Effects of Combustor Size on Behavior of Rotating Detonation Waves

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1 Introduction

Recently detonation engines have attracted attention because of their higher theoretical thermal efficiency and simple structure. In particular, rotating detonation engines (RDEs) have a characteristic of continuous propagation of detonation waves in a combustor, resulting in higher performance as compared to pulse detonation engines.

George et al. [1] have reported that the operation modes of RDEs are determined by the fresh mixture height injected ahead of detonation wave and the mixture cell width. The number of detonation waves within the combustor ranges from one to three and increases in a predictable manner when the normalized perimeter of a detonation front exceeds 7.4 times of the mixture cell width.

Kindracki et al. [2] have studied propagation speed of rotating detonation waves (RDWs) using different combustor sizes. They have revealed that the observed velocity of RDW in the large combustor is higher by about 400 m/s than in the small combustor. This was considered to be caused by the larger radius of curvature of the combustor. Namely a large curvature of the small combustor decreases the detonation propagation velocity. However, it remains still unclear how the combustor size affects the propagation mode of RDWs and performance of RDEs.

Fotia et al. [3] have studied performance scaling of RDEs with various annular channel widths under the condition that an air injection area ratio, a mass flux rate, and a nozzle area contraction ratio are kept constant. It is reported that there is a tradeoff space in which fuel efficiency and effective usage of supplied stagnation pressure can be exchanged.

In the present study, the effects of the combustor size of RDEs on the propagation mode have been experimentally studied for various mass flux rates that is defined total mass flow rate per unit cross-sectional area of the annular channel of the combustor, using two types of combustors with different sizes and various annular channel widths.

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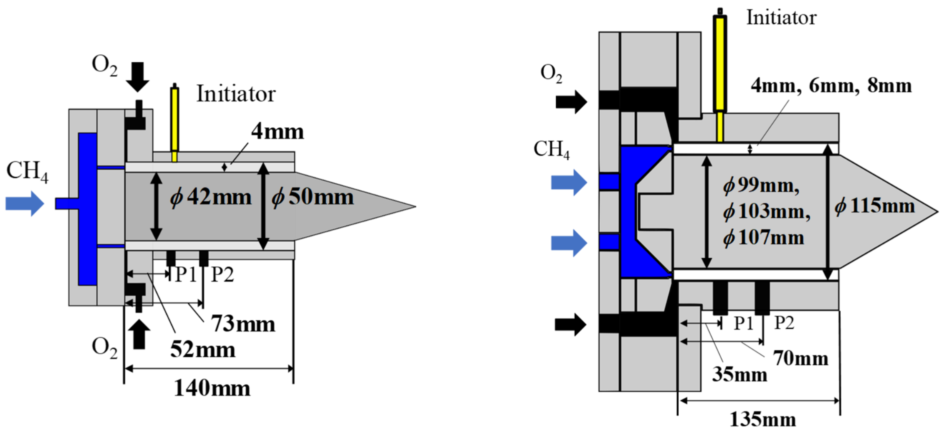
2 Experimental Apparatus

Two types of the combustor were prepared as shown in Fig. 1. The combustor A had an outer diameter *D* of 50 mm and an inner diameter *d* of 42 mm forming an annular channel width *w* of 4 mm, while the combustor B had *D* of 115 mm and *d* of 99 mm ~ 107 mm forming *w* of 4 mm ~ 8 mm. The initiator tube was connected with the combustor to detonate a mixture at the beginning of mixture supply. A conventional spark plug was used to ignite a stoichiometric oxyhydrogen mixture charged in the initiator tube. A test gas was a stoichiometric methane-oxygen mixture. The mixture supply section of the combustor consisted of a circumferential slit and axial orifice holes to control an equivalence ratio and the mass flow rate, independently. In the combustor A, oxygen was charged through a circumferential slit of 0.4 mm placed on the outer wall of the combustor, while methane was introduced through axial 72 orifice holes 0.8 mm in diameter. The combustor B had a circumferential slit of 0.6 mm and 80 orifice holes 1.5 mm in diameter. These configurations of the circumferential slit and orifices cause collision of the injected oxygen and methane effectively, leading to rapid mixing in the annular channel. To capture the behavior of RDWs and pressure history during RDE operation, two pressure transducers (Kistler 603B1) were flush-mounted on the outer wall of the combustor.



(a) Combustor A (b) Combustor B

Figure 1. Schematics of two types of combustor for rotating detonation engines.

Figure 2 shows schematic of the mixture supply system used in the present work. Oxygen and methane were initially charged in the gas tank at a desired pressure and were introduced into the combustor. Each gas flow passage had a solenoid valve to control the gas supply timing. Because the mass flow rate is an important parameter for successful operation of RDEs [1, 2, 4] and the volume of gas tanks was limited, the operation duration was set to 200 ms. To estimate the wave number of rotating detonation *n* inside the channel, high-speed video images of detonation propagation were recorded from the axial direction of the combustor.

3 Results and Discussions

Figure 3 shows the operation modes of the two different combustors for various averaged total mass flow rates $\dot{m}_{\text{total}}$. The wave number *n* was determined from the obtained pressure history and the high-speed video

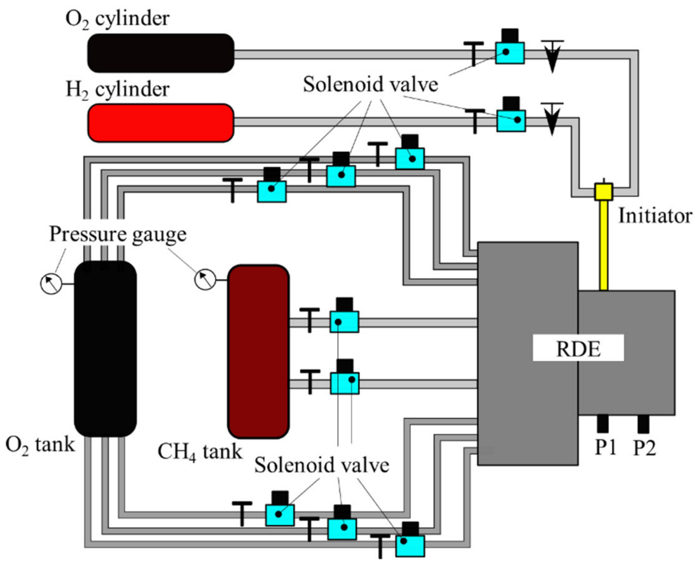


Figure 2. Mixture supply system.

images on the assumption that detonations propagate in a curved channel at a velocity slower than the Chapman–Jouguet speed [5].

For the combustor A, the operating frequency f slightly increases with the total mass flow, which agrees well with the experimental result of Bykovskii et al [4]. The wave number n jumps from 1 to 2 around $\dot{m}_{total} = 120$ g/s, where the wave velocity approaches the CJ velocity W_{CJ}. As for the combustor B, the operating frequency is almost constant for w = 6 mm and 8 mm, for which the wave number changes from

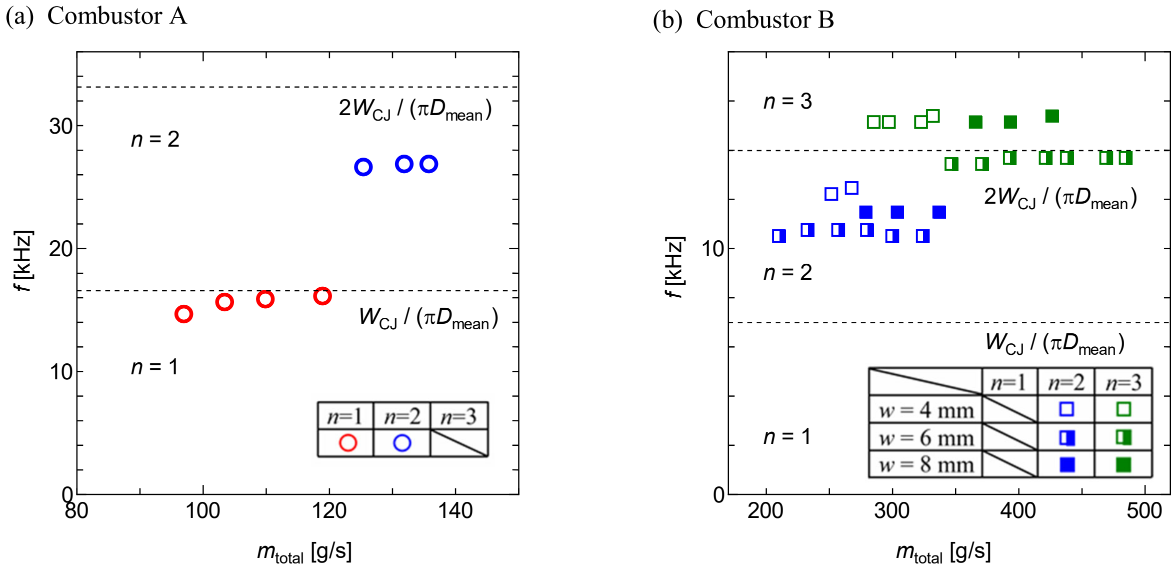


Figure 3. Propagation mode of RDW.

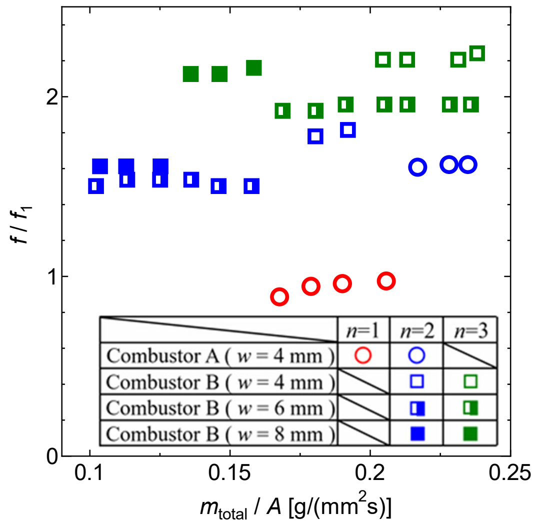


Figure 4. Effect of combustor size on normalized frequency of RDWs.

2 to 3 around $\dot{m}_{\mathrm{total}} = 350\,\mathrm{g/s}$. This critical mass flow rate for for w = 6 mm and 8 mm is larger thatn that for w = 4 mm. The wave speeds for n = 3 are obviously slower than the CJ velocity, which is consistent with the measured lower pressure amplitude. This low wave speed may be responsible for significant mixing between the fresh mixture and the burned gas, resulting in lower CJ speed of the actual mixture in which detonation wave propagate.

Figure 4 shows the effects of the mass flux rate, which is defined as $\dot{m}_{\mathrm{total}} / A$, on the normalized operating frequency, where A is the cross-sectional area of the annular channel of the combustor. The frequency is normalized by the fundamental frequency f_1 that is defined as follows:

$$f_1 = \frac{W_{\mathrm{CJ}}}{\pi D}. \tag{1}$$

It is found that the appearing wave number is strongly dependent on the combustor size and the channel width even for the same mass flux rate. For example, the combustor A shows a single RDW for $\dot{m}_{\mathrm{total}} / A = 0.16 \sim 0.20\,\mathrm{g/(\,mm^2{\cdot}s)}$, while three RDWs appear in the combustor B for the same range of the mass flux rate. Consequently, the critical mass flux rate at which the wave number jumps differs between the combustor A and B. As for the combustor B, the ciritical mass flux rate is found to increase with decrease in the channel width.

To study parameters controlling the operation mode of RDWs, the height of the mixture ahead of RDW h is calculated for various total mass flow rates as shown in Fig. 5. The calculation procedure of h can be found in Ref. 6. Regardless of the combustor size, h has a tendency to increase monotonically together with $\dot{m}_{\mathrm{total}}$. In addition, it found that there is an upper limit value of h so that the wave number keeps a certain value. If h exceeds this upper limit, the wave number jumps to sustain propagation of RDWs in the given geometry. The upper limit of h shows almost the same value for the combustor A and the combustor B with w = 4 mm and 6 mm. However, this upper limit of h becomes shorter for the combustor B with w = 8 mm.

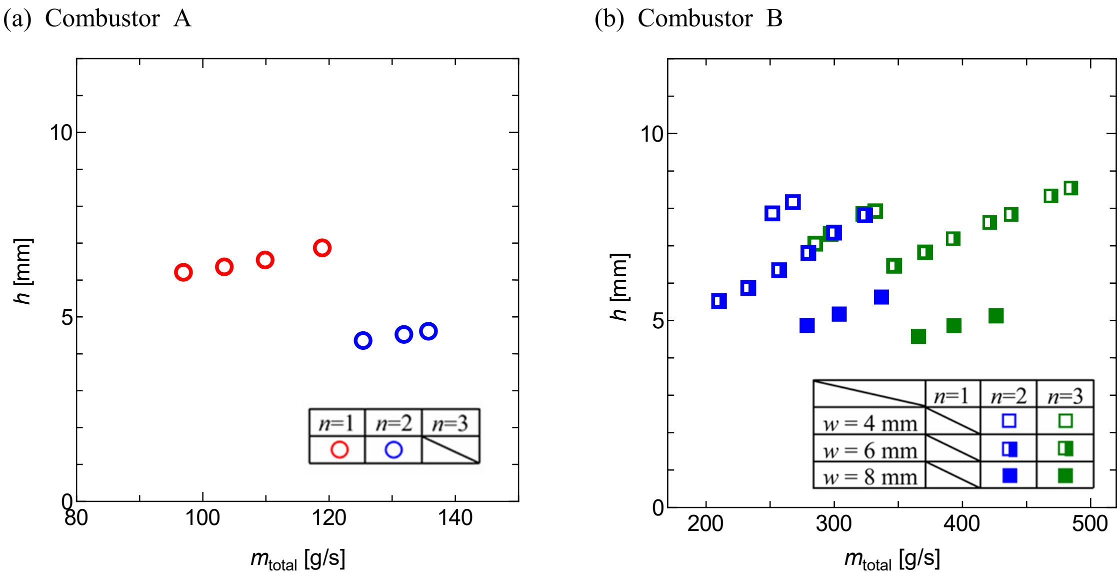


Figure 5. Relation between total mass flow rate and height of the mixture ahead of RDW.

Further study is needed to reveal scaling parameters to govern propagation modes of RDWs, wtih additional attention to the area expansion ratio between the circumferential air slit and the annular channel.

4 Summary

In the present study, the effects of combustor size on RDWs are experimentally studied using two kinds of combustors. From a series of tests conducted, the following findings are obtained.

1. For the small combustor, the operating frequency slightly increases with the total mass flow rate, while the large combustor shows almost constant operating frequency under the condition of the same wave number.
2. Regardless of the combustor size, discrepancy between the measured wave speed and the CJ speed increases together with increase in the wave number.
3. The wave number is strongly dependent on the combustor size for the same mass flux rate. The critical mass flux rate at which the wave number jumps differs between the two combustors As for the larger combustor, the critical mass flux rate increases with decrease in the channel width.
4. Concerning the height of the mixture ahead of RDW, there is an upper limit above which the wave number jumps. This upper limit shows almost the same value for the two combustors, except for the larger combustor with wider channel width.

5 Acknowledgement

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