Study of a Rotating Detonation Torch for Scramjet Engines

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1 Introduction

Today, there is a gap between the operation range of scramjet engines and turbo ramjet engines[1,2]. Therefore, it is necessary to extend the operation range of scramjet engines from the hypersonic regime to Mach 3−4 for developing aircraft capable of accelerating from takeoff to beyond Mach 5. As the flight Mach number is reduced, the total temperature of the airflow entering decreases, and ignition and flameholding become more challenging[3]. Hence, improving the performance of igniters is needed.

To address this challenge, we focused on a cylindrical Rotating Detonation Combustor (RDC). The cylindrical RDC is a combustor in which detonation waves propagate along the inner wall. Detonation waves are combustion waves coupled with shock waves that propagate at supersonic speed. In this study, the RDC was named "Rotating Detonation Torch (RD Torch)." The RD torch is expected to promote mixing and ignition in scramjet engines with shock waves and circumferential momentum of the exhaust. However, the mass flow rate of the exhaust from the igniter in the previous study[4] was about a quarter of the minimum mass flow rate of the cylindrical RDC[5] with C_2H_4-O_2 mixture.

The objectives of this study are to confirm the propagation of detonation waves at low mass flow rates and to clarify the characteristics of the RD torch under supersonic flow. We have already reported the propagation of detonation waves under low back pressure (operation in detonation mode)[6,7]. In this paper, we discuss the results of the combustion experiments in a scramjet model combustor.

2 Experimental Setup

The experiments in this paper were conducted at the direct-connected supersonic combustion wind tunnel test facility of the Institute of Fluid Science in Tohoku University[8,9]. Table 1 shows the conditions and results, and Figure 1 presents the sequence of each experiment. In Table 1, f_{vib}, t_{comb}, $\dot{m}_{det}$, Φ_{det}, ε, p_c, $\dot{m}_{MF}$ and $T_{t,MS}$ denote the propagation frequency, the duration of combustion, the

mass flow rate of the exhaust gas from the torch, the equivalence ratio in the torch, the convergence ratio and the combustion pressure in the torch, the mass flow rate of the main fuel (H_2) and the total temperature of mainstream, respectively. Based on the values of p_{ox}, p_f and p_5, it can be said that the injector holes experienced a choked flow. Therefore, the mass flow rate through injector holes $\dot{m}_{inj}$ was calculated with eq. 1[10]. The flow coefficient $C_{d,inj}$ was 0.7536 for the oxidizer and 0.7595 for the fuel.

$$\dot{m}_{inj} = C_{d,inj} \times \frac{A_t p_{ple}}{\sqrt{RT_{ple}}} \sqrt{\gamma \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}}} \tag{eq. 1}$$

A_t is the total injector cross-sectional area, p_{ple} is the pressure in each plenum, R is the gas constant, γ is the specific heat ratio, and T_{ple} is the propellant temperature (room temperature). p_{ple} was the average plenum pressure during the stable period of p_5. The total temperature, the total pressure, the mass flow rate and Mach number[8] of mainstream were 641−719 K, 0.6 MPa, 680 g/s at 689 K ($T_{t,MS}$) and 2.8, respectively. The global equivalence ratio were 0.128±0.02 ($\dot{m}_{MF} = 2.5$ g/s) and 0.056 ($\dot{m}_{MF} = 1.1$ g/s).

Table 1: Experimental conditions and results
*Data from the captured video of the logger screen/ **Flameholding during the torch was working

No.	combustion mode	Ignition Flameholding	f_{vib} [kHz]	t_{comb} [s]	$\dot{m}_{det}$ [g/s]	Φ_{det}	ε	p_c (p_5) [kPa]	$\dot{m}_{MF}$ [g/s]	$T_{t,MS}$ [K]	
1	Detonation	-	65	5.0	4.12±0.02	1.05±0.01	1.0	99±5	-	706	
2	Detonation	-	66	5.5	4.04±0.02	1.16±0.01	1.0	100±5	-	696	
3	Detonation	-	66	5.5	3.83±0.02	1.21±0.01	1.0	97±5	-	679	
4	Detonation	-	66	9.0	3.84±0.02	1.21±0.01	1.0	97±5	-	679*	Torch + Supersonic flow
5	Detonation	-	65	5.0	4.24±0.02	1.08±0.01	1.0	104±5	-	706	
6	Detonation	-	66	5.0	4.17±0.02	1.09±0.01	1.0	102±5	-	701	
7	Detonation	-	66	5.5	3.90±0.02	1.14±0.01	1.0	97±5	-	650	
8	Detonation	-	66	5.5	3.98±0.02	1.17±0.01	1.0	100±5	-	672	
9	Detonation	-	66	5.5	4.01±0.02	1.17±0.01	1.0	100±5	-	641	
10	Detonation	Success Success**	66→68	5.5	3.94±0.02	1.16±0.01	1.0	115±6	2.51	677	
11	Detonation	Success Success**	66→68	6.0	4.00±0.02	1.18±0.01	1.0	115±6	2.52	719	Torch + Main fuel + Supersonic flow
12	Detonation	Success Success**	66→68	6.0	4.05±0.02	1.20±0.01	1.0	118±6	2.51	689	
13	Detonation	Success Success**	66	6.0	4.01±0.02	1.17±0.01	1.0	102±5	1.13	660	Torch + Main fuel + Supersonic flow (Extended torch fuel injection duration)
14	Detonation	Success Success**	66	6.0	4.01±0.02	1.17±0.01	1.0	102±5	1.13	659	

Figure 2(a) is a schematic diagram of the experimental setup. The RD torch was installed on the scramjet model combustor. The torch used ethylene (C_2H_4) as fuel and oxygen (O_2) as oxidizer, and both injector holes are at the bottom of the combustor in the torch. Moreover, the torch can purge nitrogen into the oxidizer plenum and the combustor in the torch through the oxidizer injector holes. The RD torch has an inner wall diameter of 10 mm and a length of 173 mm and a convergent nozzle at the exit. The convergence ratio can be changed. We measured pressure in the plenums of C_2H_4 and O_2: p_f and p_{ox}, pressure in the combustor: $p_5…p_{157}$, temperature of the walls (distance from the inner wall was 1 mm): $T_5…T_{157}$, vibration and flame chemiluminescence images taken radially. All pressure sensors were piezoresistive pressure transmitters (PAA-23SY, KELLER Druckmesstechnik AG), temperature sensors were type K sheathed thermocouples (T35101, SAKAGUCHI Electric Heaters), vibrometer was M353B18 (PCB Piezotronics, Inc.), the camera was DMC-FZ200 (Panasonic Corporation). For ignition, gunpowder was used, and it was placed at 54 mm along the axis from the injector face.

Figure 2(b) is a detailed view of the injector holes. Both 8 injector holes were equally spaced and located on φ6 mm and φ9 mm circumferences, respectively. C_2H_4 and O_2 collided at 90 degrees.
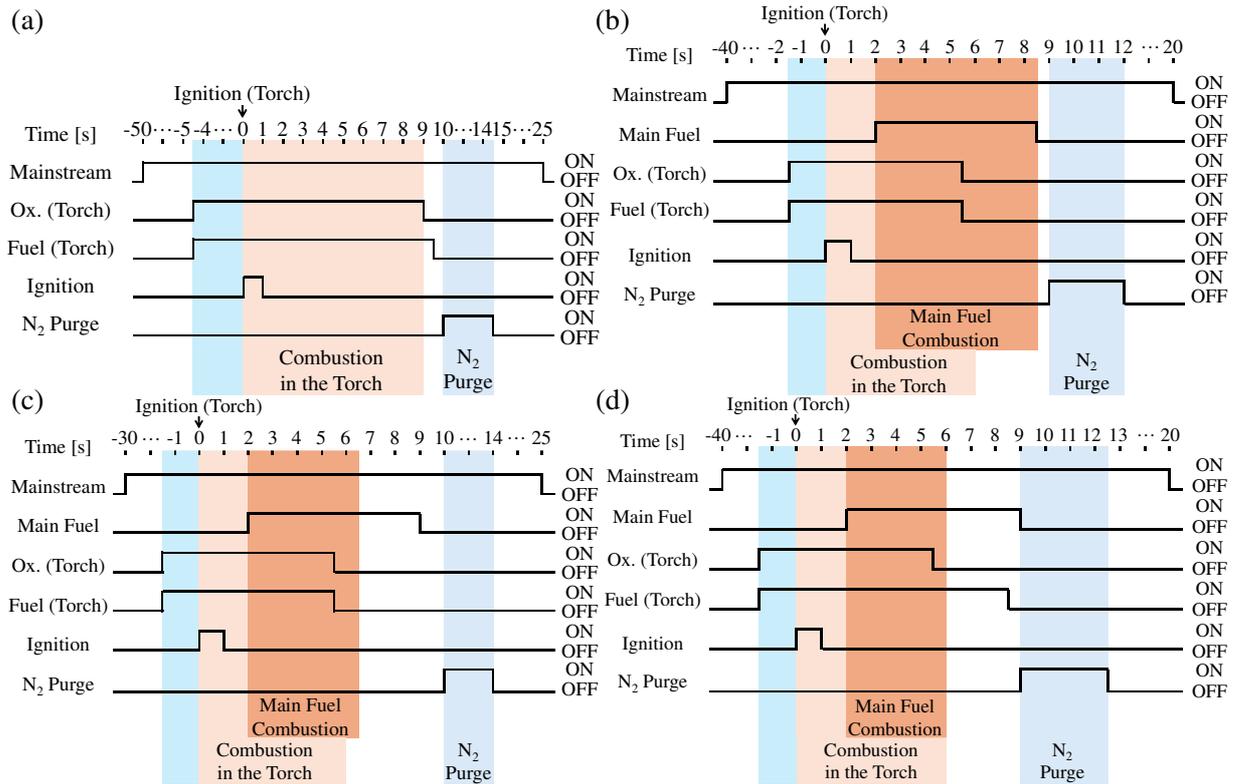
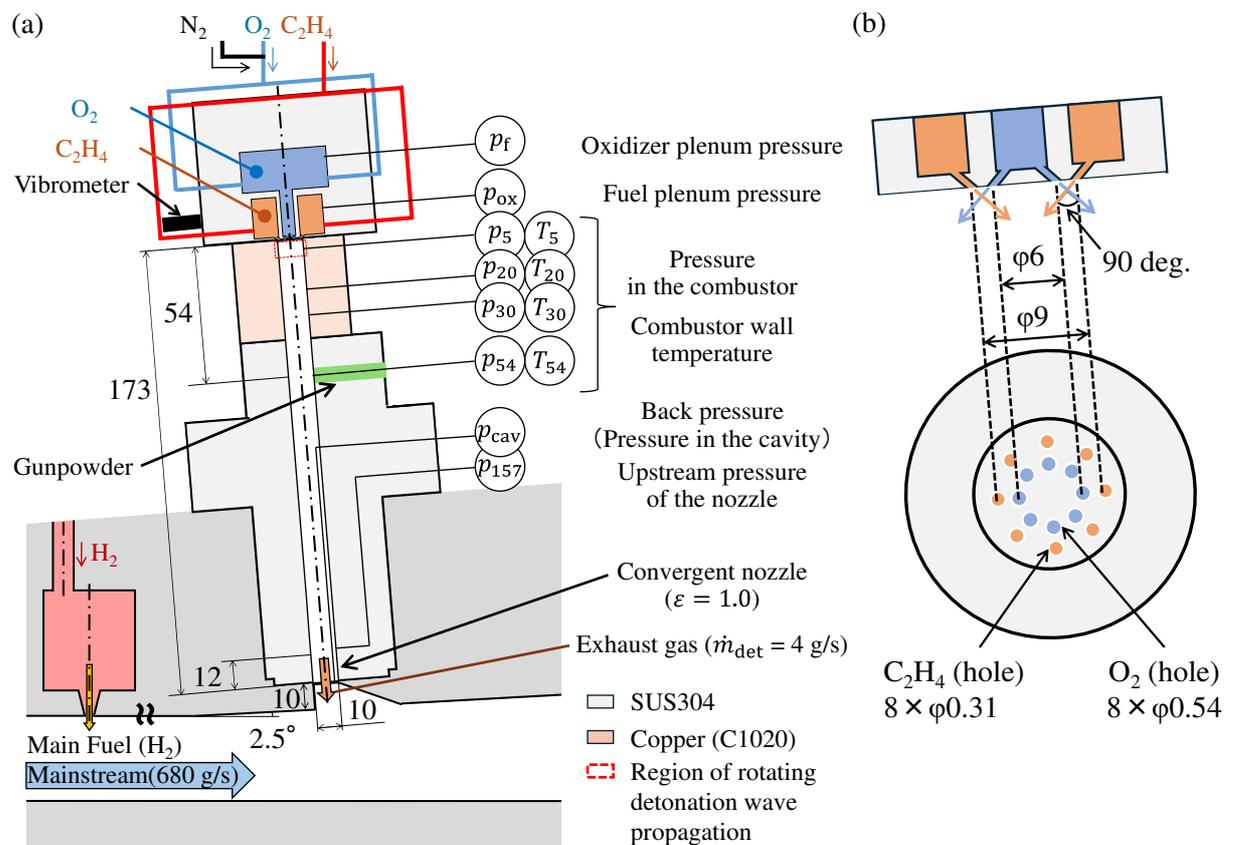Figure 1: The sequences of experiments. (a) Sh#4. (b) Sh#12. (c) Sh#13. (d) Sh#14.

Figure 2: The schematic view of the RD torch (Unit: [mm]). (a) vertical cross-sectional view including the scramjet model combustor. (b) detailed view of the injector holes in the torch.

3   Results and Discussions

Firstly, we will discuss the trends in all cases. As shown in Figure 3, the pressure histories in the torch indicate $p_5 > p_{20} > p_{30} > p_{54} > p_{157}$, and the RD torch did not experience abnormal combustion.
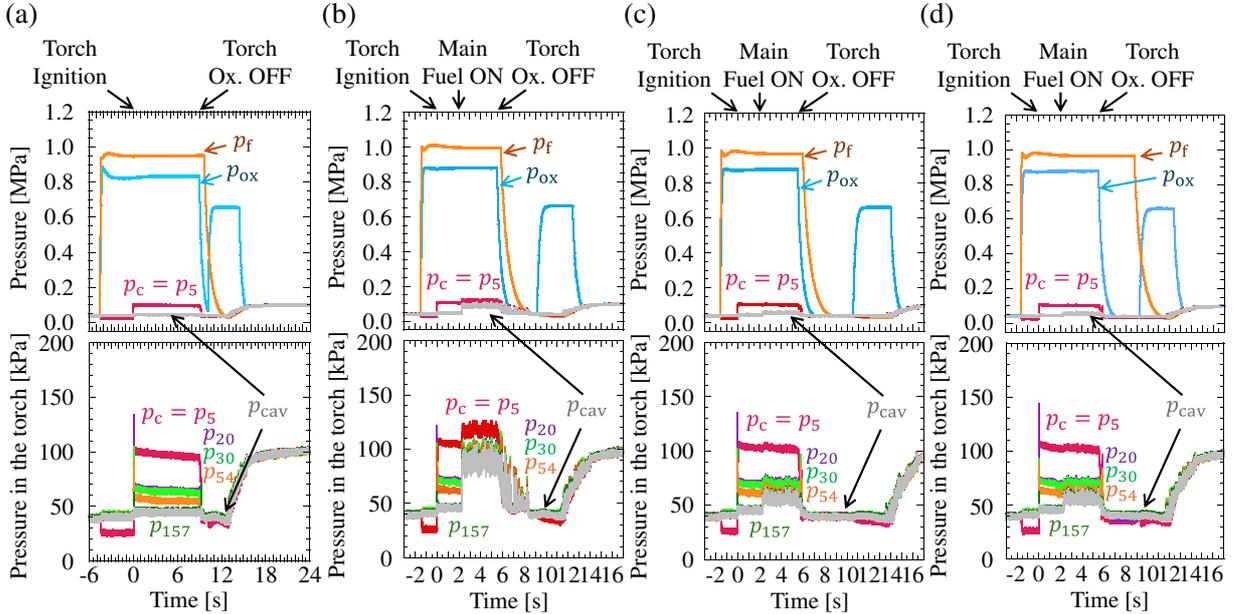

Figure 3: Pressure histories: (a) Sh#4. (b) Sh#12. (c) Sh#13. (d) Sh#14.

Secondly, we will focus on the case of "Torch + Supersonic flow." As seen in Figure 5(a), we found that the peak at 66 kHz is dominant in the Short-Time Fourier Transform (STFT) result. The frequency was almost same as that of our prior result[6], thus we concluded the torch operated in detonation mode for up to 9.0 seconds under supersonic flow.

Thirdly, we will delve into the case of "Torch + Main fuel + Supersonic flow." Figure 4 shows flame chemiluminescence images taken from the radial direction of the torch. We can see only a bluish white C_2H_4-O_2 flame in Figure 4(ii). Then, once the main fuel was injected, a white flame by main fuel combustion began to appear on the mainstream side, and it remained until the torch was turned off as you can see in Figure 4(iii)−4(viii). It means ignition and flameholding in the scramjet model combustor were achieved with the RD torch. This conclusion can be inferred from the increase in the combustion pressure in the torch as shown in Figure 3.
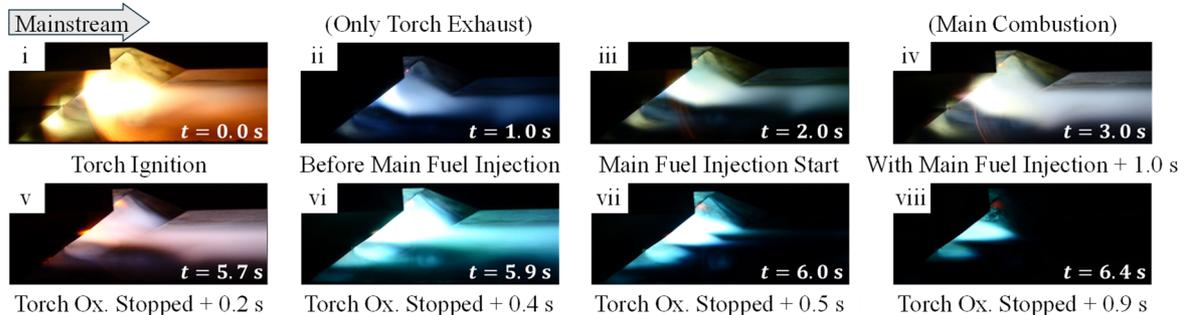

Figure 4: Images of the flame chemiluminescence in Sh#13 (all images were flipped horizontally).

Furthermore, the STFT results and our previous study[6] indicated that the RD torch worked in detonation mode even under supersonic flow and main fuel. When the mass flow rate of main fuel was 2.5 g/s, the peak at 66 kHz was outstanding before main fuel combustion, and that at 68 kHz was dominant during main fuel combustion as shown in Figure 5(b). We concluded these peaks were due to

the detonation waves in the torch, and the torch worked in detonation mode. With 1.1 g/s of the main fuel, a dominant peak appeared at 66 kHz in the STFT result (Figure 5(c)), indicating the torch worked in detonation mode. Considering the discussion on the flame chemiluminescence images, pressure histories and the STFT results, we achieved ignition of main fuel with the RD torch worked in detonation mode under supersonic flow. Flameholding was also successful; however, it finished about 0.5 seconds after the torch oxidizer was shut off. It coincided roughly with the moment when the torch stopped.
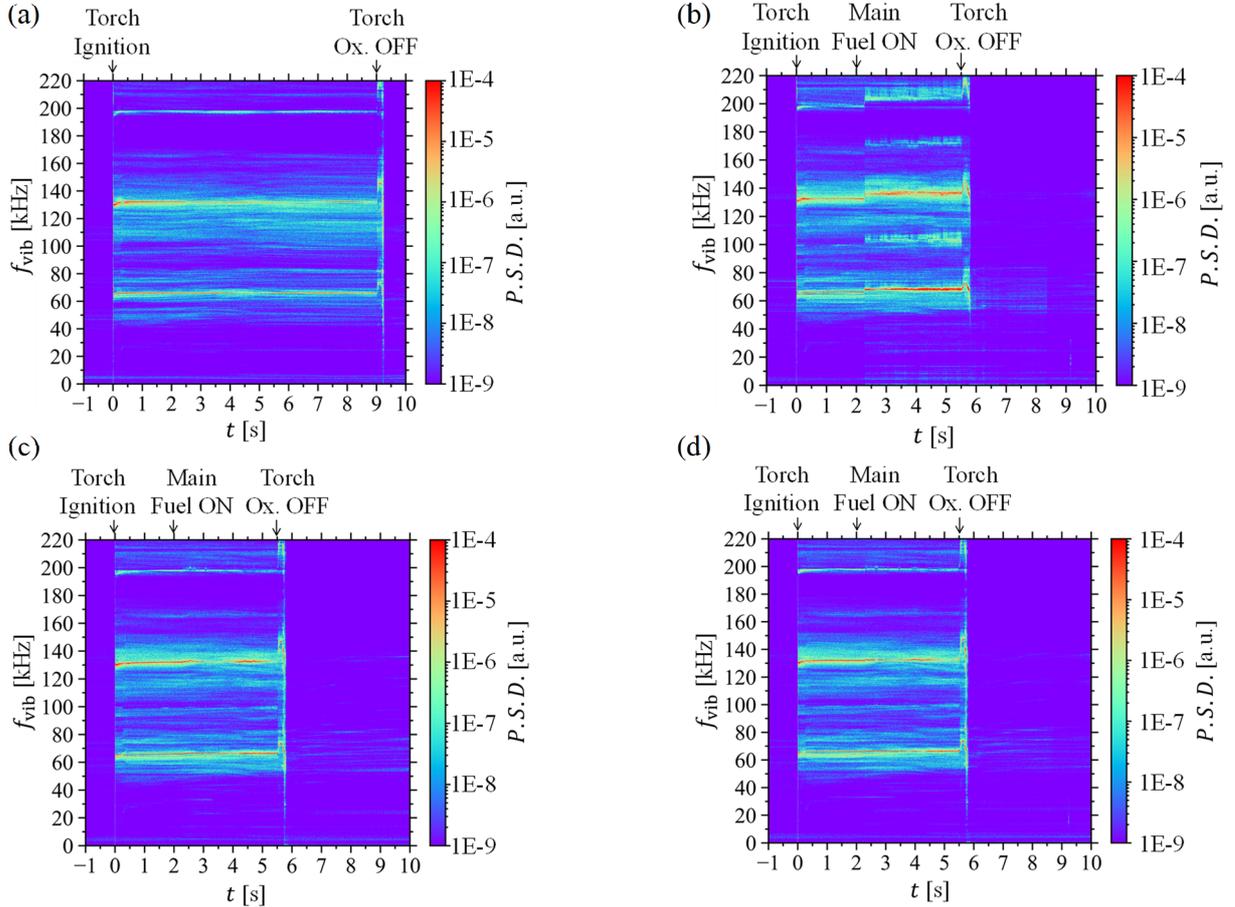

Figure 5: the STFT results of the vibration data: (a) Sh#4, (b) Sh#12, (c) Sh#13, (d) Sh#14 (Window function: Hann function, Segment length: (a) 2^{16}, (b)−(d) 2^{14})

Finally, we will dig into the case of "Torch + Main fuel + Supersonic flow (Extended torch fuel injection duration)." Even in this case, it can be said the detonation waves propagated at 66 kHz, and ignition of main fuel was successful from the STFT result (Figure 5(d)) and the prior result[6]. However, even though the duration of torch fuel injection was extended, flameholding and combustion in the torch ended about 0.5 seconds after the torch oxidizer was shut off.

Additionally, the pressure in the cavity and the combustion pressure in the torch were oscillated due to main fuel combustion; moreover, the amplitude increased with the mass flow rate of the main fuel. Although further investigation is necessary, these pressure oscillations are also important findings.

4 Conclusions

We conducted the combustion experiments of the RD torch under supersonic flow. The mass flow rate and equivalence ratio of the exhaust from the torch were 4.0 g/s and 1.15, respectively. The mass

flow rate of main fuel were 2.5 g/s (the global equivalence ratio was 0.128±0.02) and 1.1 g/s (the global equivalence ratio was 0.056). The total temperature, the total pressure and Mach number of mainstream were from 641 K to 719 K, 0.6 MPa and 2.8, respectively. Our conclusions are as follows.

1. The RD torch successfully operated in detonation mode for a maximum of 9.0 seconds under supersonic flow. The frequency were 66 kHz and 68 kHz, consistent with the previous results[6].

2. Ignition of main fuel (H_2) with the RD torch was achieved in supersonic flow. Regarding flameholding, the hydrogen flame was maintained during the torch operation.

3. During main fuel combustion, the combustion pressure in the torch and the detonation wave frequency went up, and pressure in the cavity and the combustion pressure in the torch oscillated. The higher the mass flow rate of the main fuel was, the larger the amplitude became.

Acknowledgement

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