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Experimental Study of Propulsion Performance by Single Pulse Rotating Detonation with Gaseous Fuels-oxygen Mixtures

Kazuhiko Toshimitsu[*1], Kosei Hara[*2], Shuuto Mikajiri[*2], Naoki Takiguchi[*2], Ryo Takahashi[*3], Wakaba Uno[*4] and Shouhei Kawano[*5]

[*1] Fukuoka Institute of Technology,

[*2]Advanced Course of Oita National College of Technology,

[*3]Graduate school of Kyushu Institute of Technology,

[*4]Hitachi Construction Machinery Co., Ltd. and [*5]Toray Industries Inc.

JAPAN

[*1]E-mail: toshimitsu@fit.ac.jp

Abstract

A rotating detonation engine is one of candidates of aerospace engines for supersonic cruse, which is better for propulsion system than a pulse detonation engine from the view of continuous thrust. In addition, it can be simple structure than a jet engine. The propulsion performance of the proto-type rotating detonation engine by single pulse explosion with methane-oxygen and acetylene-oxygen gas mixtures is investigated. Its impulse is estimated through ballistic pendulum method with maximum displacement and damping ratio. The comparison of specific impulses of the mixture gases at atmospheric pressure is shown. The specific impulses of the rotating detonation engine and a pulse detonation engine are almost same with methane-oxygen. Furthermore, the fuel-base specific impulse of acetylene-oxygen gas mixture is about 2 times as large as one of methane-oxygen, and its maximum specific impulse is 1100 seconds. In addition, the combustion state of the rotating detonation engine with methane-oxygen and acetylene-oxygen gas mixtures is shown.

Keywords: Rotating detonation engine, Propulsion, Specific impulse, Gaseous fuel, Rocket, Pulse detonation

1. Introduction

A detonation propulsion device for supersonic and hypersonic flight is studied in aeronautics and astronautics. Recently, a Rotating Detonation Engine (RDE) is developed by many researchers. This is because it has advantages of thermal efficiency, simple design and continuous thrust. Figure1 shows the rotating detonation diagram of the RDE [1, 2].

All detonation engines are divided into three groups. For example, it is reviewed by Wolanski [2]. The first one is called the Standing Detonation Engine [3], which detonation wave is stabilized inside the engine. However it is very limited range of operation conditions of Mach number and injection velocity of gas mixture.

The second group of detonation engines is called the Pulse Detonation Engine (PDE). Its design is very simple and it can operate in wide range of condition for flight Mach number is from 0 to 5, however its thrust changes during the operation cycle for tens periodic frequency [4], [5].

The third group of detonation engines is called the RDE (also known as the Continuous Detonation Wave Engine). The RDE can operate for any flight velocity for very high frequency repetition (thousands of cycles per second depending on the mixture and geometry of the engine), so that it generates a stable thrust. Furthermore, its length of combustion chamber can be shorter than the PDE, because the combustion zone is shorter than that in the deflagration mode, and does not need a mixing with secondary air flow [1], [6].

The present study is basic research of the RDE. We investigate the propulsion performance of a proto-type RDE by single pulse explosion with methane-oxygen and acetylene-oxygen gas mixtures through ballistic pendulum method.

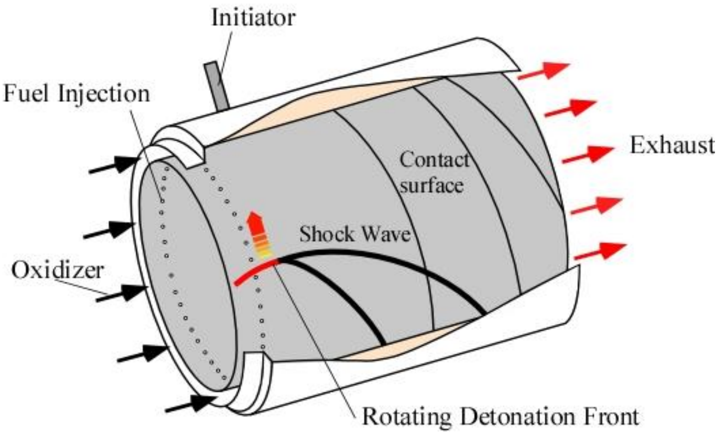

Fig. 1: Rotating detonation diagram [1, 2].

2. Experimental Apparatus

2.1 Rotating detonation engine

Figure 2 and 3 illustrate a schematic diagram and photograph of the RDE. The suspended mass and total length are 29.82 kg and 218mm respectively. The radial gap of annular chamber with channel expansion for combustion varies from 5mm to 27.4mm. The combustion volume of the RDE is 6.69×10^{-4} m^3.

2.2 Ballistic pendulum method

The RDE is suspended by two stainless wires of diameter 1mm, and is made free oscillation by impulsive single pulse detonation. Its impulse I can be calculated by Eq. (1) which is proposed by Yatsufusa, et al. [7] based on the ballistic pendulum method.

$$I = m \cdot x \cdot e^{\frac{\pi}{2}\varsigma} \cdot \frac{2\pi}{T} \quad (1)$$

Here, m, x, ς and T denote the suspended mass [kg], the maximum displacement from the neutral position [m], the damping coefficient and the oscillation period [s], respectively.

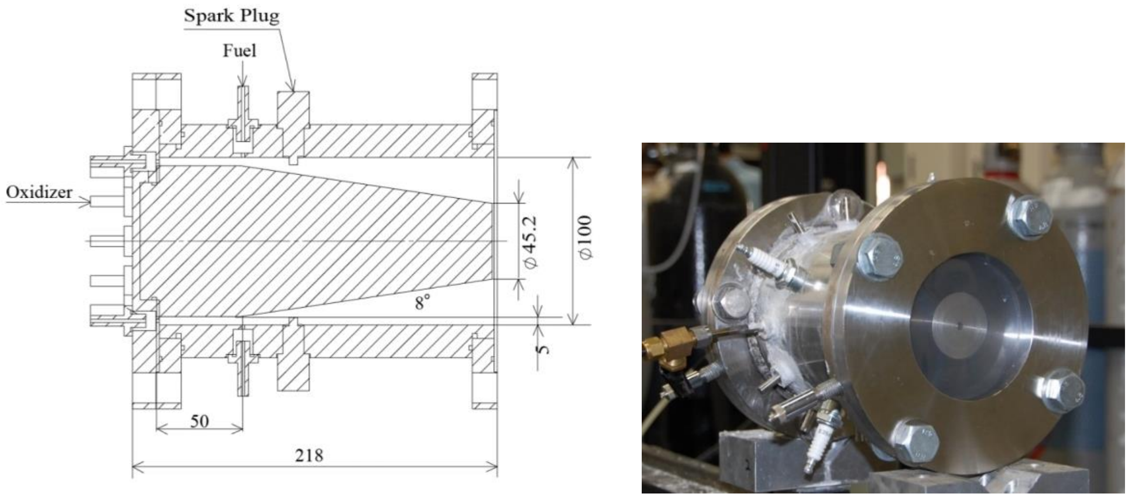

Fig. 2: Schematic figure and photograph of the rotating detonation engine.

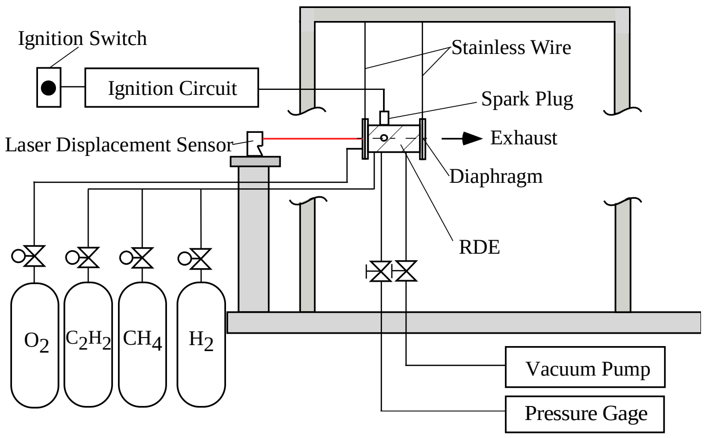

Fig. 3: Experimental apparatus to measure impulse by single pulse detonation through the ballistic pendulum method.

3. Experiment

Fuel and oxidizer gases are filled separately in the RDE, and pressure of mixture gas is set at atmospheric pressure.

3.1 Combustion State

Figure 4 shows the example pictures of circumferential propagating flame with CH_4-O_2 and C_2H_2-O_2 gas mixtures at equivalence ratio is 1.0, which are recorded by 16000 fps with a high speed video camera. As the results, the circumferential propagation velocity of flame with CH_4-O_2 and C_2H_2-O_2 are about 335m/s and 1885m/s respectively. Here, the C-J velocities of CH_4-O_2 and C_2H_2-O_2 are 2435m/s and

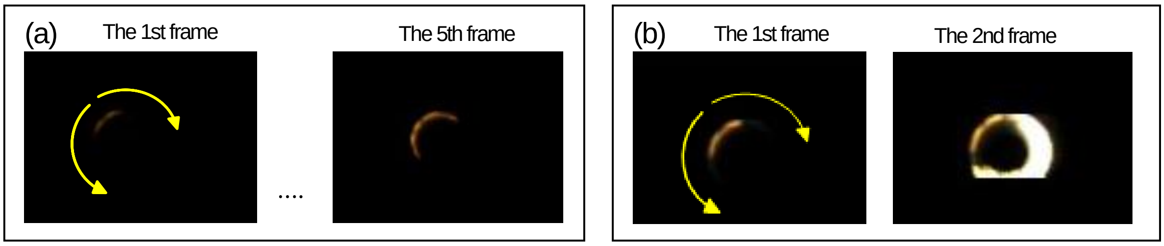

Fig. 4: Comparison of circumferential flame propagation; (a) CH_4-O_2 with 5 frames; (b) C_2H_2-O_2 with continuous frame.

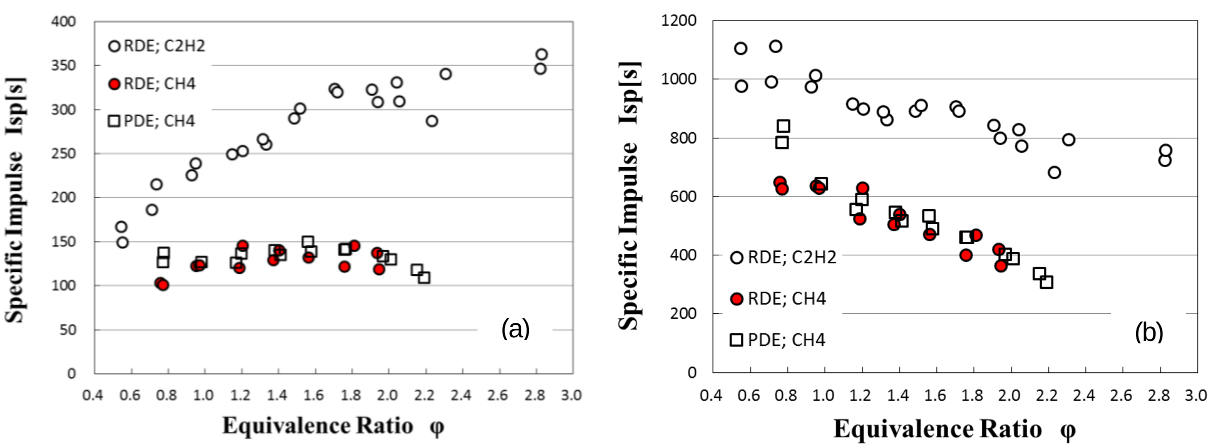

Fig. 5: Comparison of specfic impulses I_{SP} of single pulse rotating detonation and pulse detonation with methane-oxygen and acetylene-oxygen gas mixtures with atmospheric gas pressure; (a) mixtgure-base; (b) fuel-base.

2424m/s respectively, and C_2H_2-O_2 combustion is 5.8 times faster than CH_4-O_2. Thus we presume that CH_4-O_2 and C_2H_2-O_2 combustions are DDT and DT states respectively.

3.2 Specific impulse

The specific impulse I_{SP} is defined by Eq. (2). It represents the continuous time which thrust 1N can be maintained by the propellant mass $m = 1$kg.

$$I_{SP} = \frac{F_t}{\dot{m}g} = \frac{I}{mg} \tag{2}$$

Here, F_t, I and m mean thrust, impulse, propellant mass. We should mention that the propellant mass m is defined as fuel and Oxidizer for rocket and only fuel for air-breathing engine. The former and latter I_{SP} are called as “mixture-base” and “fuel-base” specific impulses respectively.

Figure 5 (a) and (b) show the mixture-base and fuel-base specific impulses with varying equivalence ratio φ of CH_4-O_2 and C_2H_2-O_2 gas mixtures for RDE, respectively. In addition, we also show the specific impulse of the pulse detonation engine with CH_4-O_2 gas mixture [8] to compare between the RDE and PDE. Here, the total length, inner diameter and tube thickness of the PDE are 1000mm, 30mm 10mm, respectively, and its suspended mass and combustion space are 23.42 kg and 7.07×10^{-4} m^3 respectively. Here, we should mention that the combustion space of the RDE is as almost same as one of the PDE.

The mixture-base I_{SP} of CH_4-O_2 is almost constant with varying φ for both RDE and PDE, and the both value is almost same. On the other hand, I_{SP} of the RDE with C_2H_2-O_2 increases with increasing φ, and it is larger than one with CH_4-O_2. The maximum I_{SP} of C_2H_2-O_2 and CH_4-O_2 are 350s at φ = 2.8 and 150s at φ = 1.2 – 2.0 respectively.

The all fuel-base specific impulses decrease with increasing φ. The maximum I_{SP} is 1100s at φ =0.8 with C_2H_2-O_2. Thus, lean combustion is better for air-breathing engine for all cases.

4. Conclusion

The thrust performance of a proto-type rotating detonation engine is investigated by single pulse combustion. The effect of the mixture gases of methane-oxygen and acetylene-oxygen on specific impulse is investigated through ballistic pendulum method. The following results are collected:

- Generally, the thrust with acetylene-oxygen is over twice as large as one with methane-oxygen.
- The mixture-base specific impulses of the RDE and PDE are almost same with methane-oxygen.
- The fuel-base specific impulses decrease with increasing equivalence ratio, so that lean combustion is suitable for air-breathing engine.
- The fuel base-specific impulse of acetylene-oxygen gas mixture is about 2 times as large as one of methane-oxygen, and its maximum specific impulse is 1100 seconds.

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