Performance Evaluation of a Rotating Detonation Engine for Space use

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1 Introduction

An engine using detonation waves is called a detonation engine. It became clear that detonation cycle has higher thermal efficiency than Humphry cycle and Brayton cycle have by analysis of detonation cyle. From this, many researches on detonation engines have been conducted around the world. There are two kinds of detonation engines; one is a pulse detonation engine (PDE) [1,2], the other is a rotating detonation engine (RDE). A PDE has a straight tube combustor and generates pulsed thrust. Researches on a PDE combined with a turbine and a rocket system using PDE have been conducted. An RDE has an

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annular combustor and continuously generates thrust. Reserches on a propulsion system using an RDE [3-5] and the structure of detonation waves in the combustor [6] have been conducted. There are several problems to be solved prior to the practical use of an RDE though application of an RDE as a kick rocket motor is expected. One of the most critical problems is heat-trafer problem. It is reported that the combustor is subjected by strong heat load. It is estimated that heat flux at the combustor wall surface is approximately 1~10 MW/m^2 [7-9]. There are some researches to decrease the heat load at the combustor wall [10, 11]. The objecive is a practical use of an RDE as a kick rocket motor for deep-space exploration. Long-duration ground combsution tests in the atmosphere and vacuum tests in the low back pressure are presented.

2 Experimental apparatus

The RDE used in experiments is shown in Fig. 1. The combustor is annular type. The Details of the dimension of the combustor are reported in [12].

The RDE is mainly composed of copper. In the long-duration tests, the wall around combustion chamber is consisted of C/C composites which have a high heat-resistance. In the vacuum tests, the wall around the combustion chamber is composed of copper instead of C/C composites.

The fuel is gaseous ethylene and the oxidizer is gaseous oxygen. The fuel is injected into combustion chamber through the 120 pairs of injector holes. The injector holes of the oxidizer are also 120 sets. The fuel and the oxidizer collide at the right angle each other.

The temperature of the combustor is measured by k-type thermocouples. The placement of the thermocouples is shown in Fig. 2. The temperature is measured at distances of 1, 2 mm from the outer cylindrical wall. The thermocouples were installed in the cross sections at z=2, 9, 18, 35, 65 mm and nozzle throat (z=0 mm is the bottom of combustion chamber).

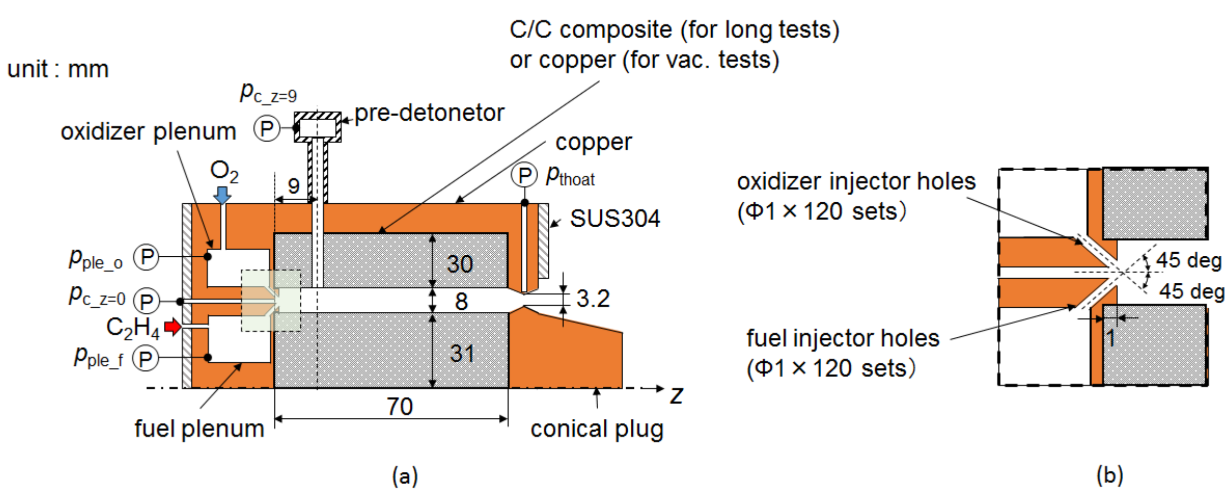


Fig. 1 (a) Schematic of the RDE, (b) Enlarged view around the injector

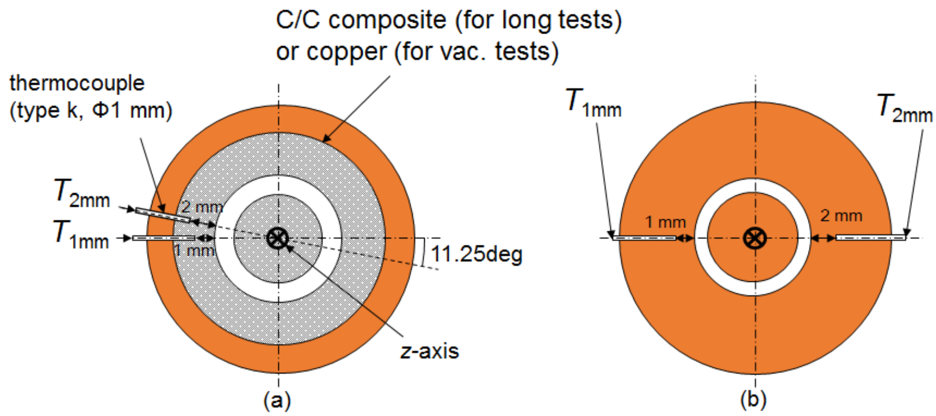


Fig. 2 Placement of the thermocouples, (a) cross sectional view at z=2, 9, 18, 35, 65 mm, (b) at the throat

The pre-detonator is used to initiate detonation. The detonation wave initiated on the pre-detonator propagates into the combustion chamber and ignites main propellant. Finally, the rotating detonation waves are generated and starts the RDE.

The vacuum tests are conducted in the vacuum chamber with a volume of 36.6 m^3. The long-duration tests are performed in the Aerospace Plane Research Center of Muroran Institute of Technology.

3 Experimental results

The vacuum tests are conducted in the vacuum chamber. The picture of the vacuum chamber is shown in Experimental conditions of vacuum tests are shown in Table 1. Experimental results of thrust and combustion pressure of sh#2_vac. are shown in Fig. 3. The operating duration is 0.3 s. Average thrust and average combustion pressure are 488 N and 0.396 MPa, respectively. The specific impulse is calculated as 250 s by average thrust and propellant mas flow rate. Visualized images of detonation waves propagating in the combustion chamber are shown in Fig. 4. Self-emission of detonation waves shot by high speed camera through the optical window are shown in Fig. 4 (a). It is confirmed that eight detonation waves propagate in the combustion chamber. Four of them propagate clockwise and the others are countercloclwise. Streak image obtained by self-emission images is shown in Fig. 4 (b). The horizontal axis represents the time from ignition and the vertical axis shows the circumferential angle. Detonation velocty estimated the streak image are approximately 1175 m/s.

Table 1 Experimental conditions of vacuum tests

shot number	propellant mass flow rate $\dot{m}$[g/s]	equivalence ratio Φ[-]	back pressure p_b [atm]
sh#1_vac.	191	1.28	0.6
sh#2_vac.	183	1.29	0.4

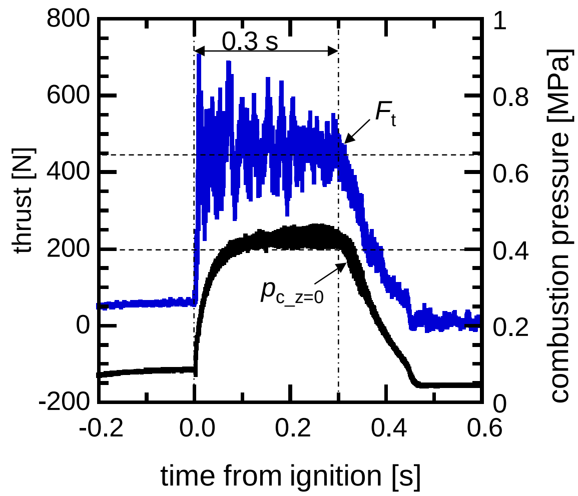


Fig. 3 Thrust and combustion pressure of sh#2_vac.

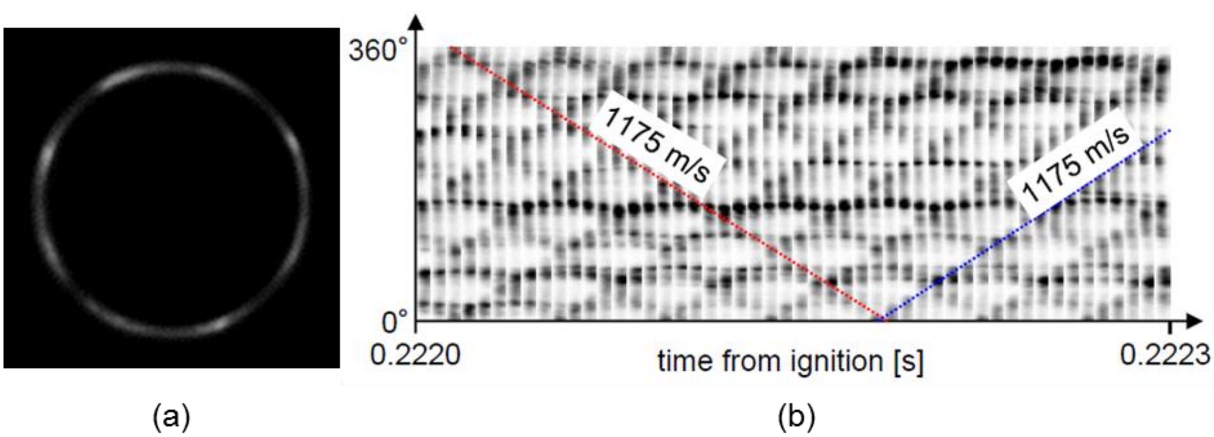
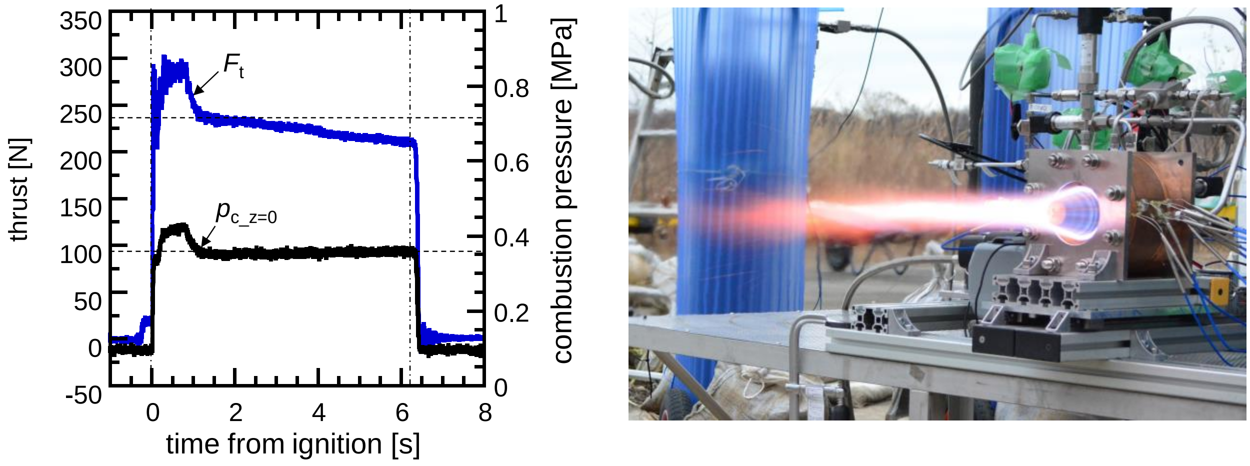


Fig. 4 Visualized images (a) self-emission of detonation waves
(b) streak image and detonation velocity

Experimental conditions of long-duration tests are shown in Table 2. Experimental results of thrust, combustion pressure at z=0 mm of sh#2_long are shown in Fig. 5. Average values of F_t and $p_{c\_z=0}$ were 231 N and 0.359 MPa, respectively.

Table 2 Experimental conditions of long-duration tests

shot number	propellant mass flow rate $\dot{m}$[g/s]	equivalence ratio Φ[-]	operation duration t_{ope}[s]
sh#1_long	96	1.63	10.2
sh#2_long	214	0.90	6.3



(a) (b)

Fig. 5 Experimental results (a) thrust and combustion pressure (b) a picture during combustion test

According to T_{1mm} and T_{2mm} obtained by the tests, heat flux in the outer cylindrical wall is estimated by following equation:

$$\dot{q} = \lambda \frac{\Delta T}{\Delta r} = \lambda \frac{T_{1mm} - T_{2mm}}{0.001} \ [\mathrm{W/m^2}] \tag{1}$$

Here, λ is thermal conductivity. The values of λ are 386 W/mK of copper and 35 W/mK of C/C composites. In this calculation, we assume that the value of λ is constant. The maxumum heat flux in the combustion chamber during the operating duration are shown in Fig. 6.

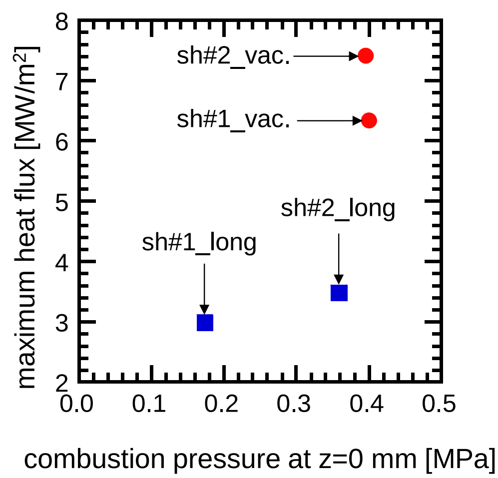


Fig. 6 Influence of the combustion pressure on heat flux

In cases of the long tests, large heat flows into the copper combustor and its temperature rises excessibly high. Thus, C/C composites are used as the combustor to resist high temperature. It is can be seen from comparison between sh#1_long and sh#2_long, heat flux has almost linear dependence on combution pressure. The combusstion pressure has a greater impact rather than equivalence ratio on heat flux.

4 Conclusions

We succeeded in 10-second and 6-second ground tests and vacuum tests of an RDE using C_2H_4-O_2. Under the back pressure of 0.4 atm, we achieved the specific impulse of 250 s. From long-duration tests, heat flux is estimated and it is confirmed that C/C composites effectively work as heat insulating material.

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