Experimental Research of the Effect of the Slit on the Coupled Rotating Detonation Engine

Akihito NAKAMA[1], Shuhei INAMORI[1], Yuichiro IDE[1],
Noboru ITOUYAMA[1], Ken MATSUOKA[1], Masaaki YASUI[1], Jiro KASAHARA[1]
Akiko MATSUO[2], Ikkoh FUNAKI[3], and Hideyuki TANNO[3]

[1] Nagoya University, Furo-Cho, Chikusa-ku, Nagoya, Aichi, 466-8603, Japan
[2] Keio University, 3-14-1, Hiyoshi, Kohoku-ku, Yokohama, Kanagawa, 223-8522, Japan
[3] JAXA, 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-5210, Japan

1 Introduction

Detonation is a combustion phenomenon in which supersonic combustion waves, detonation waves, propagate in a premixed gas [1]. Detonation combustion is characterized by its ability to achieve high temperatures and pressures through shock waves, resulting in theoretically higher thermal efficiency than the Brayton cycle, commonly employed in conventional internal combustion engines. Additionally, since the propagation speed of the combustion wave reaches supersonic velocities, the combustion process is completed within an extremely short time. Consequently, detonation engines, which apply detonation combustion to internal combustion systems, have the potential to achieve miniaturization and enhanced performance compared to conventional aerospace propulsion engines [2, 3].

A representative example of a detonation engine is the rotating detonation engine (RDE) [4]. Traditionally, RDEs have featured a combustor with an annular structure consisting of an inner and an outer cylinder. This configuration injects propellants into the annular channel, where detonation waves propagate and generate thrust. However, the conventional RDE faces structural and thermal challenges regarding an inner cylinder. In response to the aforementioned challenges, recent studies have demonstrated that detonation waves can continuously propagate in cylindrical RDEs without an inner cylinder [5-7]. Research on the propulsion performance of cylindrical RDEs was conducted by Kawasaki et al. [8] and Yokoo et al. [9, 10], confirming that cylindrical RDEs achieved comparable thrust performance to conventional RDEs. These studies indicate that the thermal challenges associated with RDEs featuring an inner cylinder can be resolved, and cylindrical RDEs offer the potential for simpler structures and more compact combustors than conventional RDEs.

However, it has been experimentally demonstrated that in cylindrical RDE, detonation waves cannot be clearly observed during operation at high flow rates exceeding a certain threshold relative to the inner diameter. This fact indicates that there are limitations to the operational range of detonation combustion, raising the issue that achieving high flow rates and high thrust with a single unit is challenging. In response to this problem, the clustering of multiple cylindrical RDEs of identical design is proposed. By clustering, it is possible to leverage the advantages of the compactness offered by

Correspondence to: nakama.akihito.a0@s.mail.nagoya-u.ac.jp

detonation combustion while enabling higher flow rates, thereby making high-thrust engines feasible [11].

A critical challenge for the practical implementation of cylindrical RDE clustering is achieving synchronized ignition of multiple cylindrical RDEs using a single igniter. Sakata et al. [12] demonstrated synchronized ignition in two connected cylindrical RDEs by introducing perforations in the inner wall or lowering the height of the inner wall relative to the outer wall, confirming that this approach did not adversely affect propulsion performance, and the propagation modes of detonation in this approach was different from that of conventional cylindrical RDE. In this study, we investigated and evaluated a coupled RDE consisting of two cylindrical RDEs connected by a slit. By igniting only one side, we experimentally examined the effects of slit width on ignition delay, differences in propulsion performance, and propagation modes of the detonation wave.

2   Experimental Setup

A schematic diagram of the coupled cylindrical RDE is shown in Figure 1. Both combustors had a combustor inner diameter of 23 mm and an axial length of 42 mm. The distance between the centers of the two RDEs was 28 mm, and the wall of the combustor was 5 mm thick at its thinnest point. There were 24 pairs of injector holes arranged in a circle with respective diameters of 10 mm for oxidizer and 16mm for fuel. Each of the holes had a diameter of 0.8 mm. The gaseous C_2H_4 and O_2 were used as the propellant. The ignition system employed a gunpowder ignition, with the gunpowder installed on only one combustor and no ignition device on the other side. The pressure sensor ports were located on the combustor sidewall (z = 3, 15, 27, and 39 mm, $p_3, p_{15}, p_{27}, p_{39}$) of both RDEs. All pressure sensors were 1 kHz-sampling pressure transducers (PAA-23SY, KELLER). The ignition delay of the two cylindrical RDEs was evaluated by forcusing on the rises of the respective pressures.

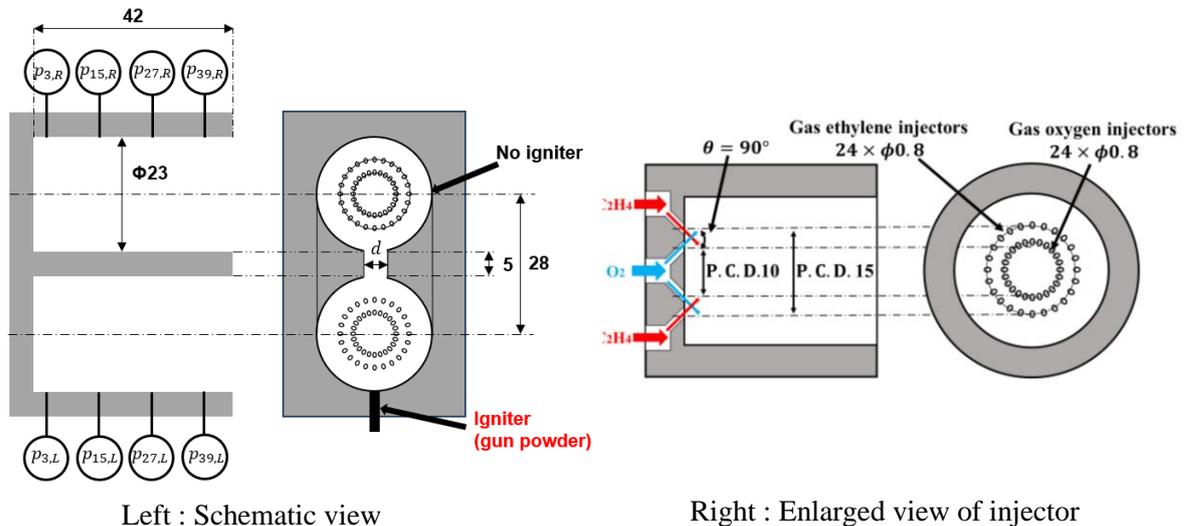Left : Schematic view   Right : Enlarged view of injector
Fig. 1 Schematic diagram of a coupled cylindrical RDE

Combustion experiments were conducted with propellant mass flow rates in the range of 36 ± 1 g/s (total flow rate supplied to the two cylindrical RDEs) and an equivalence ratio of 1.5 ± 0.1. The propellant flow rate was measured using a mass flow meter (MQ3000SLPM, ALICAT) installed in the pipeline. The back pressure p_b was controlled at approximately 10 kPa in a vacuum chamber with a volume of 8 m³. The thrust stand was preloaded with a mass of 10 kg, and the thrust was measured by a load cell (DUD-100K, Aikoh Engineering). A high-speed camera (v2021, Phantom) was put outside the vacuum chamber to visualize the self-luminescence downstream of the combustor in the axial direction. In this experiment, tests were conducted by varying the slit witdh d ($d = 0, 1, 3, 5, 7, 10$ mm) as a

parameter, while replacing the inner wall of the combustor. The experimental conditions and the results are summarized in Table 1.

Table 1 Experimental conditions

Shot	Slit d, mm	$\dot{m}$, g/s	Φ, -	p_b, kPa
#1	0	36.7 ± 0.5	1.53 ± 0.02	10 ± 1
#2	1	36.5 ± 0.7	1.54 ± 0.04	10 ± 1
#3	3	36.6 ± 0.6	1.52 ± 0.03	10 ± 1
#4	5	36.5 ± 0.5	1.53 ± 0.04	10 ± 1
#5	7	36.8 ± 0.5	1.52 ± 0.03	10 ± 1
#6	10	36.4 ± 0.8	1.53 ± 0.05	10 ± 1

3   Results and Discussion

Figure 2 shows the pressure and thrust time histories in Shot 1 ($d = 0$ mm). There was an apparent ignition time delay between the two cylindrical RDEs when there was no slit. The cylindrical RDE equipped with the gunpowder began combustion at $t = 0$ ms, followed by the other cylindrical RDE without the gunpowder at around $t = 140$ ms. In the case of no slit, the ignition mechanism is thought to be that the high-temperature gas from the exhaust plume of the gunpowder-ignited-cylindrical RDE on one side ignited the unburned mixture supplied from the other cylindrical RDE to begin combustion [13], and the above ignition mechanism was observed in the movie taken with a high-speed camera.

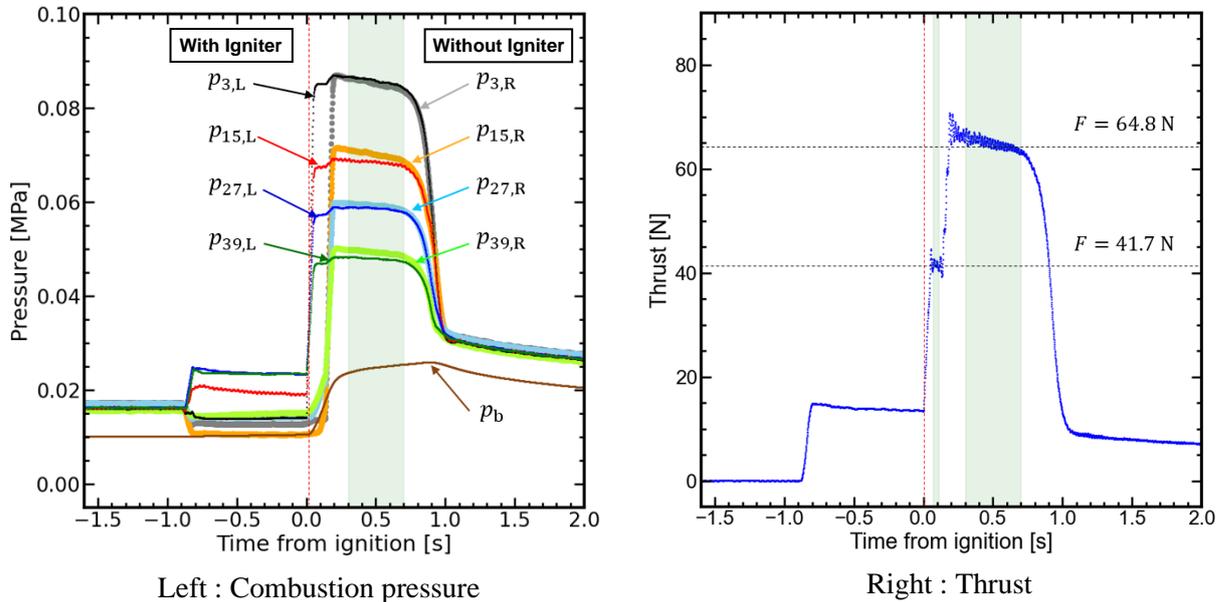Left : Combustion pressure   Right : Thrust

Fig. 2 Time history of the combustor pressure, and thrust in Shot 1
($d = 0$ mm, $\dot{m} = 36.7 \pm 0.5$ g/s, $\Phi = 1.53 \pm 0.04$, $p_b = 10 \pm 1$ kPa)

Figure 3 shows the pressure and thrust time histories in Shot 2 ($d = 1$ mm). Compared to the case without the slit, combustion pressure of both cylindrical RDEs increased from the moment of ignition when there was the slit. Except for the ignition time delay, there was no significant difference in the pressure and thrust histories with and without the slit, and the time history graphs show that the presence of the slit did not affect the propulsive performance. The gradual decrease in thrust from the start of

combustion is thought to be due to the thrust produced by the difference between combustion pressure and back pressure decreasing with time as the back pressure in the vacuum chamber increased.
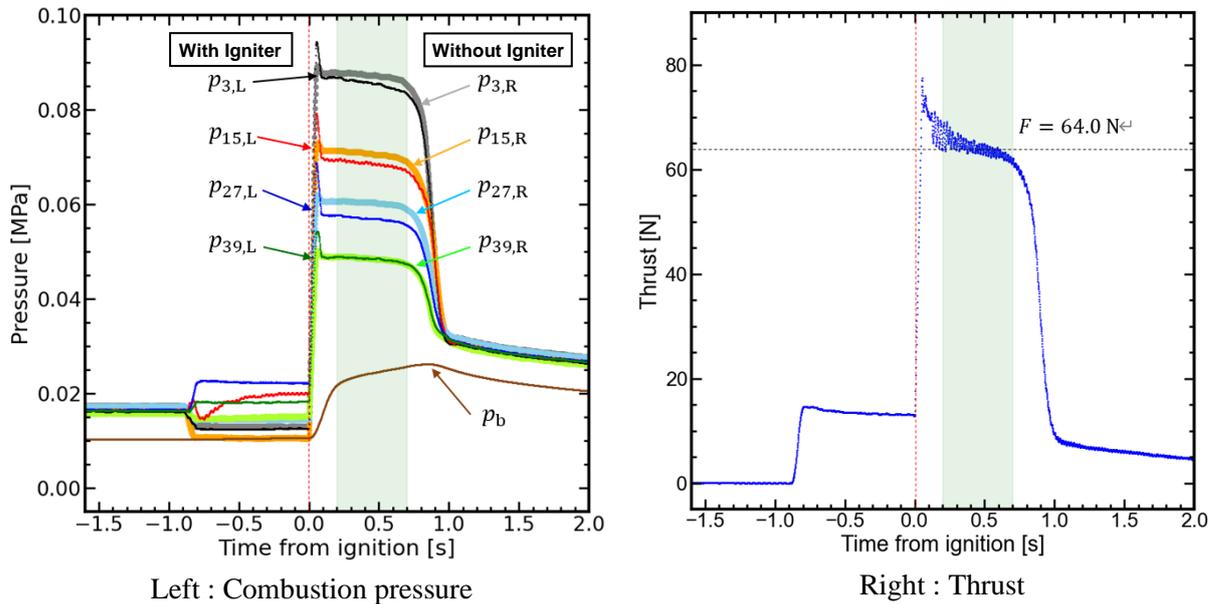
Left : Combustion pressure

Right : Thrust

Fig. 3 Time history of the combustor pressure, and thrust in Shot 2
($d = 1$ mm, $\dot{m} = 36.5 \pm 0.7$ g/s, $\Phi = 1.54 \pm 0.04$, $p_b = 10 \pm 1$ kPa)

The experimental results under the conditions shown in Table 1 are presented in Figure 4. In Figure 4 (Left), the average static pressure on the combustor sidewall ($p_3, p_{15}, p_{27}, p_{39}$) of both cylindrical RDEs for each slit width are plotted, while Figure 4 (Right) shows the average thrust. Figure 4 shows that there was no significant difference in combustion pressure and thrust between the conditions without slit width (Shot 1, $d = 0$ mm) and with slit width (Shot 2-6, $d = 1$-10 mm), indicating that slit width up to less than half of the inner diameter ($r = 11.5$ mm) had no adverse effect on propulsion performance.
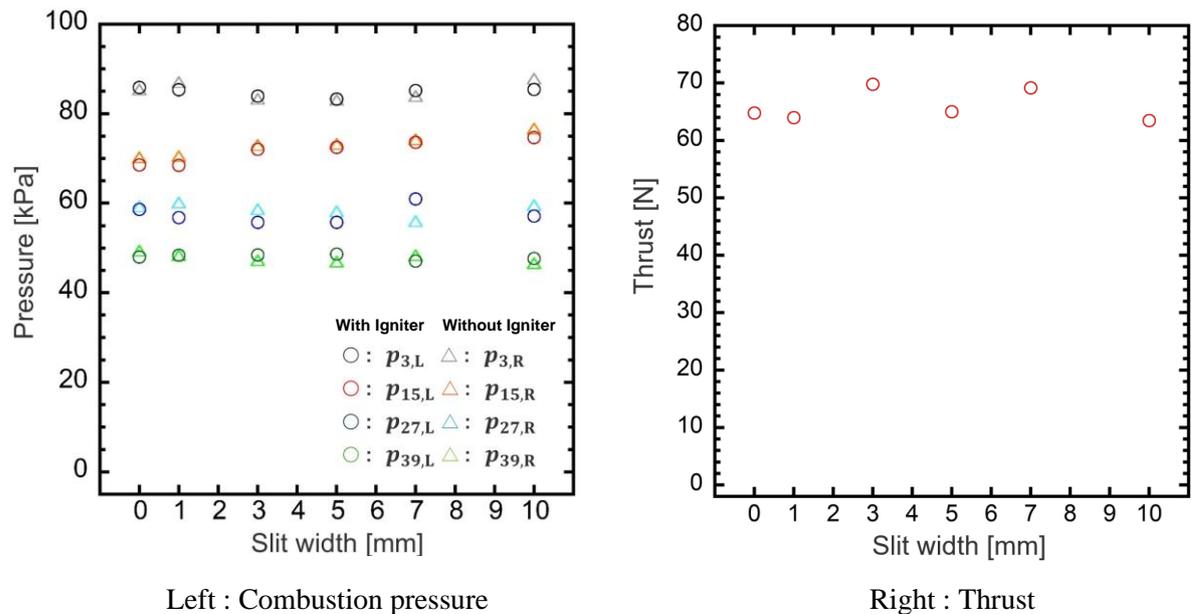
Left : Combustion pressure

Right : Thrust

Fig. 4 Results for each experimental condition

As for the ignition delay, when there was the slit (Shot 2-6, $d = 1\text{-}10$ mm), the rise time delay of the combustion pressure of the two cylindrical RDEs was less than 1 ms, which was the sampling period of the pressure sensor used. Therefore, in this experiment, synchronous iginition of the two cylindrical RDEs using the slit is considered to have been achieved.

Figure 5 shows a series of self-illuminated images of Shot 2 ($d = 1$ mm) and Shot 6 ($d = 10$ mm) visualized by a high-speed camera.
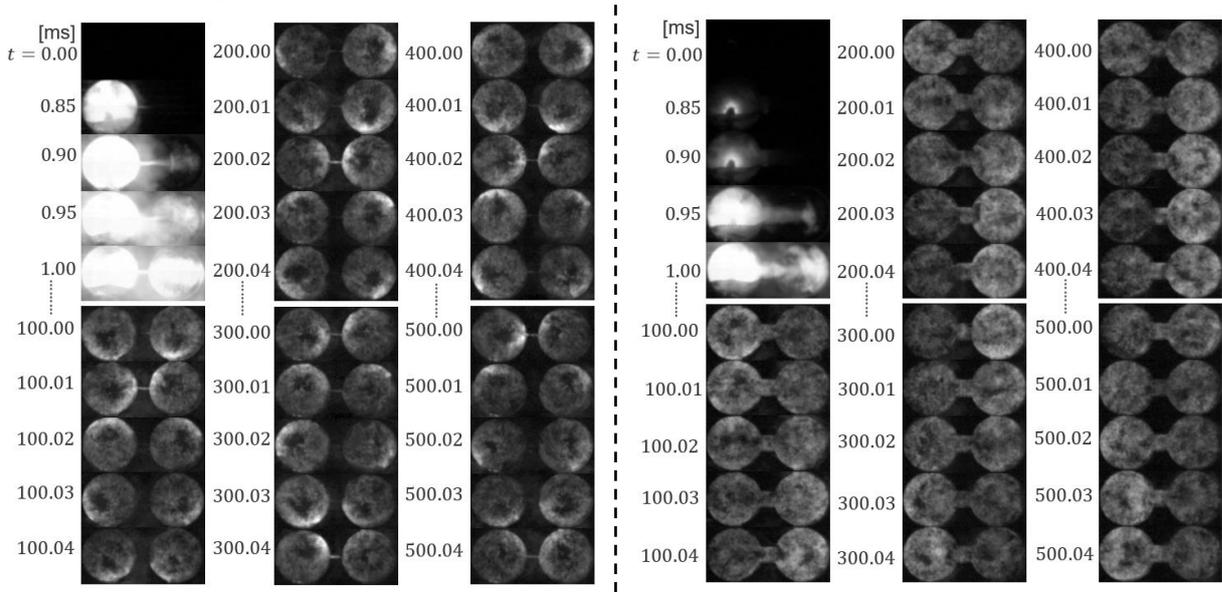
Left : Shot 2 ($d = 1$ mm, $\dot{m} = 36.5 \pm 0.7$ g/s, $\Phi = 1.54 \pm 0.04$, $p_\text{b} = 10 \pm 1$ kPa)   Right : Shot 6 ($d = 10$ mm, $\dot{m} = 36.4 \pm 0.8$ g/s, $\Phi = 1.53 \pm 0.05$, $p_\text{b} = 10 \pm 1$ kPa)

Fig. 5 Sequential axial self-luminescence images captured

For the slit width of 1 mm, after synchronous ignition, detonation waves propagated circumferentially in each cylindrical RDE as in the detonation wave propagation mode of conventional cylindrical RDEs. In addition, a phenomenon was observed in which the self-luminous region overlapped at the slit. This phenomenon needs to be investigated in more detail by conducting experiments with different mass flow rates and equivalent ratios. Nevertheless, the fact that this phenomenon could not be confirmed for slit widths of 3 mm or greater suggests that slit widths of about 1 mm be attributed to this phenomenon.

As the slit width was increased, a difference in the propagation mode of the detonation wave was observed. For slit widths other than 1 mm, three modes of propagation were observed: circumferential, radial, and horizontal. It was observed that as the slit width increased, the propagation modes of the detonation wave that propagated between each other's cylindrical RDEs became more dominant.

4   Conclusion

In this study, we examined and evaluated the effect of the slit on the ignition delay, propulsion performance, and propagation modes of the coupled RDE. As a result, it was found that the presence or absence of the slit had no significant effect on the propulsive performance. However, the slit was largely attributed to the realization of synchronous ignition of two cylindrical RDEs. Moreover, the propagation mode of the detonation wave varied with slit width. When the slit width was 1mm, detonation waves

propagated in the circumferential direction as in conventional cylindrical RDEs, however, when the slit width was increased, the dominant mode of propagation was back and forth between each other's RDEs.

Acknowledgments

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