Acceleration of Burned Gas to Supersonic in a Throat-less Rotating Detonation Engine

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1 Introduction

Increasing exhaust velocity is one of the essential thrust generation requirements in rocket propulsion system. A combustion wave in deflagration combustion, widely used in conventional chemical rocket engines, propagates at a subsonic speed, and some distance is required for the combustion to be completed. Because heat released by such combustion is distributed over a certain length, flow accelerated by the combustion cannot be choked thermally. Therefore, a converging section is required to achieve supersonic exhaust in a conventional rocket engine [1]. On the other hand, in detonation combustion, a shock wave leading to the combustion wave continuously triggers the combustion process. The supersonic combustion wave leads to instantaneous completion of the combustion [2-5] and, thus, to engine downsizing. Furthermore, the short combustion-completion distance and large heat released rate enable the flow of the burned gas to satisfy the choking condition even in a diverging channel without a structural throat [6]. Therefore, detonation combustion can realize a new type of compact and straightforward rocket engine.

The rotating detonation engine (RDE) is a widely studied pressure gain architecture. Several researchers studied the effects of change in combustor geometry and using nozzles to improve the performance of RDEs [7-9]. Hansmetzger et al. [7] conducted an experimental investigation of the relationship between combustor geometrical change and detonation rotation. Bach et al. [8] focused on the combustor geometry effects on the stagnation pressure, an indicator of an engine's performance. Rankin et al. [9] varied and tested the shape of a nozzle of an RDE. Although these studies implied that RDEs have the potential to be high-performance engines, the difficulty in cooling the inner cylinder composing the annular channel is an operational constraint. Additionally, the cylinder is a disadvantage

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in terms of weight reduction. Recently, several researchers investigated RDEs without an inner cylinder (cylindrical or hollow RDE) [10-13]. A numerical demonstration of the continuous propagation of detonation waves in a cylindrical combustor was conducted by Tang et al. [10]. Kawasaki et al. [11] varied the inner cylinder diameter to investigate the effect on the thrust performance of an RDE. Visualization and a flow model in Yokoo et al. [12,13] suggested short completion of detonation combustion in a small cylindrical RDE and sonic exhaust flow engines with a uniform cross-sectional area. These results indicate the feasibility of a new type, high-performance engine with detonation combustion.

Motivated by the combustion characteristics of the detonation and recent achievements of cylindrical RDEs, we focus on the acceleration process of burned gas within diverging channels. In a previous study, we proposed and demonstrated an inner-cylinder-less RDE whose channel has diverging conical shape (diverging angle $\alpha = 5$ deg). The exhaust flow was suggested to be supersonic with values up to Mach 1.7 [14]. In this study, RDEs with different channel diverging angles and lengths were tested, and the validity of the RDE flow model that includes the length of the combustion completion distance was investigated.

2 Experimental Setup

A schematic of the RDEs is shown in Fig. 1. The inlet diameter of the engine d_0 is 20 mm, and the channel length L is 35 or 70 mm. A diverging angle of the engine α is 5 or 10 deg from the inlet. The inlet-to-outlet area ratio $(\pi d_e^2/4)$ / $(\pi d_0^2/4)$ for the 70-mm type is 2.6 and 5.0 for the 5-deg and 10-deg type, respectively. There are 24 pairs of doublet injector holes arranged in a circle with respective diameters of 9 mm for oxidizer and 15 mm for fuel. Each of the holes has a diameter of 0.8 mm. The gaseous C_2H_4 and O_2 were used as the propellant. The pressure sensor ports are located on the injector surface ($z = 0$ mm, p_0) and the sidewall ($z = 5$, 10, 20, 30, 40, 60, 65 mm, p_5 to p_{65} for the 70-mm type, and $z = 5$, 10, 20, 30 mm, p_5 to p_{30} for the 35-mm type) of the engines. All pressure sensors are 1kHz-sampling pressure transducers (KELLAR Piezoresistive Pressure Transmitter: PAA-23). Gunpowder ignitors were utilized for the firing and added to the engine via an ignitor port at $z = 10$ or 63 mm for the 70-mm type, and the exit for the 35-mm type.

Combustion tests were conducted in a vacuum chamber with a volume of 30 m^3. The back pressure p_b was set to be 16 to 33 kPa during the tests. The RDE was set on a thrust stand inside the vacuum chamber. 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 using known weights in advance. A color camera (GoPro Hero9) was put inside the vacuum chamber to capture the exhaust plume. The combustion duration was set to be 0.5 or1.0 s. The experimental conditions are summarized in Table 1.

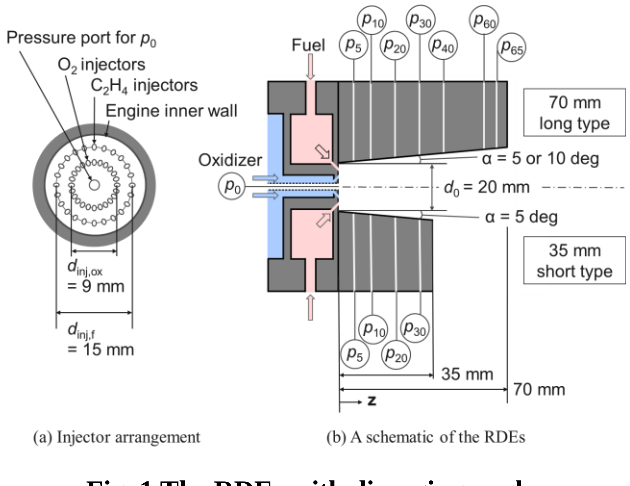

Fig. 1 The RDEs with diverging angle
(a) Injector arrangement; (b) A schematic of the RDEs

Table 1 Experimental conditions

No.	L [mm]	α [deg]	$\dot{m}$ [g/s]	ϕ^{**} [-]	p_b [kPa]
1*	70	5	72	1.5	17
2*	70		134	1.4	16
3	35		68	1.5	16
4	35		131	1.4	20
5	70	10	125	1.0	33
6	70	10	145	1.1	22

* The conditions and results of shots 1 and 2 are from a previous study [14].
** Equivalence ratio

3 Results and Discussion

Figure 2 presents a typical variation of pressure and thrust. The injection condition was considered not to be changed before and after the ignition because the pressure values in the plenum were steady just before and during the combustion duration. Under the smaller mass flow rate conditions for the 5-deg type (shots 1 and 3) and both of the 10-deg type tests (shots 5 and 6), circumferential propagation of the high-luminescence area was occasionally observed. The other tests observed the stable propagation of the high-luminescence area at approximately 1150 m/s (shots 2 and 4). Figure 3 shows time-averaged axial pressure distribution for all test cases. In all combustion tests, the maximum pressure value was p_5, and then the pressure was decreased according to the axial position. The pressure ratio between the maximum pressure in the engine p_5 and the pressure in the vicinity of the exit p_{65} was

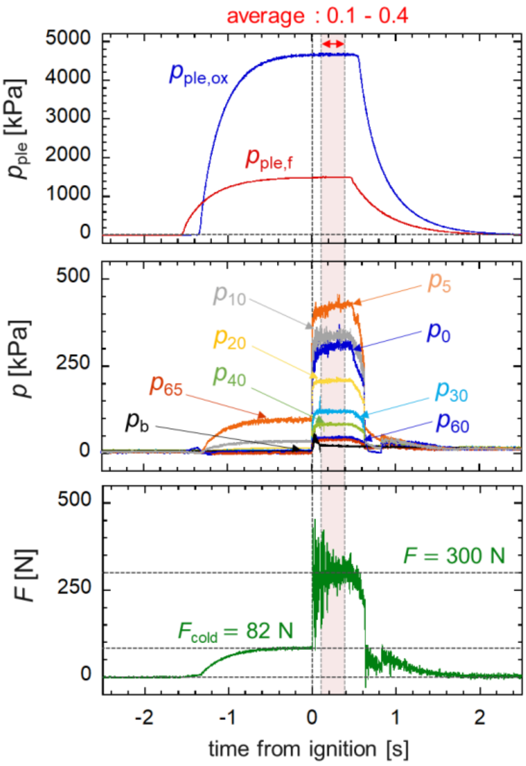

Fig. 3 Time variation of pressure and thrust of the RDE (L = 70 mm, α = 10 deg, $\dot{m}$ = 145 g/s, ϕ = 1.1, p_b = 22 kPa)

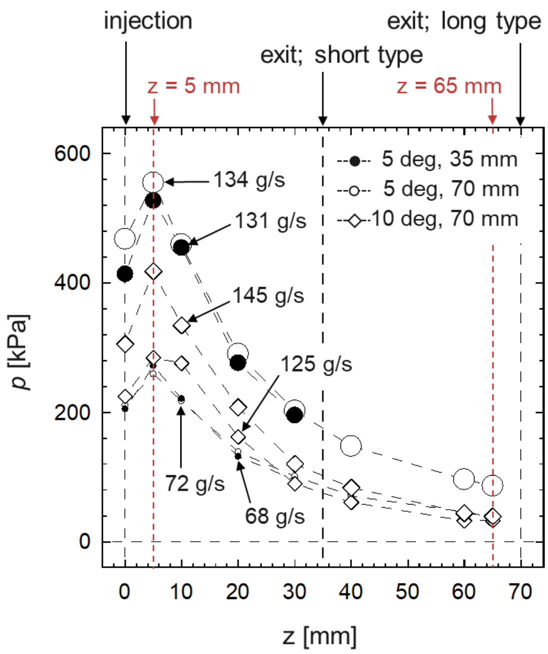

Fig. 2 Time-averaged pressure distribution

approximately 0.16 for the 5-deg diverging and 70-mm channel type. The ratio was 0.09 or 0.11 for the 10-deg type.

The Mach number at the exit of the engine can be estimated by the measured pressure and the geometric parameter of the channel. Based on the self-luminescence observation in the previous study [14], the main part of the combustion was suggested to be completed in the region near the injector surface. Thus, the effect of the chemical reaction on the flow in the vicinity of the exit was limited, and the flow in the region can be treated as an isentropic flow. When the measured pressure value and the cross-sectional area at $z = 60$, 65 mm were used, the Mach number of the flow at these positions, M_{60} and M_{65} respectively, can be calculated by Eq. (1) and Eq. (2) assuming a calorically perfect gas flow.

$$\frac{p_{65}}{p_{60}} = \left[\frac{(\gamma-1)M_{60}^2+2}{(\gamma-1)M_{65}^2+2}\right]^{\frac{\gamma}{\gamma-1}} \tag{1}$$

$$\frac{A_{65}}{A_{60}} = \frac{M_{60}}{M_{65}}\left[\frac{(\gamma-1)M_{65}^2+2}{(\gamma-1)M_{60}^2+2}\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{2}$$

From the assumptions above, the maximum Mach number $M_{\mathrm{e,P}}(\approx M_{65})$ in the 5-deg type and 10-deg type was 1.7 and 2.0, respectively. The specific heat ratio for the Eqs. (1) and (2) were calculated by the NASA-CEA detonation mode [15], with as input the pressure p_5, which was the maximum value in the engine, equivalence ratio ϕ, and temperature of the room in the experiments as the initial condition. Note that the Mach number $M_{\mathrm{e,P}}$ was calculated using the properties at $z = 60$ and 65 for the 70-mm type engine except for shot 5. The Mach number $M_{\mathrm{e,P}}$ for shot five was based on the property at $z = 40$ and 60 mm, i.e., the maximum Mach number was at $z = 60$ mm because of the pressure rise from p_{60} to p_{65} due to the higher back pressure comparing the pressure near the exit. The experiment's time-averaged axial pressure distribution was compared to the calculation from the quasi-one-dimensional (quasi-1-D) steady flow model suggested in the previous study [14] in Fig. 4. Considering the amount of the heat released from the combustion was not so different depending on the diverging angle, a larger exit Mach number from the 10 deg diverging channel suggested that a diverging angle has a small effect on the length of the heat release region in the range from 5 to 10 deg.

Based on the quasi-1-D steady flow model, the axial position of the choking point in the 5 deg type engine was suggested to range in $z = 28$–37 mm depending on the experimental conditions [14]. In addition, the ratio between the maximum pressure and the pressure at the sonic point was approximately 0.4. To check the validity of the flow model, the engine length was shortened and tested. Axial pressure distributions of the 70-mm type engine and 35-mm type engine have the same tendency (see Fig. 3), and the pressure ratio $p_{30}\ /\ p_5$ ranged from approximately 0.35 to 0.39 for all test cases. The results suggested the inner flow of the RDE did not change when the engine was shortened, and the flow was accelerated to sonic speed within 35 mm. A Mach number estimation was also conducted via semiempirical formulas by Love et al. [16] using the shock cell length. When the pressure ratio $p_{\mathrm{e}}\ /\ p_{\mathrm{b}}$ is more than approximately 2, the formula is described as follows:

$$\begin{aligned}\frac{l_1}{d_{\mathrm{e}}} = 1.52\left(\frac{p_{\mathrm{e}}}{p_{\mathrm{b}}}\right)^{0.437} + 1.55\left(\sqrt{2M_{\mathrm{e,E}}^2-1}-1\right) - 0.55\sqrt{M_{\mathrm{e,E}}^2-1} \\ +0.5\left[\frac{1}{1.55}\sqrt{\left(\frac{p_{\mathrm{e}}}{p_{\mathrm{b}}}-2\right)\sqrt{M_{\mathrm{e,E}}^2-1}}-1\right]\end{aligned} \tag{3}$$

Although, the formula was made for the flow from the nozzle whose diverging angle at the exit was 0 deg, we consider the angle does not have significant effects on the length of the first cell of the shock-train when the diverging angle at the exit is small. When the p_{30} was assumed to be p_{e}, the Mach number based on the length of the shock train $M_{\mathrm{e,E}}$ was approximately 1.1 for both shots three and four. The Mach number estimation via semiempirical formulas was used for the shorter type, because the flow in the vicinity of the 35 mm was considered to be affected by the chemical reaction of the combustion. The pressure ratio p_{30} / p_5 and the Mach number estimation coherently indicated that the quasi-1-D model could reasonably describe the inner flow of the 5-deg type RDE. The summary of the estimated Mach numbers based on the measured pressure ratio and the cross-sectional area $M_{\mathrm{e,P}}$, and based on the exhaust plume $M_{\mathrm{e,E}}$ is shown in Fig. 5.

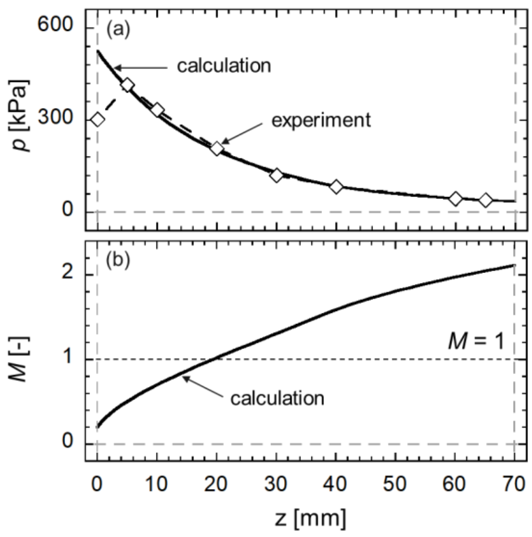

Fig. 4 Time-averaged axial distribution of (a) pressure; and (b) Mach number for a 10 deg diverging RDE ($L = 70$ mm, $\alpha = 10$ deg, $\dot{m}$ = 145 g/s, ϕ = 1.1, p_{b} = 22 kPa)

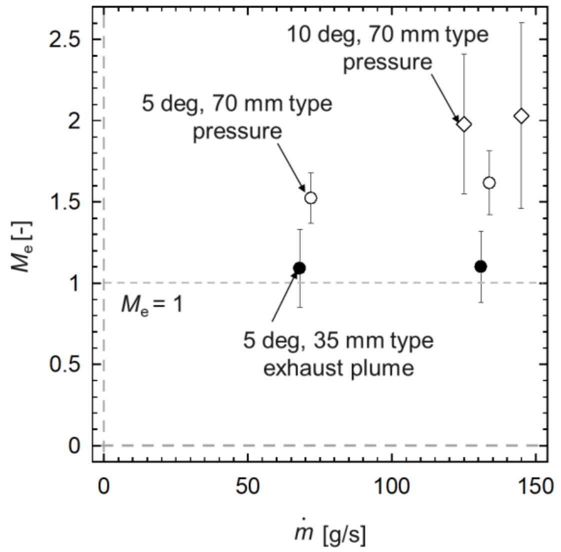

Fig. 5 Mach number estimated by the different proposed methods

4 Conclusion

Acceleration of the subsonic gas without converging section via heat addition was focused on and demonstrated in this study. Detonation combustion with a short combustion completion distance was applied to investigate the possibility of acceleration. An RDE with an inlet diameter of 20 mm, an axial length of 70 or 35 mm, and a constant diverging angle of 5 or 10 deg was designed and tested. In addition to the pressure and thrust measurement, normal-speed imaging for the exhaust plume was conducted. The results suggested that the exhaust flow of the RDEs was supersonic, with exit Mach numbers up to 1.7 for a 5-deg type and 2.0 for a 10-deg type when the engine length was 70 mm. The speed of the exhaust flow of the shorter type, in which the engine length was 35 mm, was estimated to be above Mach 1. This result indicates the validity of the quasi-1-D flow model presented in the previous study [14]. Furthermore, the supersonic exhaust with a larger Mach number from a 10-deg type compared to the 5-deg type suggested that the diverging angle of the channel has a limited effect on the length of the heat release region in the range from 5 to 10 deg.

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