Effect of Injector Expansion Angle on a Rotating Detonation Engine Performance

Kosuke Nakajima[1)], Ken Matsuoka[1)], Noboru Itouyama[2)], Jiro Kasahara[2)], Akira Kawasaki[3)], Akiko Matsuo[4)]

[1)]Department of Aerospace Engineering, Nagoya University, Nagoya, Japan
[2)]Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Japan
[3)]Department of Mechanical Engineering, Shizuoka University, Hamamatsu, Japan
[4)]Department of Mechanical Engineering, Keio University, Yokohama, Japan

1 Introduction

Engines using Pressure Gain Combustion (PGC), in which the total pressure of the working fluid increases before and after the combustion reaction, have higher thermal efficiency than engines based on the conventional Brayton cycle. Engines using detonation combustion are expected to achieve Pressure Gain in addition to the temperature increase during the combustion process. In particular, the rotating detonation engine (RDE) simultaneously reduces the size and weight of the PGC and combustor and simplifies the system. in the RDE, the detonation wave propagates continuously in a circumferential direction at a supersonic speed of approximately 2000 m/s. The realization of pressure gain is an important advantage comparing the propulsive performance of RDEs with current constant-pressure combustion engines.

Kaemming and Paxson [1] proposed the Equivalent Available Pressure (EAP), which calculates the outlet total pressure from experimentally measured thrust, as a metric for evaluating the comparative PG performance of RDEs. Bach et al. [2] used a Kiel probe to calculate the outlet the total pressure was measured experimentally and an empirical model was developed in conjunction with other reported experimental EAP results; Brophy et al. [3] confirmed the operation at $P.G. = -3.1\%$ by increasing the combustion chamber width, thereby reducing heat transfer and wall friction losses. No previous experiments have exceeded $P.G. > 0\%$, and there is a large discrepancy between the RDE under ideal assumptions and the experimental results. Visualization experiments using a race-track-shaped RDE by Chacon and Gamba [4] identified Parasitic Combustion (PC) occurring ahead of the detonation wave. It was suggested that PC causes a reduction in propagation velocity and peak pressure, which reduces the overall thermal efficiency of the engine. Matsuoka et al. [5] experimentally investigated the combustion gas backflow process by varying the ratio of oxidizer injector area to combustion chamber area. The results showed that as the injector area increased, the reverse flow rate and hydrodynamic blockage ratio of the combustion gas increased and the propagation velocity of the detonation wave decreased. Athmanathan et al. [6] investigated the internal structure of the flow by visualizing the cross-section of the RDE channel using the PLIF method. The results suggested that the presence of recirculation zones

Correspondence to: nakajima.kosuke.j8@s.mail.nagoya-u.ac.jp

forms a mixture of already burned gas and unburned propellant, which changes the shape of the detonation wave.

This study focuses on the effect of changes in the recirculation zone caused by injection on Pressure Gain performance. Experiments were conducted using time-averaged static pressure, fluctuating pressure at the bottom of the combustion chamber, thrust, and self-luminescence visualization from axial and radial directions simultaneously, with the expansion angle at the bottom of the combustor as a parameter.

2 Experimental Set-Up

Figure 1 shows a schematic of the RDE used in the experiment. The dimensions of the annular-shaped combustion chamber were as follows: outer diameter, 60 mm; inner diameter, 50 mm; width, 5 mm; and length, 30 mm. A polar coordinate system was set at the bottom of the combustor as the origin. As shown in Fig. 1 (b), fuel was injected into the combustor from injectors that were equally spaced in a 72-hole inner cylinder (diameter = 0.6 mm at $z = -1.5$ mm). The total area of the fuel injector was $A_\mathrm{f} = 20.4\ \mathrm{mm}^2$, and the fuel injection direction was the same as that of the r-axis. The oxidizer was filled in the z-axis by means of a 1.9 mm wide slit between the outer cylinder and the fuel plenum component on the inner cylinder side. The cross-sectional area ratio of the combustion chamber to the oxidizer inlet was $A_\mathrm{o}/A_\mathrm{ch} = 0.401$. The expansion angles at the bottom of the combustor were 90 and 30 degrees. We used gaseous ethylene and oxygen as the reactants.

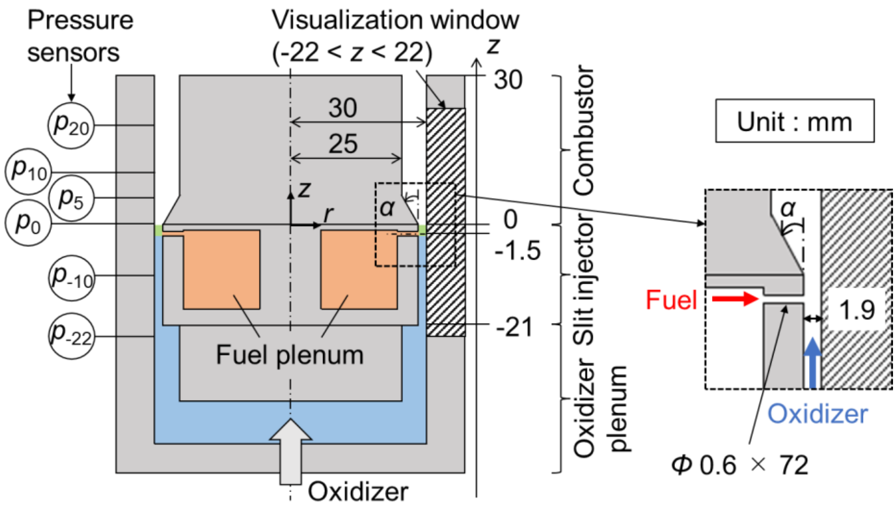

Fig. 1 Schematic cross-sectional view of the RDE used in the combustion test: (a) overview of the RDE, (b) injector geometry (unit: mm).

The pressure sensor ports are located side wall ($z = -22, -10$, 0, 5, 10, and 20 mm, $p_{-22} - p_{20}$) of the engine. All of the pressure sensors are 1 kHz pressure transducers (PAA-23SY, Keller piezoresistive pressure transmitter). A piezoelectric pressure transducer (113B24, PCB Piezotronics) with a limiting frequency higher than 1 MHz was flush mounted at $z = 0$ mm on the outer body to acquire a fluctuation pressure $p_{0,\mathrm{high}}$. The combustor was fixed on a slide-type thrust stand, and the thrust F was measured using a load cell (Aikoh, DUD50K). Ignition was performed by the gunpowder connected to an electric fuse (Kayaku Japan). The axial self-luminescence images of the RDE were captured using a high-speed camera (Photron, SA5). The radial self-luminescence images were observed using a high-speed camera (Vision Research, Phantom V 2011) through a removable acrylic visualization window ($-22\ \mathrm{mm} \le z \le 22$ mm, $\Delta\theta = 39$ deg) installed in the outer cylinder of the combustor. Figure 2 presents a schematic of the thrust measurement and visualization setup in a vacuum chamber.

The mass flow rate of the fuel and oxidizer were set using orifices installed upstream of the RDE supply line. Flow calibration was performed by flow test with a mass flow meter (ALICAT, MQ 3000 SLPM) attached directly upstream of the RDE.

The back pressure (p_b) before combustion test sequence was p_b =10.0 ± 0.3 kPa.

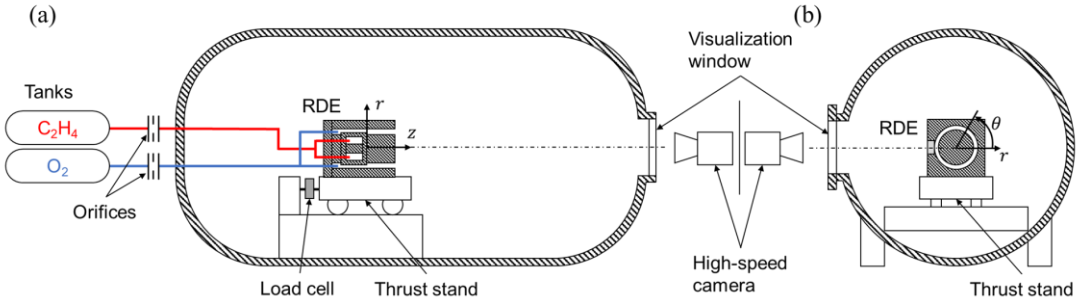

Fig. 2 Schematic of the experimental setup: (a) Viewing from the radial direction, (b) Viewing from the axial direction.

3 Results and Discussion

The experiment was conducted by fixing the equivalence ratio (ER) at ER = 1.0 ± 0.1 and varying the mass flux. Figure 3 shows the representative time history of pressure ($p_{-22} - p_{20}$) and thrust. At t = 0 s, an ignition signal is applied to the gunpowder, and after the propellant is ignited, a combustion wave propagates in the RDE. The combustion wave transitioned to a detonation wave, and the pressure in the plenum and combustion chamber increased. As the mass flow rate was increased, the number of detonation waves became two. As shown in Figure 3(b), when the propagating wave number (n_{wave}) is n_{wave} = 2, the plenum pressure and combustor pressure are larger than when n_{wave} = 1. At α = 30 deg, the rotational propagation of the detonation wave could no longer be observed when the mass flux was decreased, and the operating range as an RDE was larger at α = 90 deg.

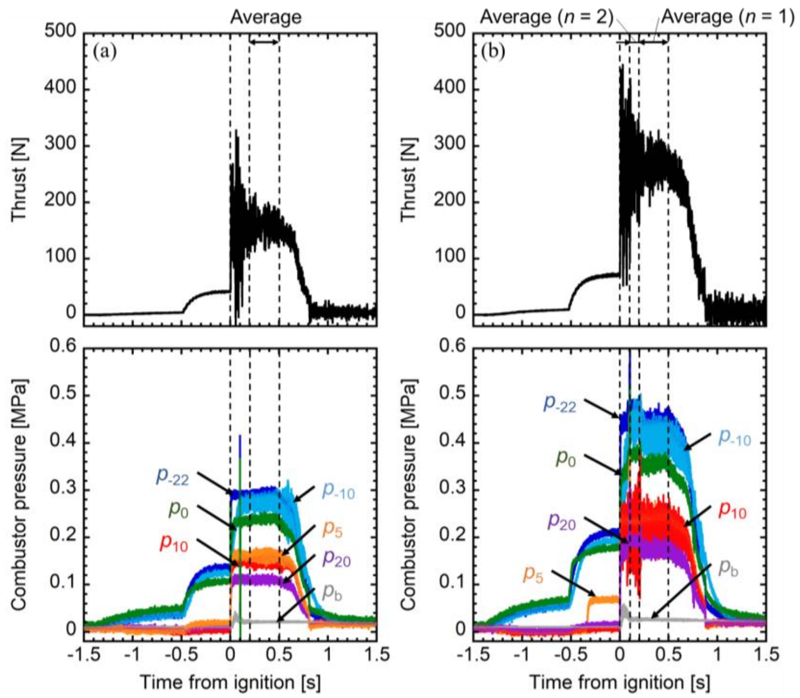

Fig. 3 Time variation of pressure and thrust of the RDE: (a) α = 90 deg, $\dot{m}/A_{ch}$ = 97.2 kg/(m²·s), ER = 0.95, (b) α = 90 deg, $\dot{m}/A_{ch}$ = 148 kg/(m²·s), ER = 0.98.

Figure 4 shows the time-averaged value of the thrust (a) and the observed detonation propagation velocity (b). As shown in Figure 3 (b), we took time averages for n_w = 1 and 2, respectively. As shown in Figure 4, no significant change in thrust was observed at constant mass flux, but the velocity of propagation of the detonation wave was larger for α = 90 deg. The propagation velocity of the Chapman-Jouguet detonation (D_{CJ}) in Figure 4 (b) was calculated from the combustor pressure for each condition using the NASA-CEA det mode [7].

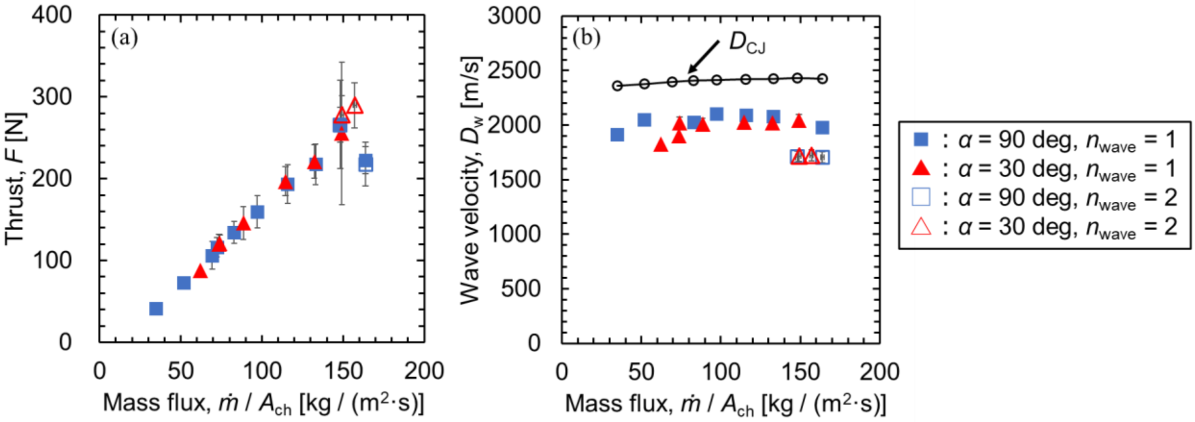

Fig. 4 (a) Thrust and (b) wave velocity of the RDE in the various mass flux conditions.

Figure 5 shows the Pressure Gain values (*P.G.*) calculated using EAP [1]. The *P.G.* did not change significantly under any condition and was approximately *P.G.* = -40%. *EAP* and *P.G.* were calculated using Equations (1) and (2).

$$EAP = \frac{F + p_b A_{exit}}{(1+\gamma)A_{exit}}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} \tag{1}$$

$$P.G. = \frac{EAP}{p_{t,-22}} - 1 \tag{2}$$

where A_{exit} is the area of the combustor exit, and is equal to the area A_{ch} of the combustor channel. Equation (1) neglects the base drag force due to pressure on the structure at the RDE exit. This is because the base drag force is less than 1% of the main thrust under low back pressure [8].

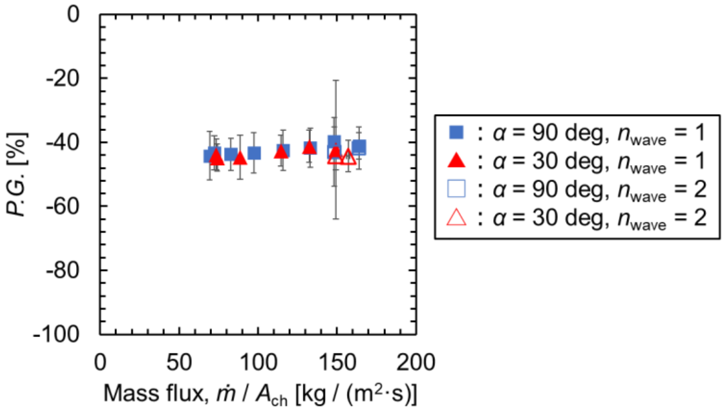

Fig. 5 Pressure Gain value of the RDE in the various mass flux conditions.

Figure 6 (a) shows a portion of the image of the self-luminescence visualization from the radial direction. The visualization from the radial direction confirmed the detonation wave and the backflow by the burned gas. Figure 6 (b) shows the distribution of self-luminous intensity in the θ - z and t - z diagrams. It was found that the backflow process and filling height differed depending on the expansion angle. At α = 30 deg, a larger backflow was observed than at α = 90 deg. Also, the self-luminous area is larger and the detonation wave appears to propagate downstream of the combustor. The wavefront shape of the detonation wave appears smooth at α = 30 deg.

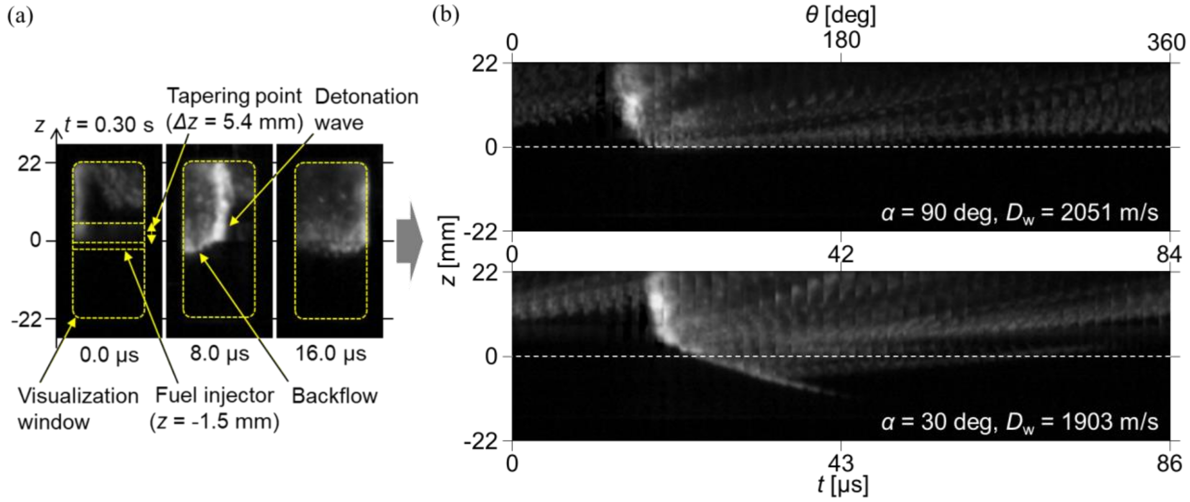

Fig. 5 (a) Part of self-luminescence image from radial direction, (b) distribution of self-luminous intensity in $\theta - z$ and $t - z$ diagram ($\dot{m}/A_{ch}$ = 73 kg/(m^2·s), ER = 1.0).

Conclusion

In this study, self-luminescence visualization, pressure, and thrust measurements were conducted simultaneously to investigate the pressure gain performance of the RDE. The expansion angle of the oxidizer injector at the bottom of the combustor was varied from α = 30 deg to 90 deg. It was confirmed that the operating range as an RDE differs depending on the expansion angle.

The pressure gain value *P.G.* did not change significantly with the expansion angle, but the propagation velocity D_w was smaller for α = 30 deg.

Radial visualization results showed a large backflow at α = 30 deg. The shape of the detonation wave was also confirmed more clearly at α = 30 deg.

Acknowledgments

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