows a photograph of the newly fabricated RDTE. Figure 2 shows the detailed structure of the RDTE. As shown in Figure 2, the air entering from the intake passes the compressor, and separates into the air for combustion and the bypass air for cooling of the combustor and turbine. Burned gas and bypass air are mixing after combustion and exhausted through the turbine.

The number of rotation of the turbine is calculated based on the signal of an infrared LED, which is attached above the compressor. We measured pressure at the pre-detonator, fuel plenum, and oxidizer plenum and temperature at the compressor outlet, turbine inlet, and turbine outlet. In consideration of the cell size (2.08mm at H_2-O_2 mixture, initial pressure 101.63 kPa, initial temperature 239K, ϕ =1 [9]) and the combustion chamber width, *i.e.* clearance between inner wall and outer wall, C_2H_4-O_2 and H_2-O_2 were used as the fuel and oxidizer of the pre-detonator and the main combustor, respectively.

We experimented under three experimental conditions which are mentioned in Table 1. Shot 1 and 2 are combustion tests in rich or (almost) stoichiometric conditions, respectively. Shot 3 is a cold-flow test to observe the change of the rotational speed by the gas flow without combustion.

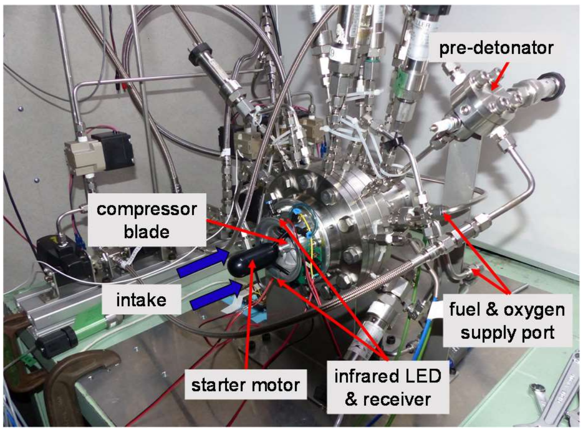

Figure 1. Photograph of the RDTE

Prior to the experiments, we calibrated the mass flow rates of oxigen and hydrogen based on changes in the tank pressures between before and after injection. In addition, particularly for hydrogen, changes in the wet mass of the tank were measured directly. Mass flow rate $\dot{m}_{\rm pre}$ which can be calculated by the tank internal pressure is,

$$\dot{m}_{\rm pre} = \left\{\frac{V_{\rm act}}{RT}(P_0 - P_1)\right\}/t_{\rm act}, \tag{1}$$

where subscript 0 and 1 are the state before and after injection, respectively, R is the gas constant, T is room temperature, P is tank pressure, V_{act} is effective volume (i.e. tank volume), t_{act} is injection time. Besides, mass flow rate $\dot{m}_{\text{mass}}$ which can be calculate by the tank mass measurement is,

$$\dot{m}_{\text{mass}} = \frac{\{(M_0 - M_1) - \rho_1 V_{\text{loss}}\}}{t_{\text{act}}}, \tag{2}$$

where M is measured tank mass, ρ is the density of the gas, V_{loss} is loss volume (i.e. the plumbing volume).

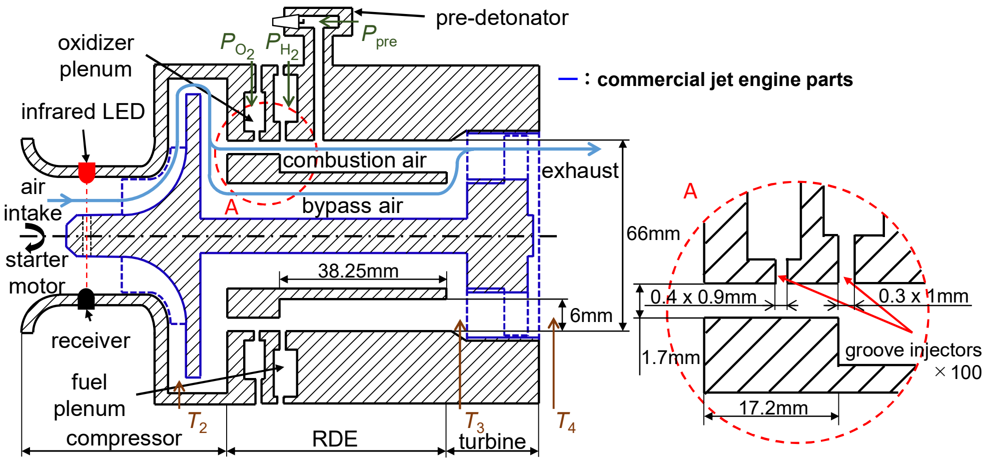

Figure 2. schematic cross-sectional diagram of the RDTE

Table 1: Experimental condition of RDTE combustion test

Experiment	t (s)	ignition	$\dot{m}_{H_2}$ (g/s)	$\dot{m}_{O_2}$ (g/s)	Equivalence ratio
Shot 1	0.5	yes	3.63	19.13	1.52
Shot 2	0.5	yes	3.51	29.34	0.96
Shot 3	0.5	no	3.63	19.13	1.52

Figure 3 shows the spark plug and the details of the sequence of the valve in the experiment.

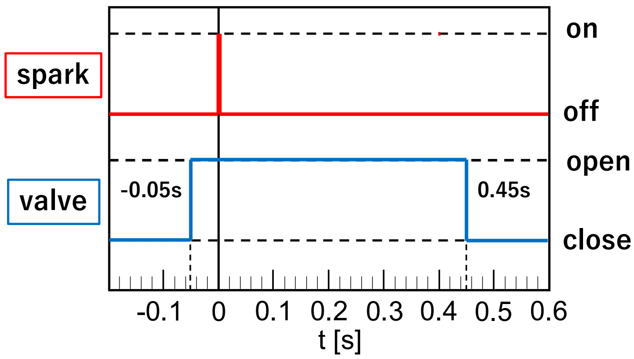

Figure 3. Sequence of the valve and the spark plug

3 Experimental Result

3.1 Visualization of a Rotating Detonation Combustor (RDC)

Figure 4 shows visualization of an RDC in experiment which has same experimental condition with shot 2.

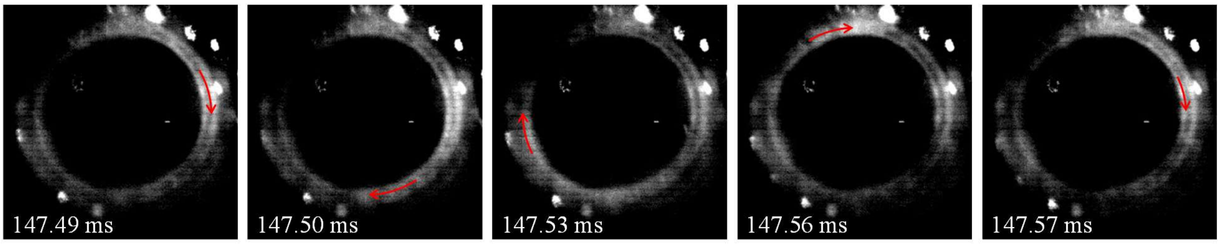

Figure 4. Visualization of the RDC in same experimental condition of shot 2

To visualize rotating detonation waves, we performed an experiment without turbine blades. The experimental conditions were same with Shot 2 except that no obstruction exists in the downstream of the combustion chamber. A high-speed camera was used for visualization of the combustion chamber and the frame rate was 180000 fps. As a result, we confirmed that a luminous wave was rotating in the combustor. Average speed of the wave D_{shot2} was 2.34×10^3 m/s (at one-wave mode), which was 0.916 D_{CJ}. The number of detonative waves changed from one to three irregularly. Above-mentioned phenomena strongly suggests that rotating detonation occurred in the combustor.

3.2 Temperature Variation Measurement

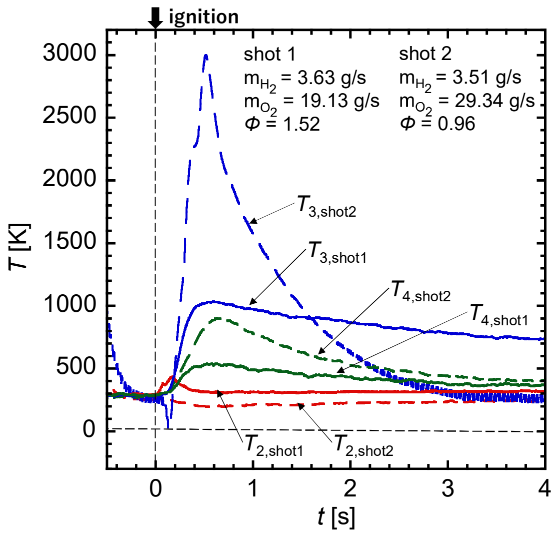

Figure 5. Histories of T_2, T_3, and T_4 in Shot 1 and 2

Figure 5 shows histories of compressor-exit temperature T_2, turbine-entrance temperature T_3, and turbine-exit temperature T_4 in Shot 1 and 2. From Figure 5, we can confirm that all the temperature rises significantly after the ignition in both Shot 1 and 2. Compare the histories of T_2 and T_3 in both experiments, the temperature of burned gas decreases by through a turbine. It suggests that a burned gas worked in a turbine.

Furthermore, from the comparison between both experimental results, the temperature increase in Shot 2 was dramatically higher than Shot 1. In particular, the maximum temperature of T_3 in Shot 2 was approximately three-times higher than that of Shot 1. This result suggests that detonative combustion is made in a RDC at Shot 2. The reason of the T_2 increas immediately after the ignition in Shot 1 may because counterflow occured.

3.3 Comparison of Rotational speed

Figure 6 shows comparison of the time variation data of the rotational speed ω of engine in all experiments.

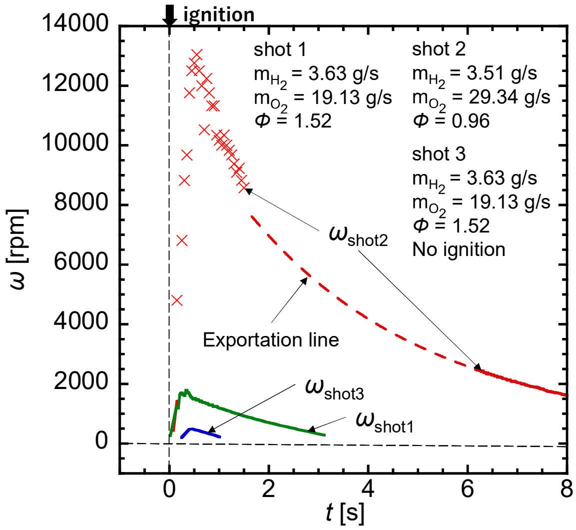

Figure 6. Rotational speed of engine in all experiments

Because of unexpectedly high number of rotational speed in shot 2, it was not able to calculate the rotational speed of all domains with an infrared LED signal. Thus, we calculated rotational speed by the frame of high-speed camera in high number of rotational speed domain. In addition, we drew an extrapolation line by use the low rotational speed domain histories. Figure 6 shows that maximum rotational speed of the shot 2 shows a marked increase than that of the shot 1. The rotational speed rise to about 1,800 rpm in shot 1 which equivalence ratio was approximately 1.5. In shot 2, On the other hand, which equivalence ratio was approximately stoichiometric, the rotational speed dramatically rise to about 13,000 rpm. This result means that the burned gas of Shot 2 is more workable and it suggests detonative combustion was occured in Shot 2. The detonative combustion interrelated to higher rotational speed. We also confirmed that injection of high pressure gas to turbine blade provide rotation about 500 rpm. It suggests that giving pre-rotation to a RDTE by injecting high-pressure gas is possible.

4 Conclusion

In this study, we newly designed a small RDTE and measured changes in temperature history, pressure, and rotational speed. We performed three experiments, two were combustion tests and the other one was a cold-flow test. In combustion tests, experiments were performed in the rich condition (φ = 1.52) (Shot 1) and the almost stoichiometric condition (φ = 0.96) (Shot 2). The results of combustion tests show that turbine-entrance gas temperature and rotational speed of the turbine are larger in Shot 2 than in Shot 1. The maximum turbine-entrance gas temperature in Shot 2 was approximately 3000 K and the maximum rotational speed of the turbine was approximately 13000 rpm. In addition, we visualized the combustion chamber by dismounting the turbine blades with a high-speed camera in the same conditions as Shot 2. The high-speed photograph showed that the speed of the rotating luminous wave was 0.916 D_{CJ}. We think that the wave seen in the RDC was close to detonation wave. Finally, we confirmed that injection of high-pressure gas could drive the turbine.

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