Experimental Research on Water-Cooled Rotating Detonation Engine

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1 Background

1-1 Motivation

As of 2021, about 82.3% of the world's energy comes from fossil fuels, and our lives heavily depend on them (oil: 30.9%, coal: 26.9%, natural gas: 24.5%) [1]. However, when fossil fuels are burned, carbon dioxide, nitrogen oxides, and sulfur oxides are emitted into the atmosphere. These cause environmental problems such as global warming or extreme weather conditions that have a large impact on the world. In addition, fossil fuels are finite resources and if they are consumed at the current rate, oil and natural gas will be depleted in the remaining 50 or so years, and coal in about 130 years. Recently hydrogen started attracting attention as a next-generation energy supply.

It is known that detonation yields higher heat release and lower entropy production compared to deflagration. This means that the theoretical thermal efficiency of a combustion cycle based on detonation is higher than that of deflagration. Therefore, detonation-based combustion is attracting attention for a few decades leading to more ecological power generation systems. In this study, experiments on rotating detonation engine (RDE) fed with hydrogen were conducted. To briefly explain RDE, it is the coaxial cylindrical combustor, where detonation waves continue to rotate as long as fuel is supplied. Using hot combustion products, electric power can be achieved by connecting a turbine. However, RDE has some disadvantages that need to be resolved. In particular, the stability of rotating detonation, noise, and the establishment of a cooling system are major issues. Our research focuses on the establishment of a cooling system.

1-2 Purpose

The purpose of this study is to contribute to applied research of RDE by enabling long-time operation with water cooling. If a long operation time can be achieved, it could be applied to power generation systems using turbines or as a propulsion system for rockets.

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1-3 Background

In 1960, Voitsekhovskii [2] proposed the basic concept of a continuous detonation wave (CDW). He first achieved a short-lived CDW in his experiment. This experiment is considered to be the first step in the development of RDE. Later, Adamson and Olsson [3], and Nicholls et al. [4] conducted theoretical analysis and preliminary experiments on the application of continuous detonation to the new generation propulsion system. In the latest research, on July 27, 2021, a research group from Japan succeeded an experiment of operating RDE in space for the first time in the world. A maximum thrust of 518N was obtained in 6 seconds [5]. In this experiment, they were able to collect a lot of data such as pictures, pressure, temperature, vibration, and attitude data.

2 Experimental setups

RDE used in this study has an inner diameter of 95 mm and an outer of 115 mm (Fig. 1). The length of the combustor is 280 mm and the width of the combustor is 300 mm. In this study, the injection mode of fuel and oxidizer is the orifice-slot type. Hydrogen, which is used as fuel, is injected into the chamber through 80 orifices with a diameter of 1 mm uniformly distributed in front of the chamber. Air, which is used as an oxidizer, is injected into the chamber through an annular slot of 1 mm in width. The hydrogen-oxygen pre-detonator was used in this experiment. Water was cooling the combustor from both inside and outside. Figure 2 is a schematic drawing of the system. Gases are supplied from seven lines to the chamber through the pre-detonator line (①,②), the main line (③,④,⑤), the line for driving FV1 (⑥), and the purge line (⑦). The pre-detonator line is a line for sending hydrogen as fuel and oxygen as an oxidizer to the pre-detonation tube. The main line brings hydrogen and air to the combustor. The flow rate of hydrogen and air was calculated for each line. The line for driving FV1 is the safety line connecting to hydrogen on the main line. When pressure is applied to FV1 with flowing nitrogen, the valve opens and hydrogen can flow. The purge pushes the remaining hydrogen out of the main and pre-detonator line using nitrogen. In this experiment, the temperature and the flow rate of the cooling water, the surface temperature of the engine, and the thrust were measured.

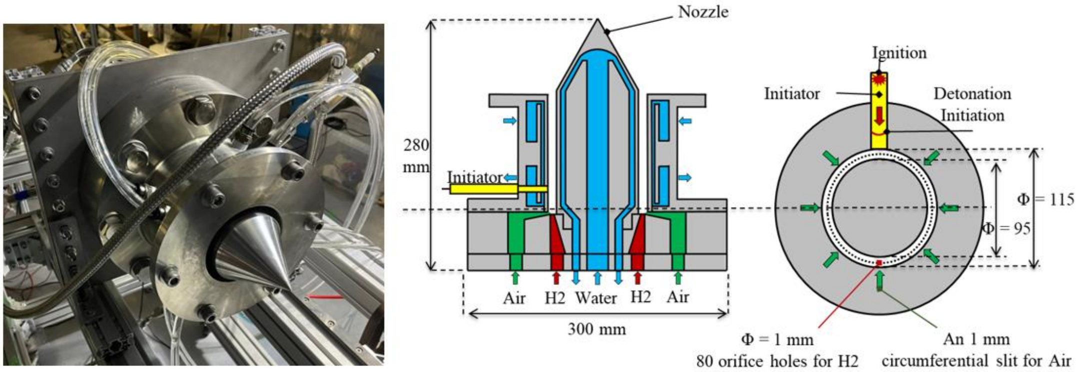

Figure 1: Rotating detonation engine and its schematic drawing

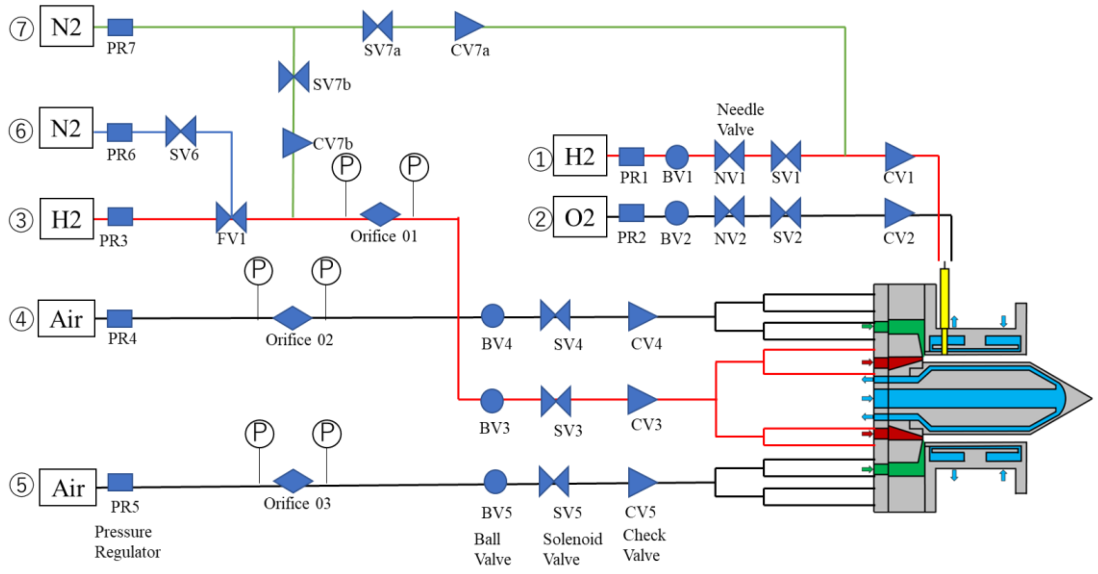

Figure 2: Schematic drawing of the system

3 Initial conditions

The experiment was conducted at a stoichiometric (φ = 1) and lean ratios (φ = 0.9). The mass flow rate of the air-hydrogen mixture varied between 90-135 g/s, and the operation time was between 1 to 6 seconds or longer (Fig. 3).

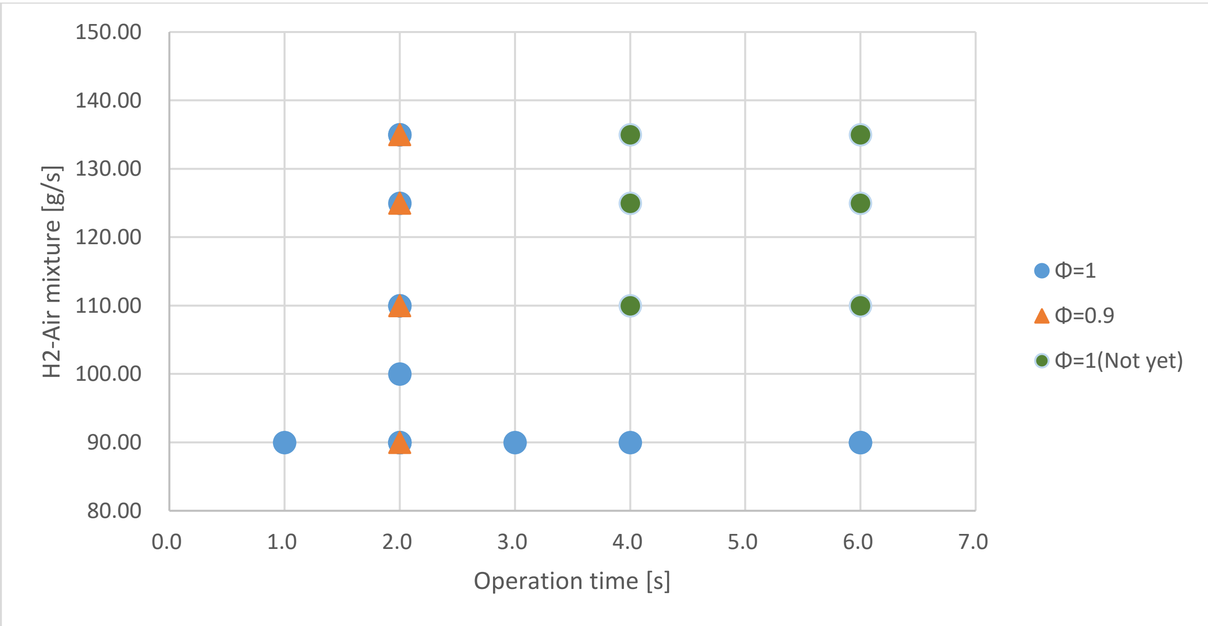

Figure 3: Initial conditions

4 Results

4-1 Cooling water temperature

Figure 4 shows the temperature increase with operation time. The temperature of the cooling water flowing on the outside increased by up to 23°C after 6 seconds of combustion. The temperature of the cooling water flowing on the outside was higher than that of the cooling water flowing on the inside. This is because the outer wall is designed to be thinner than the inner wall. Figure 5 shows the temperature increase per second with H2-Air mixture. As the mass flow rate of the fuel and oxidizer increased, the temperature rise of the cooling water per second increased.

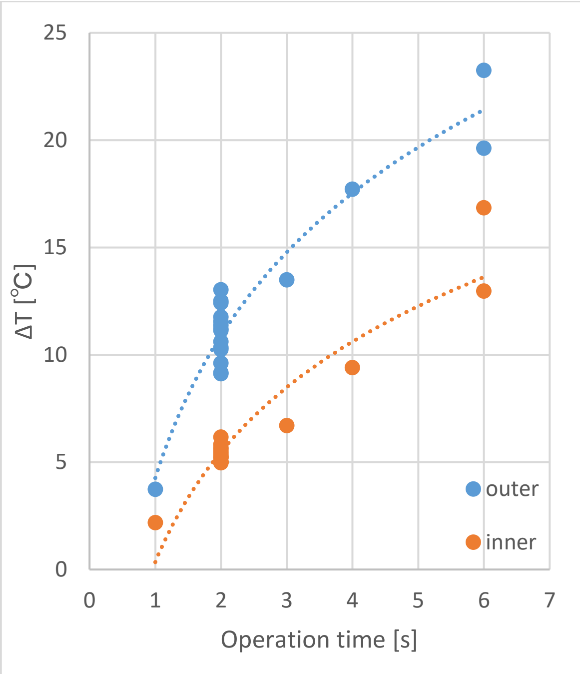

Figure 4: Temperature increase with operation time.

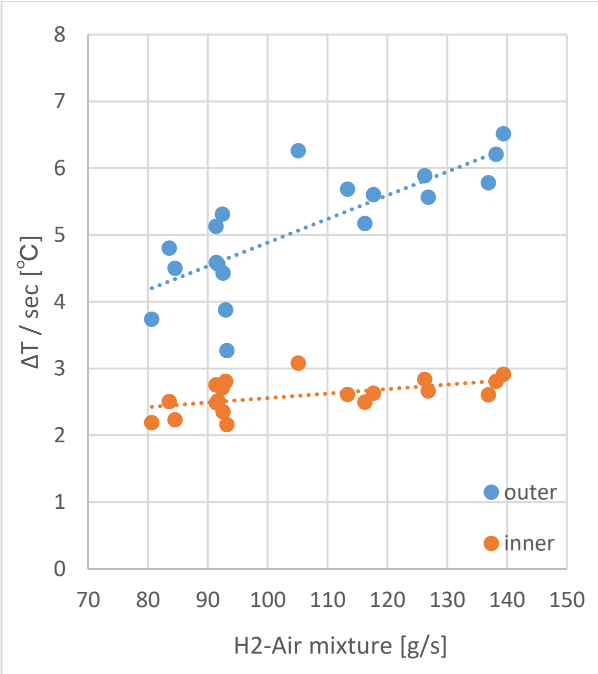

Figure 5: Temperature increase per second.

4-2 Velocity of RDW

Figure 6 shows the velocity of rotating detonation waves with H2-Air mixture. Detonation velocity was measured using a high-speed camera. The maximum velocity of 1195 m/s was observed when the mass flow rate of the hydrogen-air mixture was 139 g/s. As the fuel and oxidizer mass flow rates were increased, the velocity of detonation waves increased. Also, focusing on the equivalence ratio, the larger the equivalence ratio, the higher the velocity of detonation waves. Figure 7 shows the experimental velocity relative to CJ velocity (calculated using NASA-CEA [6]) with H2-Air mixture. It can be considered that the closer to the CJ velocity, the more stable the detonation wave is. It was observed 62% of the CJ velocity when the mass flow rate of the hydrogen-air mixture was 133 g/s. It can be seen that as the fuel and oxidizer mass flow rate increased, the experimental velocity approached the CJ velocity.

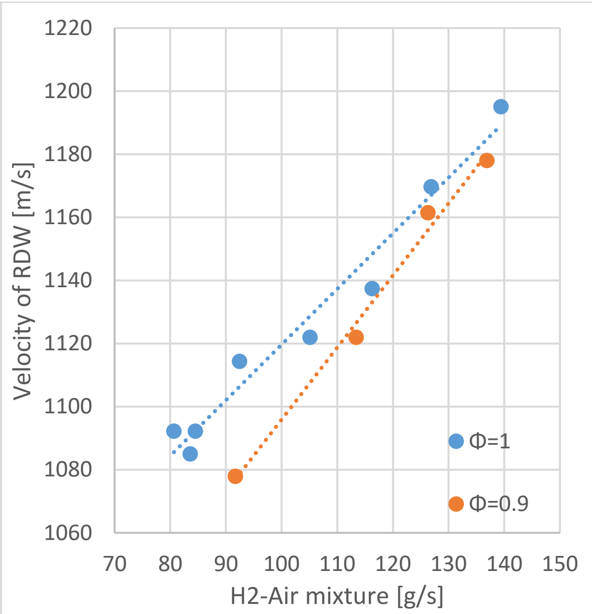

Figure 6: Velocity of RDW.

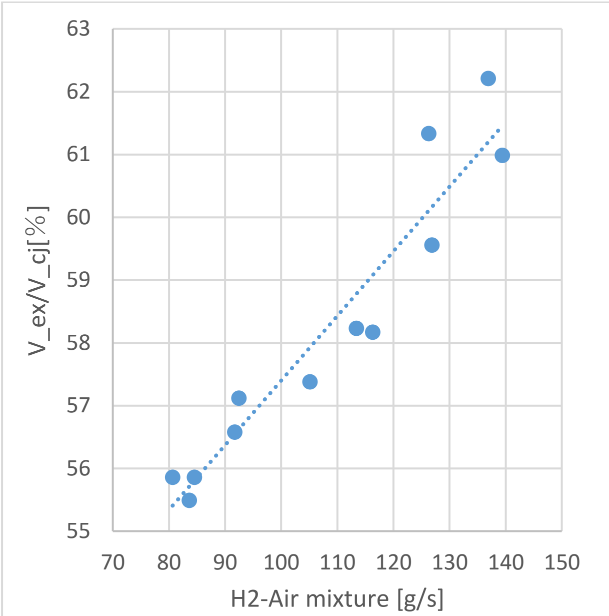

Figure 7: Experimental velocity relative to CJ velocity.

4-3 Thrust

Figures 8 and 9 show the maximum and average thrust under the condition of φ = 1 and φ = 0.9 respectively. A maximum thrust of 9.3 kgf and an average thrust of 7.1 kgf were observed when the mass flow rate of the mixture was 135 g/s at φ=1. Regardless of the equivalence ratio tested, the more the mass flow rate, the greater the thrust obtained. The average thrust was approximately 80% of the maximum thrust. This does not appear to be related to mass flow rate or equivalence ratio.

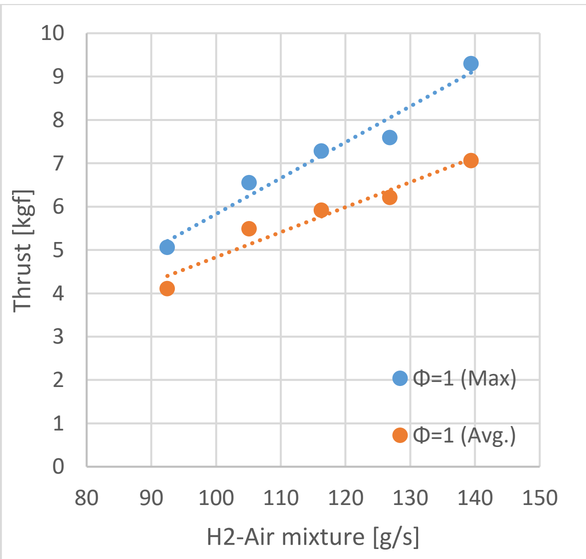

Figure 8: Maximum and average thrust under the condition of φ = 1.

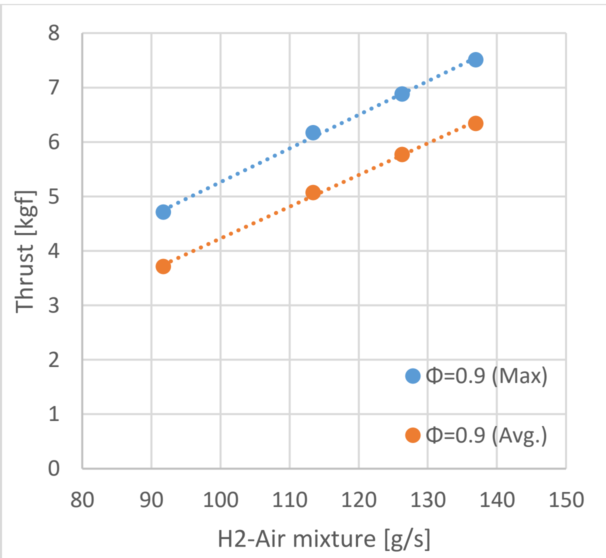

Figure 9: Maximum and average thrust under the condition of φ = 0.9.

Figures 10 and 11 show the maximum and average thrust respectively. From these two figures, it can be concluded that the larger the equivalence ratio, the greater the maximum and average thrust.

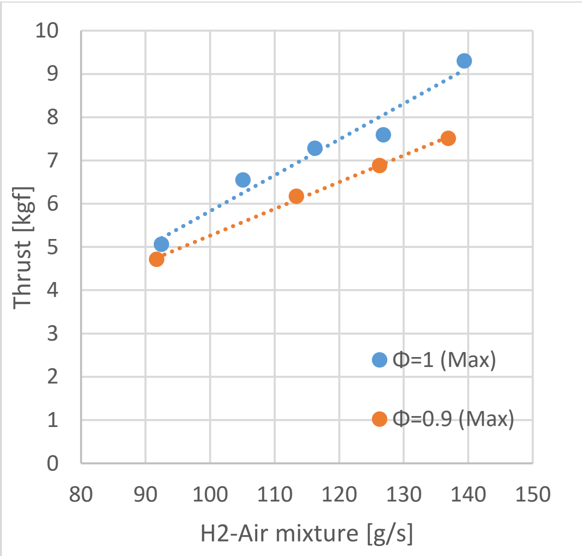

Figure 10: Maximum thrust.

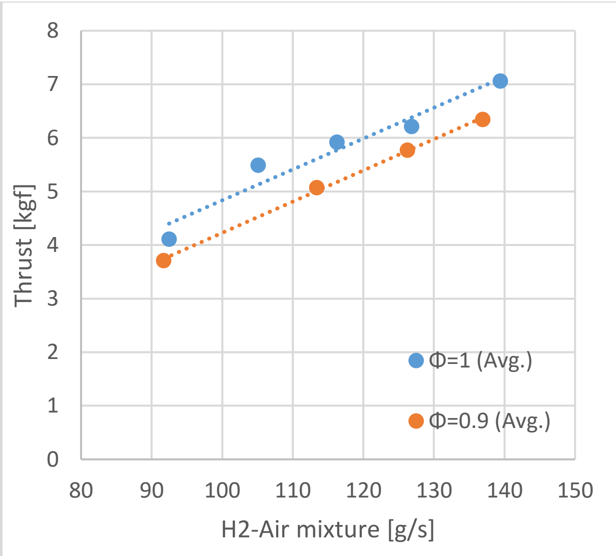

Figure 11: Average thrust.

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