Operation Characteristics of a Throatless Rotating Detonation Engine with Diverging Channel

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1 Introduction

Acceleration of burned gas to higher velocity is one of the essential thrust generation requirements in propulsive systems. Deflagrative combustion, widely used in conventional heat engines, operates through material diffusion and heat transfer, and some distance is needed for the combustion to be completed. Thus, heat released from the combustion is distributed over a certain distance, and burned gas cannot be thermally choked. This feature of deflagrative combustion requires conventional propulsive systems such as rocket engine to have a converging section [1]. In detonation combustion, on the other hand, a supersonic shock wave continuously triggers the combustion process. Thus, the wave leads to instantaneous completion of the combustion [2-4]. The short completion of the combustion that has a large heating value enables the burned gas to satisfy a thermal choking condition even in a diverging channel [5]. This feature of detonation combustion enables the flow to be accelerated to supersonic without a need of converging section, and more flexibility in the design of the engine shape.

The rotating detonation engine is a typical kind of heat engine that utilizes detonation combustion. An RDE usually has an inner cylinder for detonation wave to propagate circumferentially [6,7], and is called an annular RDE. The inner flow structure of annular RDEs have been investigated utilizing various methods including visualization technics [8-10]. Athmanathan et al. [8] investigated detailed wave structure in a non-premixed RDE combining MHz PLIF and OH* chemiluminescence visualization of H_2-air combustion, and 3D URANS simulation. Rankin et al. [9] investigated the wave structure for H_2-air in a range of equivalence ratio via mid-infrared imaging. Bohon et al. [10] conducted high-speed imaging of chemiluminescence and high-frequency pressure measurement to investigate combustion mode in an RDE. These studies have revealed various characteristics of detonation waves in the annular RDEs in actual operations. However, the inner cylinder composing the annular channel is heavy and difficult to cool. Therefore, several researchers have investigated RDEs without an inner cylinder, called cylindrical or hollow RDEs [11-13]. From the stand point of experimental study on cylindrical RDEs, Kawasaki et al. [11] investigated the effect of inner cylinder diameter on thrust performance of an RDE. Yokoo et al. evaluated the thrust performance of a small cylindrical RDE with a uniform cross-sectional area channel [12], as well as conducted visualization inside the channel suggesting short completion of the combustion [13]. These studies imply feasibility of high-performance heat engines utilizing detonation combustion, and demonstrate important contribution of visualization combining with other techniques such as pressure measurement for further understanding of detonation engines.

We focus on the acceleration process of burned gas within diverging channel utilizing detonation combustion. In previous studies, we demonstrated supersonic exhaust flow from a diverging channel (diverging angle $\alpha = 5$ deg) without a structural throat [14], and visualized its inner flow via self-luminescence and CH* luminosity from C_2H_4-O_2 combustion [15]. In this study, combustion tests using H_2-O_2 as the propellants were conducted to provide further insight into operation range and inner flow of the diverging RDE. In the experiments, visualization of the inner flow via high-speed imaging, as well as pressure and thrust measurement were performed.

2 Experimental Setup

The diameter of the engine inlet d_0 is 20 mm and the channel length L is 70 mm. The channel has a diverging angle α of 5 deg, and the inlet-to-outlet area ratio $(\pi d_e^2/4)\ /\ (\pi d_0^2/4)$ is 2.6. The gaseous C_2H_4-O_2 or H_2-O_2 were used as the propellants. Gunpowder (Kayaku Japan Electric Ignitor) or a pre-detonator located at z = 65 mm was used as the ignitor. The engine has two types of channels. The one is made from stainless steel (SUS304) for pressure measurement, and the other one is made from acrylic (PMMA) for visualization. The SUS wall type has 8 pressure sensor ports at the injector surface (z = 0 mm, p_0) and a side wall (z = 5, 10, 20, 30, 40, 60, and 65 mm, p_5–p_{65}). The PMMA wall type also has pressure ports at the injector surface, and at z = 65 mm. All pressure sensors are 1.0 or 3.5 kHz-sampling pressure transducers (Keller PAA-23, GE UNIK 5000).

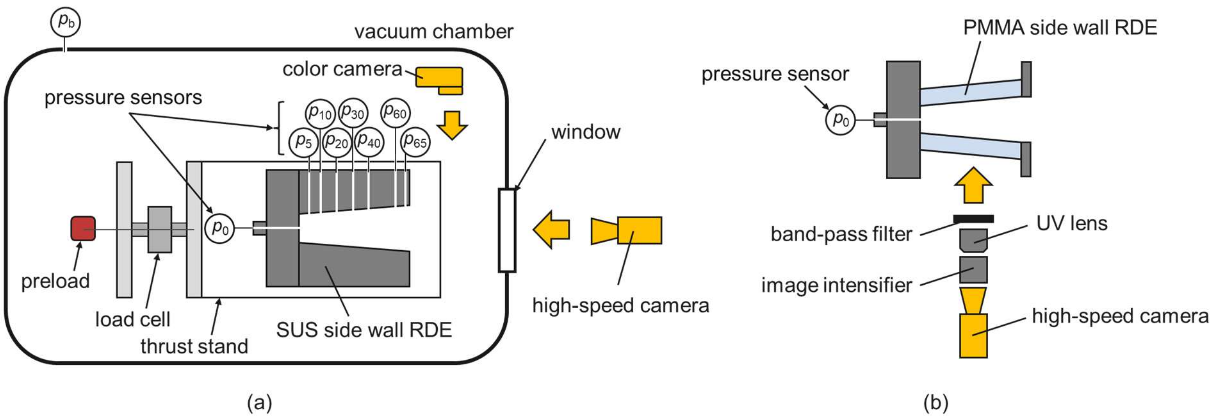

Fig 1 Top view of experimental set up under (a) low back pressure condition; and (b) atmospheric condition.

Figure 1 shows schematics of the experimental set up top views. Combustion tests were conducted in a 30 m^3 volume vacuum chamber or on a test stand under atmospheric condition. The back-pressure in the vacuum chamber was set in the range of 12 to 14 kPa during the tests. In the low back-pressure combustion tests, the RDE was set on a thrust stand. The thrust stand was pre-loaded and the thrust was measured by a load cell (AIKOH DUD-50K, rating capacity: 500 N). The load cell was calibrated via known weights in advance. The vacuum chamber has windows for visualization. Self-luminescence in the RDE was captured from the axial direction by a high-speed camera (Phantom v2011) set outside the chamber. A color camera (GoPro Hero 9) was put inside the chamber to capture the exhaust plume.

In the combustion tests under atmospheric condition, a high-speed camera (Shimadzu HPV-X2) combined with an image intensifier (Lambert Instruments HiCatt 25) and a band-pass filter (Semrock FF02–320/40–50) set at the side of the RDE. The visualized area ranged from the injector surface to 60 mm, an additional 10-mm length is not visible due to the metal end plate. This configuration is for visualization of OH* luminosity from H_2-O_2 combustion. All the combustion duration was set to 0.5–1.0 s. The experimental conditions are summarized in Table 1.

Table 1 Experimental conditions

No.	wall	propellants	α [deg]	$\dot{m}$ [g/s]	ϕ^{**} [-]	p_b [atm]
1*	SUS	C_2H_4-O_2	5	62	1.3	0.14
2	SUS	H_2-O_2	5	35	1.2	0.12
3	SUS	H_2-O_2	5	48	1.0	0.14
4	PMMA	H_2-O_2	5	37	1.8	1.0

* The conditions and results of shots 1 is from previous studies [14].

** Equivalence ratio

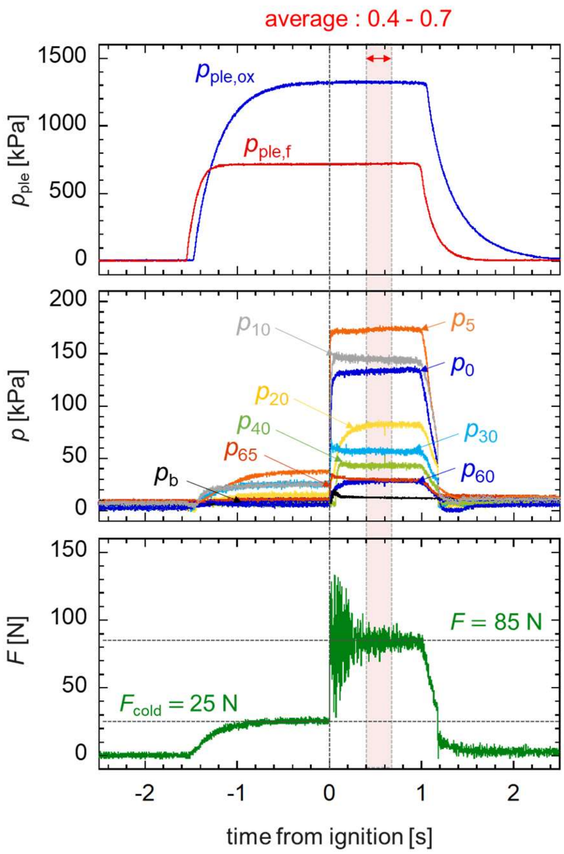

Fig 2 Time variation of presure and thrust of the RDE ($\dot{m}$ = 35 g/s, ϕ = 1.2)

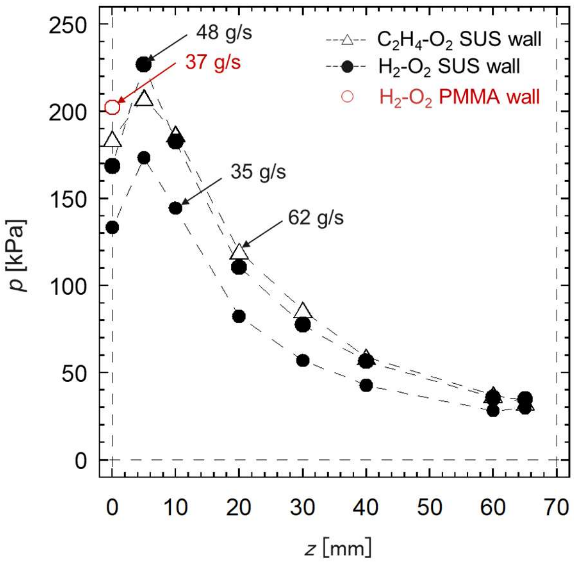

Fig 3 Time-averaged axial pressure distribution

3 Results and Discussion

Figure 2 contains time variations of measured pressure and thrust for shot 2 in which gaseous H_2-O_2 were used as the propellants. Steady ignition condition was achieved considering steady pressure value in the plenum before and after the ignition signal. Figure 3 shows time-averaged axial pressure distribution for all test cases. The maximum pressure ratio in the engine, which is p_{65}/p_5 for shots 1 and 3, and p_{60}/p_5 for shot 2, was below 0.17 for all test cases. These pressure ratios suggested that the flow was accelerated to supersonic speed [14]. In shot 2, shock waves were considered to be generated between $z = 60$ mm to $z = 65$ mm, resulting in pressure rise from p_{60} to p_{65}. Although, shot 2 and 4 were in the same mass flow range, pressure value at the injector surface in shot 4 was higher than that of shot 2. The exit condition was considered to be adjusted to the atmospheric condition resulting in the higher pressure in shot 4.

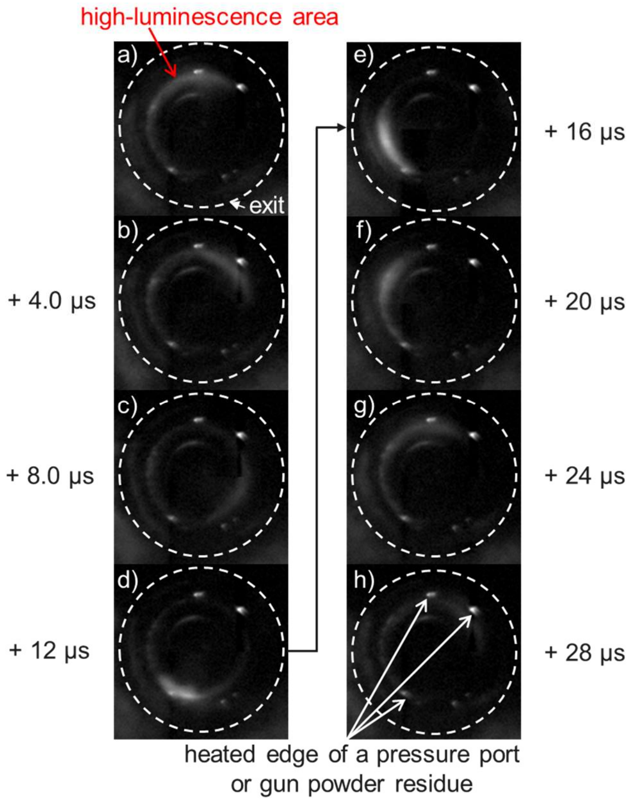

Fig 4 Propagating high-luimnescence area in the diverging RDE ($\dot{m} = 35$ g/s, $\phi = 1.2$)

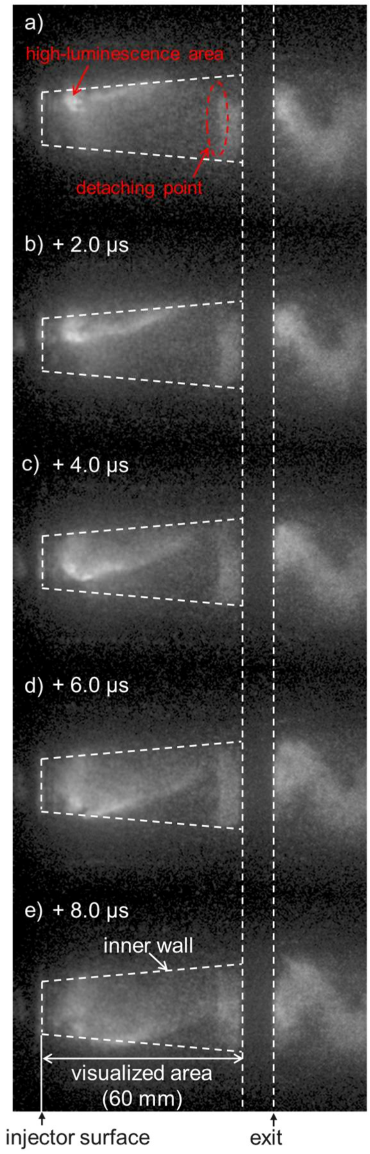

Fig 5 Side view of inner flow of the diverging RDE ($\dot{m} = 37$ g/s, $\phi = 1.8$)
***These images are flipped horizontally.**

Figure 4 presents typical axial images of self-luminescence in the RDE. In H_2-O_2 combustion tests, stable propagation of a high-luminescence area was observed under lower mass flow rate conditions ($\dot{m} \leq 48$ g/s) compared to C_2H_4-O_2 combustion tests. The velocity of the high-luminescence area ranged from approximately 1870–1900 m/s at d = 15 mm. The velocity was 62–67 % of the C-J detonation velocity calcurated by the NASA-CEA detonation mode [16] imputting the maximum pressure in the engine p_5, equivalance ratio ϕ, and room temperature as the initial condition. In C_2H_4-O_2 combustion tests, a high-luminescence area stably propagated when the mass flow rate was 105 g/s or more, and axial oscillation or occasional propagation were observed under lower mass flow rate condition ($\dot{m} < 105$ g/s) [14].

Side views of inner flow of the RDE in the combustion duration are shown in Fig. 5. The frame time and the exposure of the high-speed camera were 1.0 μs and 0.5 μs, respectively. A strong luminescence area, which was considered to be a detonation wave, propagated circumferentially near the injector surface. A relatively weak luminescence area, which was estimated to be an oblique shock wave, propagated downstream of the strong luminescence area, and the flow was detached from the inner wall before the end plate. Although, the detailed analysis of the inner flow structure of the RDE remains to be conducted, these results suggested that the diverging shaped RDE can be operated via gaseous H_2 and O_2 under lower mass flow rate condition compared to via gaseous C_2H_4 and O_2.

4 Conclusion

An RDE, which has a throatless and diverging channel with constat diverging angle $\alpha = 5$ deg, was utilized to investigate acceleration of the burned gas via heat addition. The inlet diameter and length of the RDE were 20 mm and 70 mm, respectively. Pressure and thrust measurement as well as high-speed imaging was conducted under low back-pressure or atmospheric conditions. Gaseous H_2 and O_2 were used as the propellants, and the results were compared with that of gaseous C_2H_4 and O_2. Pressure value in the engine suggested that the flow was supersonic at the exit via H_2-O_2 combustion. Based on the high-speed imaging from the axial direction and the side, the diverging shaped RDE using H_2-O_2 as the propellants can be stably operated under lower mass flow rate condition compared to that of C_2H_4-O_2.

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