Operation Characteristics of a Disk-Type Rotating Detonation Engine

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1 Introduction

Detonation engines have attracted attention because of their higher theoretical thermal efficiency with the potential to realize pressure gain combustion [1] bringing innovation to gas turbine engines. In particular, rotating detonation engines (RDEs) have a feature of continuous propagation of detonation waves in a combustor, resulting in higher performance as compared to pulse detonation engines and feasibility in terms of detonation operation in the combustor.

As compared to conventional combustors with deflagrative combustion mode, a disk-type RDE (DRDE) in which a combustible mixture flows radially inward before turning to the axial direction, has an advantage of the length savings besides its better thermal efficiency [2, 3]. These studies of DRDEs are motivated by a radial RDE developed to visualize the structure of rotating detonation waves in a disk-shaped combustor [4]. Huff et al. have originally developed a modular-designed DRDE with a constant chamber area with the controlled injection area of fuel and air. Recently Boller et al. have clarified the motion of rotating detonation waves in the DRDE combustor and reported that a rotating detonation wave is located closer to its inner radius for a single wave mode, while a multiple wave mode shows detonation's location at the outer radius [5].

The authors' group has studied the flow structure and performance of the DRDE experimentally and numerically for a couple of years [6, 7]. In the present work, operation characteristics of the DRDE with a constant cross-sectional channel area are experimentally studied to grasp performance of the present configuration of the combustor.

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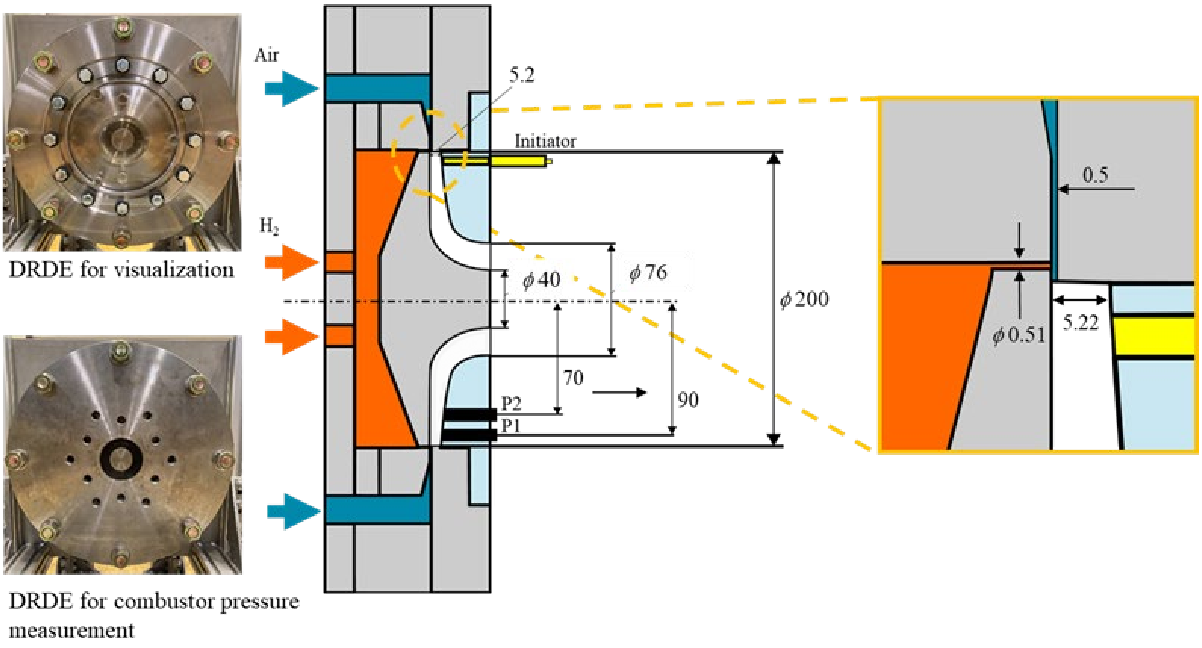


Figure 1: Schematic of combustor of the disk-type rotating detonation engine

2 Experimental Apparatus

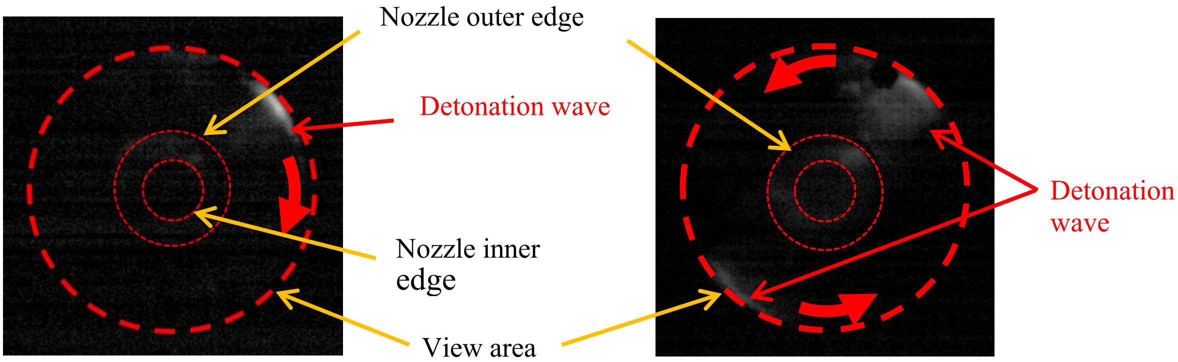
The combustor of the DRDE uses in the present work is shown in Fig. 1. Hydrogen-air mixtures with various equivalence ratios ranging from 0.6 to 1.5 are used with test gas. Hydrogen is introduced through 120 axial orifice holes 0.51 mm in diameter, while air is charged through a circumferential slit 0.5 mm wide. This configuration of the circumferential slit and orifices causes a vertical collision of the injected hydrogen and air effectively, leading to enhanced mixing in the combustion chamber. The mixture flows along the curved chamber wall, changing the gas direction gradually from a radial to an axial direction. Note that the present combustor is so designed that the cross-sectional area of the channel is kept constant as with conventional RDEs with an annular combustion chamber. A conventional spark plug is used to ignite a stoichiometric oxyhydrogen mixture charged in the initiator tube, which is connected with the combustor to detonate the main mixture.

To capture the behavior of rotating detonation waves and pressure history during the DRDE operation, two pressure transducers (Kistler 603B1) P1 and P2 are flush-mounted on the top wall of the combustor. In addition, a static chamber pressure is evaluated with capillary tube average pressure (CTAP) measurement [8]. The CTAP tube made of a 1/8-inch stainless-steel tube 500 mm long is installed at the same radial position as P1. The CTAP tube is instrumented with a conventional pressure sensor (Keller PAA-23SYEi).

Replacing a portion of the top wall with a window made of Plexiglas makes it possible to visualize the motion of rotating detonation waves. The top-left photograph in Fig. 1 shows the DRDE equipped with the window for visualization tests. The behavior of rotating detonation waves is recorded with a high-speed camera (nac image technology, MEMRECAM ACS-1 M40). The top-bottom photograph is the exterior of the DRDE for combustor pressure measurement with the CTAP.

3 Results and Discussion

Figure 2 shows the operation modes observed in the present work with almost the same total mass flow rates $\dot{m}$ and different equivalence ratios of the mixture ϕ. In Fig. 2 (a) a single detonation wave is found to rotate clockwise, while double wave mode is detected in Fig. 2 (b) for the slightly richer mixture than Fig. 2 (a). In both modes the brightest area is located near the peripheral wall of the combustion chamber,



(a) Single wave mode
($\dot{m}$ = 297 g/s, ϕ = 0.77)

(b) Double wave mode
($\dot{m}$ = 300 g/s, ϕ = 0.84)

Figure 2: Propagation mode of rotaing detonaion waves in DRDE.

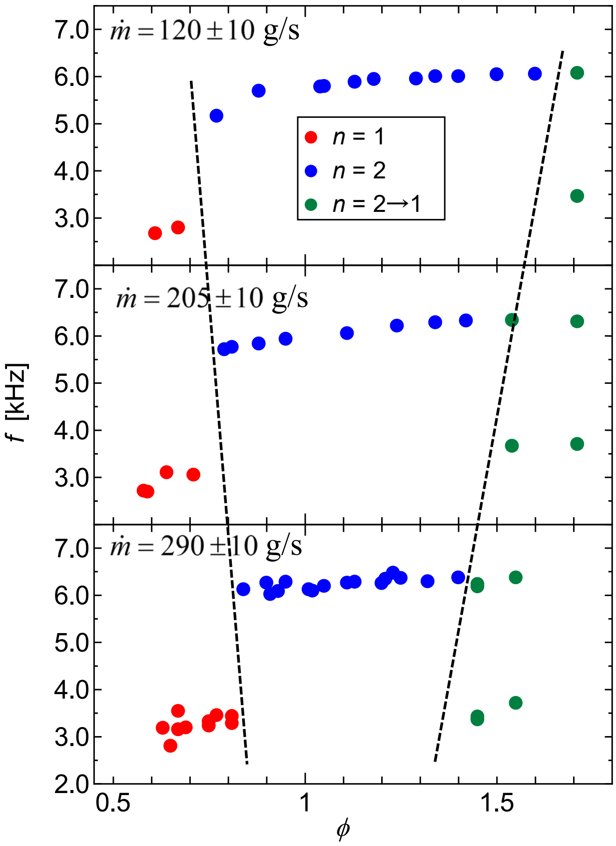


Figure 3: Operating frequency of rotating detonation waves for diffrent total mass flow rates.

indicating that the rotating detonation wave mainly propagates near the outer chamber circumference regardless of the wave mode. This result does not agree with that of Ref. [5] reporting that the rotating detonation wave propagates near the inner radius of the combustion chamber for the single wave mode. This is probably due to the difference of the inlet area ratio $A_{3.1}/A_{3.2}$, where $A_{3.1}$ is the minimal air inlet area and $A_{3.2}$ is the combustion chamber cross-sectional area. As shown in Fig. 1, $A_{3.1}/A_{3.2}$ is 0.1 in the present DRDE configuration, leading to stable propagation of rotating detonation waves. In Ref. 5, $A_{3.1}/A_{3.2}$ is set to 0.2, which is responsible for the inner location of the rotating detonation wave.

The effect of the equivalence ratio on the operating frequency of the DRDE is shown in Fig. 3. In the present configurations, a single and double wave modes are observed in all the test conditions. The wave number n = 2 is found to be available for a wide variety of equivalence ratios around unity, while the wave number n = 1 appears in the case of leaner and richer mixtures. For the equivalence ratio greater than 1.45, a transition mode, in which the operation mode changes from double to a single wave, is detected. In this mode, two operating frequencies corresponding to the two modes are plotted in Fig. 3. There is a tendency that a range of the equivalence ratio showing n = 2 shrinks, as the total mass flow rate increases.

Figure 4 shows the time-averaged static chamber pressure measure by the CTAP technique for different total mass flow rates. The chamber pressure apparently increases with increase in the total mass flow rate, while the equivalence ratio has a small effect on the chamber pressure under the same wave number. It is also found that the higher chamber pressure is obtained for n = 1 as compared to n = 2, although its difference is less than 20 %.

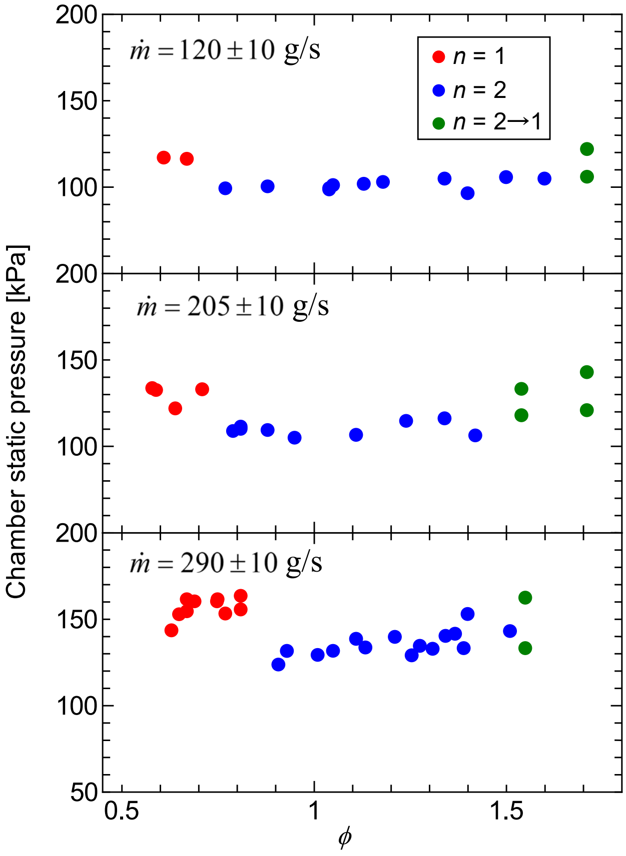


Figure 4: Time averaged chamber static pressure for different total mass flow rates.

From the measured chamber static pressure, the pressure gain is evaluated in the following manner. At first, the thrust F is calculated using the following equation

$$F = \dot{m}w_8 , \tag{1}$$

where w and P denote velocity and pressure, respectively. Subscripts 0 and 8 indicate an atmospheric condition and the chamber exit. The static pressure at the chamber exit is assumed to be balanced with the atmospheric pressure P_e, because the chamber static pressure shown in Fig. 4 is too low for choking at the chamber exit. The exit velocity w_8 is calculated from the one-dimensional flow model that is a combination of Rayleigh and Fanno flow. Then the equivalent available pressure EAP [1] is obtained using the flow Mach number at the chamber exit M_8:

$$EAP = P_e\left(1+\frac{\gamma-1}{2}M_8{}^2\right)^{\left(\frac{\gamma}{\gamma-1}\right)} , \tag{2}$$

where γ is a ratio of specific heats. The pressure gain PG, which is pressure incremental over the combustor, is evaluated based on the air supply pressure P_{air}:

$$PG = \frac{EAP - P_{air}}{P_{air}} , \tag{3}$$

The pressure gain calculated in this manner is shown in Fig. 5. It is found that the present DRDE provides negative pressure gain ranging from -80 % to -70 %, depending on the total mass flow rate. There is a tendency that the pressure gain increases with decrease in the total mass flow rate. In addition, the single wave mode is superior to the double wave mode in terms of the pressure gain, which is consistent with the results in Fig. 4. There are mainly two reasons for the negative pressure gain in all the test conditions. One is that the chamber cross-sectional area is constant through the flow path, namely, no throat at the chamber exit. This no constriction in the flow path corresponds to the condition of $A_8/A_{3.2}$ in Ref. 6 and gives less chamber static pressure. The other is the thin air slit as mentioned above. The small value of

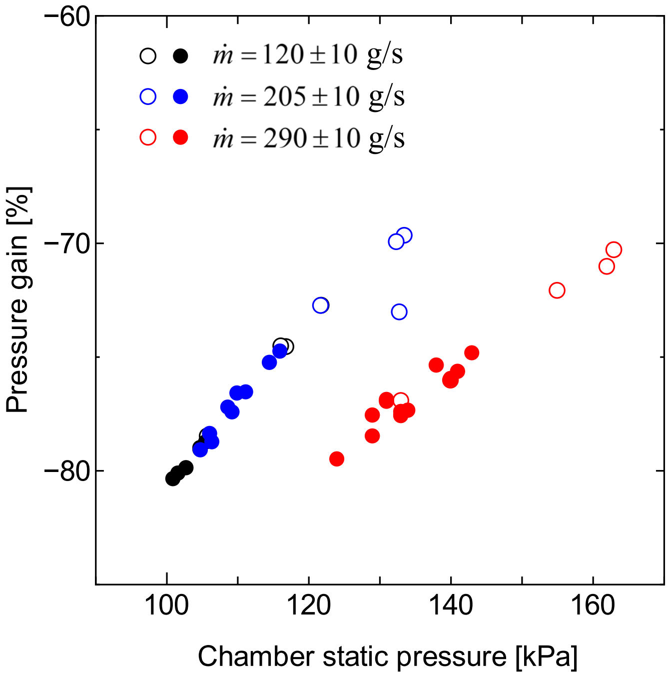


Figure 5: Pressure gain calculated from the chamber static pressure for vaioustotal total mass flow rates. Open symol: single wave mode; closed symbol: double wave mode.

$A_{3.1}/A_{3.2}$ is responsible for large total pressure loss, although stable propagation of rotating detonation waves is realized. The positive pressure gain is expected by attaching the nozzle to the chamber exit and increase of the air slit width.

4 Summary

In the present work, the behavior of rotating detonation waves in the disk-type rotating detonation engine with a constant chamber area was experimentally studied for various total mass flow rates and a wide variety of equivalence ratios of hydrogen-air mixtures. From the visualization, the rotating detonation wave was found to propagate near the outer wall of the combustion chamber, regardless of the wave mode. In the present test conditions, single and double wave modes are observed, depending on the equivalence ratio of the mixture. The pressure gain was evaluated from the chamber static pressure measured with the CTAP technique. Although the present DRDE configuration provided the negative pressure gain in all the test conditions, it was found that the single wave mode was superior to the double wave mode in terms of the pressure gain.

References

[1] Kaemming TA., Paxson DE. (2018) Determining the pressure gain of pressure gain combustion, AIAA 2018-4567.

[2] Huff R., Polanka MD., McClearn M J., Schauer FR., Fotia M., Hoke JL. (2018) A disk rotating detonation Engine part 1: Design and buildup, AIAA 2018-0633 (2018).

[3] McClearn MJ., Schauer FR., Huff R., Polanka M., Hoke JL., Fotia M. (2018) A disk rotating detonation engine part 2: Operation, AIAA 2018-1607.

[4] Nakagami S., Matsuoka K., Kasahara J. (2017) Experimental visualization of the structure of rotating detonation waves in a disk-shaped combustor, J. Propuls. Power 33: 80.

[5] Boller SA., Polanka MD., Huff R., Schauler FR., Fotia, ML., Hoke JL. (2019) Experimental flow visualization in a radial rotating detonation engine, AIAA 2019-1253.

[6] Hayashi AK., Xinmeng T., Tsuboi N., Ozawa K., Ishii. K., Obara T., Maeda S., Dzieminska, E., Mizukaki, M. (2019) Development of a high efficiency system with a rotating detonation engine for a gas turbine engine (RDE-GTE) using pressure gain combustion, AIAA 2019-1509.

[7] Hayashi AK., Ishii. K., Watanabe T., Tsuboi N., Ozawa K., Jourdaine NH., Dzieminska, E., Xinmeng T., Obara T., Maeda S., Mizukaki, M. (2020) Experimental and numerical study on disk-RDE: Flow structure and its performance, AIAA 2021-1253.

[8] Foita ML., Hoke JL., Schauler FR. (2018) Experimental study of the response of capillary tube attenuated pressure measurements to high amplitude, non-linear forcing, AIAA 2018-0634.