Numerical Investigation on Detonation Behavior in a Disk-shaped Rotating Detonation Combustor

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1 Introduction

Detonation is one of the premixed combustion propagating with a shock wave. Detonation gives some merits to internal combustion engines compared with comventional ones. For instance, it could improve their thermal efficiencies and simplify their structures because mechanical compressors are not needed. In the current studies, the rotating detonation engine (RDE) is known as the engine using detonation [1]. One of the difficulties for RDE research is the visualization inside the combustion chamber due to the structure of RDE. There is a special combustor to visualize the detonation wave behavior in RDE designed by Nagoya University, which is composed of a dual disk, so-called disk-shaped rotating detonation combustor [2] as shown in Fig. 1. Fuel and oxidizer are separately supplied from outer wall and detonation products are gathered to the center of this chamber. The experiments are conducted by changing the injection configuration, and the detonation behavior is revealed from their experimental outputs.

The disk-shaped rotating detonation combustor, which is proposed at Nagoya University in our group, is utilized for a computational target. The aim of the present work is to clarify the detonation behavior depending on the size of inner and outer radii within the disk-shaped rotating detonation chamber.

2 Numerical Set Up

2.1 Computational target and simulation conditions

Figure 2 shows the schematic of parameters and boundary conditions. The computational domain is a colored area over a circle, which corresponds to the chamber of disk-shaped combustor. The injection wall is adapted to outer circle boundary, and inner circle boundary is used for outflow condition. The configuration parameter is curvature κ, which is described by $\kappa = 1/r_{out}$, here r_{out} is outer radius. Table 1 shows the parameters of combustor configuration.

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Table 1 Parameters of combustor configuration

Outer radius r_{out} [mm] (Curvature κ [1/m])	Combustor height h [mm]	Periphery l [mm]	Initial wave number	h/r_{out} [-]
50.96 (19.6)	20.95	320	8	0.41
25.48 (39.2)	20.95	160	4	0.82
25.48 (39.2)	10.48	160	4	0.41

There are two types of outer radius, 25.48 mm and 50.96 mm, and therefore two curvatures are used in this study. For an initial profile to simulate the rotating detonation wave, a fully developed detonation wave propagating clockwise in 40 mm of outer wall is prepared in advance for each computational configuration. Stably propagating detonation waves are placed as an initial condition to investigate the effects of parameters. Then, 8 waves are prepared in Fig. 2. As shown in Table 1, we focus on not only the outer radius but also the similarity h/r_{out} to reveal the detonation behavior. The maximum grid size in circumferential direction is 20μm. In radial direction, the minimum and constant grid size 20μm is prepared near the outer wall, and the grid spacing gradually expands from 5 mm away from the outer wall.

Figure 3 shows the schematic of injection model. The injection width is 320 μm with 1280 μm interval wall, and therefore 20% of the outer wall is occupied by the injectors. The premixed stoichimetric gas mixture of total pressure 1.01 MPa and total temperature 293 K consists of C_2H_4 and O_2. The injector is assumed to be conversing nozzles, and injection condition depends on the pressure at the exit of the injector.

2.2 Numerical approach

The dynamics of the RDE are governed by the two-dimensional compressible Navier-Stokes equations with 9 chemical species (C_2H_4, O_2, CO_2, H_2O, H_2, H, O, OH, and CO). The chemical model is a reduced kinetic model that consists of 9 species and 10 elementary reactions proposed by Singh *et al*. [3]. The half-reaction length is about 15 μm and the cell size is about 0.7 mm for the gas of 101 kPa and 293 K. The convection term is discretized by Yee's non-MUSCL-type 2nd-order upwind scheme [4]. The multi-timescale method [5], which repeats Euler's explicit method of determining the characteristic times of the chemical reactions in ascending order until it reaches that of the fluid dynamics, is adopted as the time integration for the chemical source term. The fluid is an ideal gas with a specific heat depending on temperature. NASA thermodynamic polynomials are used to calculate the thermochemical properties.

3 Results and Discussion

3.1 Flow fields

For an initial condition, the stably propagating detonation waves are placed in the whole combustor as shown in Fig. 2. Figure 4 shows that the instantaneous temperature distribution of fully developed detonation waves in the whole combustor after some computations, and Fig. 5 shows the close-up view at the lower right of Fig. 4 to see the detailed features of detonation wave front. Figure 6 shows the pressure distribution at the same moment of Fig. 4.

The temperature distributions in Figs. 4 and 5 show the injected C_2H_4-O_2 premixed gas in the low temperature regions near the outer wall, and the premixed gas disappears behind the rotating detonation waves. Figure 6 clearly indicates the location of detonation waves, and the detonation waves are followed by the oblique shock waves in the upper region of detonation. As shown in Figs. 4-6 (a), the detonation waves propagate stably in a clockwise direction. Therefore, the detonation behavior does not change very much from the initial profile.

Table 2 Propagation velocity D
(D_{CJ} = 2477 m/s at 0.3 MPa and 220 K)

Figure 4-7	Initial wave number	Wave number after transition process	Propagation velocity D [m/s]	D / D_{CJ} [-]
(a)	8	8	2335	0.94
(b)	4	4-7/4-8	1484	0.60
(c)	4	4	2203	0.89

In Figs. 4-6 (c), stable flow field can be observed as well as the condition (a). Flow fields in the conditions (a) and (c) in Figs. 4-6 are similar and the ratio of combustor height to the length of outer radius is the same value in both conditions (h/r_{out} = 0.41). The condition (b) in Figs. 4-6 (h/r_{out} = 0.82) behaves in a different manner. As seen in Fig. 5(b), the detonation waves propagate in both direction and the number of the waves is also changed from initial condition. The amount of premixed gas is fewer and each premixed jet is surrounded by the burned gas. Thus, detonation behavior in the condition (b) is significantly different from others even though combustor height or outer radius are same as one in the cases of (a) or (c). These results suggest that the parameter h/r_{out} would be the dominant factor to determine the detonation behavior in the disk-shaped combustor.

Figure 7 is the x-t diagram of outer wall pressure, which shows the behavior of pressure waves during the computation. In the conditions (a) and (c), the detonation waves propagate from right to left, and the traces of waves are regular and strong. We can confirm that the initial profile does not change in the conditions (a) and (c). In contrast, the detonation or compression waves propagate in both directions after 100 µs in Fig.7 (b). The trace of waves is week and they are not stable. Four detonation waves disappear at 30 and 75 µs. So, we will discuss this phenomena next section.

The propagation velocities calculated from the x-t diagram in Fig. 7 are summarized in Table 2. CJ velocity, D_{CJ} = 2447 m/s, is derived from the detonation property code, AISTJAN [6], under 0.3 MPa and 220 K for a stoichiometric condition. Since the speed of sound is about 1000 m/s, all waves are supersonic. Then, the propagating waves in Figs. 4-7 are confirmed as "detonation". In the conditions (a) and (c), the propagation velocities are almost the same though they are slightly lower than CJ velocity. In the condition (b), the detonation velocity is about 60% of CJ velocity. It implies that the value of h/r_{out} is the dominant parameter for the detonation behavior, not the curvature of the outer radius having the injection port in the disk-shaped rotating detonation combustor.

Figure 8 shows the instantaneus wall pressure distribution at 145 µs. 8 and 4 strong pressure peaks are observed in Fig. 8 (a) and (c), with the constant intervals between pressure peaks, respectively. Wave shapes are also similar in both cases. In h/r_{out} = 0.41 of the conditions (a) and (c), the pressure behind wave front decreases to the choked pressure rapidly. On the other hand, there are smaller pressure peaks in Figs. 8 (b) with the random intervals. The pressure peaks correspond to the detonation or compression waves in Fig. 7 (b). As seen in Fig. 4 again, the flow fields obtained to be calculated can be classified by h/r_{out}, not outer radius and combustor height. Therefore, these results indicate that the parameter h/r_{out} would be the dominant factor to determine the detonation behavior in the disk-shaped combustor. Next section, we reveal the role of the parameter h/r_{out} for the flow fields in the disk-shaped rotating detonation combustor.

3.2 Mechanism of detonation transition

Figure 9 shows the evolution of the detonation wave front for the onset of detonation wave toward the oppsite direction consisting of 4 shots of pressure contours. To explain Fig. 9, the schematic image of this mechanism is shown in Fig. 10. A detonation wave propagates from right to left. At first, a detonation leads an oblique shock wave ((1)). After that, the incident shock and the Mach stem are formed ((2)), and then, the reflected shock appears from the intersection between the incident shock and Mach stem ((3)). The reflected shock reaches at the injection wall and the high pressure region near the wall becomes the compression wave propagating to the counterclockwise direction. Finally, the compression wave becomes detonation and the main detonation becomes weak ((4)). We consider that the main factor to generate a new detonation propagating in the opposite direction is the reflection of the reflected shock at the outer wall. Thus, what the reflected shock is generated is important. The condition is only (b) which the reflected shock is observed. It is suggested that the relation between curvature and combustor height, h/r_{out} is important, not only combustor height h. When h/r_{out} is over the criterion, oblique shock wave is changed to Mach stem and incident shock wave, and then reflected shock wave is formed. After that, compression waves are generated at reflected point and they are changed to a new detonation. We discovered that the criterion is between h/r_{out} = 0.41 and 0.82.

4 Conclusions

Following results were obtained using numerical simulation to analyze detonation behavior in a disk-shaped rotating detonation combustor considering the effect of the size of inner and outer radii under C_2H_4-O_2 premixed gas injection. We can suggest that the value of h/r_{out} is the dominant parameter for the detonation behavior, not the curvature of the outer wall having the injection port, in the disk-shaped rotating detonation combustor. When h/r_{out} is 0.41, detonation waves keep steady propagation and propagation velocities are almost same as CJ detonation propagation velocity. On the other hand, the detonation waves propagate in both direction and the number of the waves is also changed from initial condition and the propagation velocity become low against the CJ velocity under h/r_{out} = 0.82. We consider that the key factor to generate a detonation propagating in the opposite direction is the reflection of the reflected shock at the outer wall. In conclusion, the behavior of detonation propagation in the disk-shaped combustor strongly depends on h/r_{out}, and the criterion is between h/r_{out} = 0.41 and 0.82.

Acknowledgements

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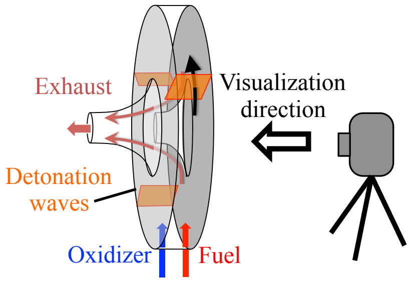


Figure 1 Schematic of disk-shaped rotating detonation combustor [3]

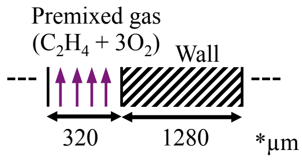


Figure 3 Schematic of premixed gas injector configuration model

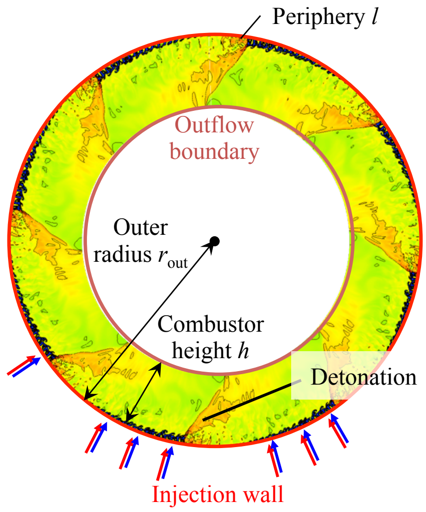
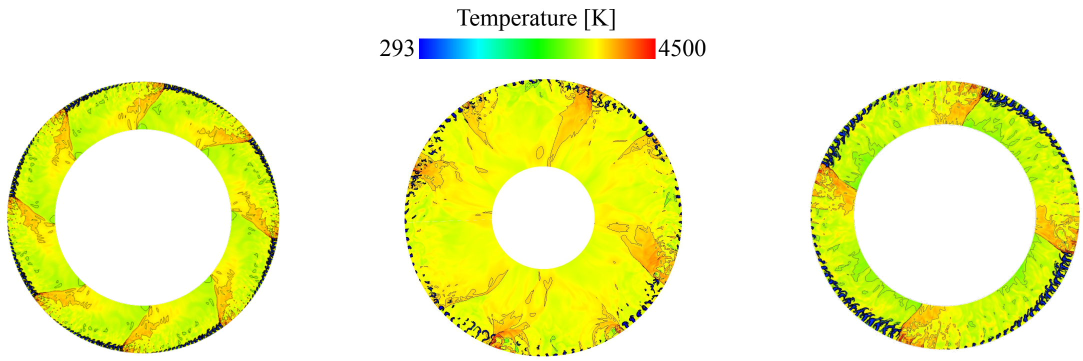
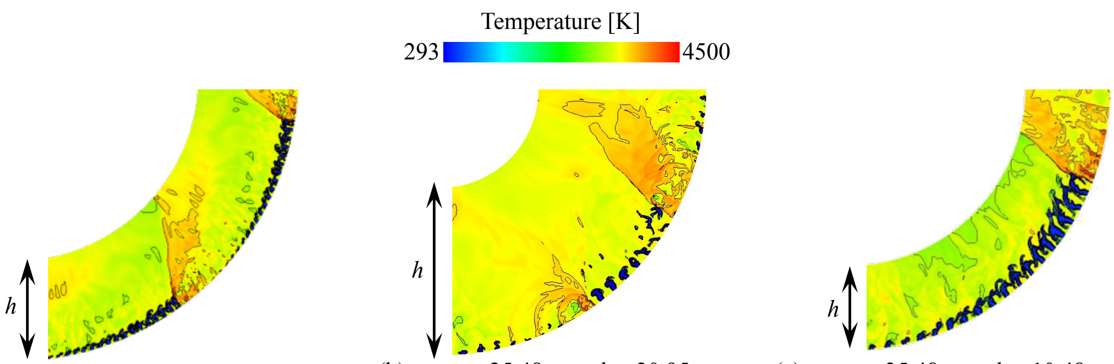


Figure 2 Initial condition and boundary condition



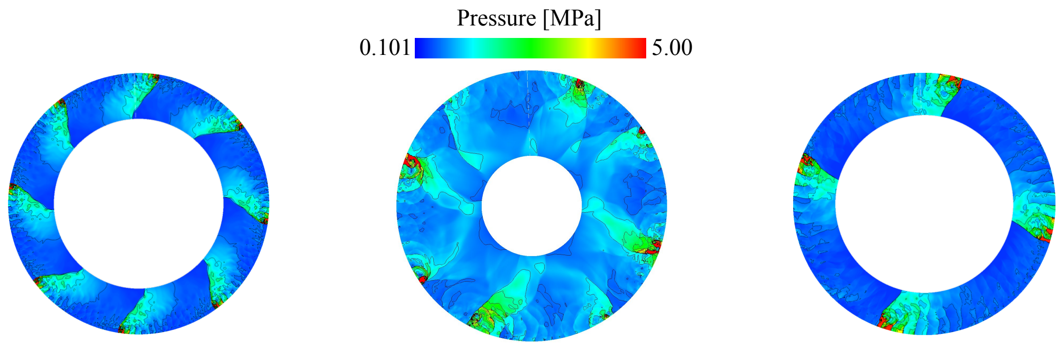
(a) r_{out} = 50.96 mm, h = 20.95 mm (b) r_{out} = 25.48 mm, h = 20.95 mm (c) r_{out} = 25.48 mm, h = 10.48 mm

Figure 4 Temperature distributions



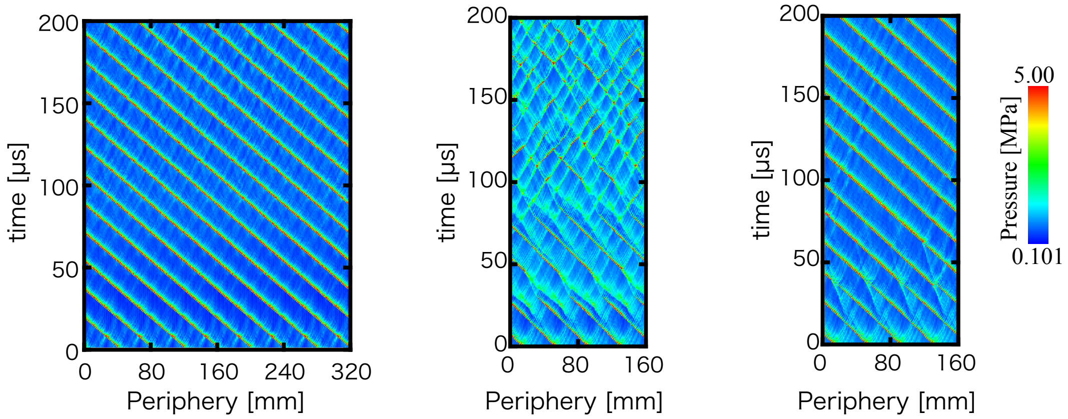
(a) r_{out} = 50.96 mm, h = 20.95 mm (b) r_{out} = 25.48 mm, h = 20.95 mm (c) r_{out} = 25.48 mm, h = 10.48 mm

Figure 5 Enlarged view of temperature distributions



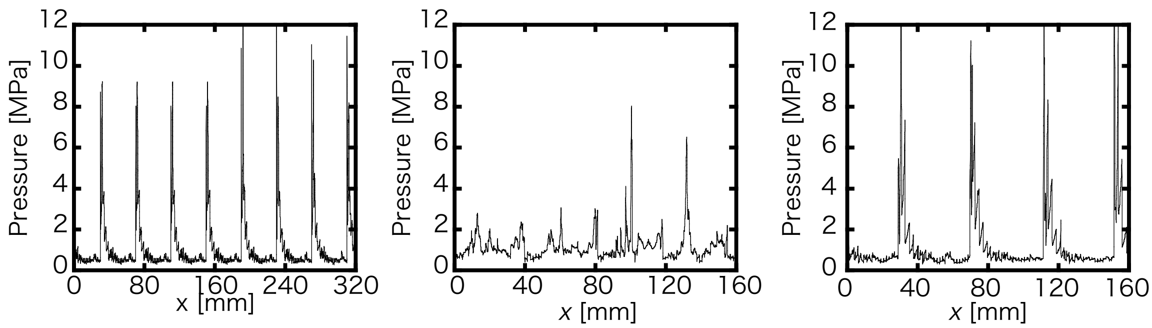
(a) r_{out} = 50.96 mm, h = 20.95 mm (b) r_{out} = 25.48 mm, h = 20.95 mm (c) r_{out} = 25.48 mm, h = 10.48 mm

Figure 6 Pressure distributions



(a) r_{out} = 50.96 mm, h = 20.95 mm (b) r_{out} = 25.48 mm, h = 20.95 mm (c) r_{out} = 25.48 mm, h = 10.48 mm

Figure 7 *x-t* diagram of wall pressure



(a) r_{out} = 50.96 mm, h = 20.95 mm (b) r_{out} = 25.48 mm, h = 20.95 mm (c) r_{out} = 25.48 mm, h = 10.48 mm

Figure 8 Wall pressure distribution at 145 µs

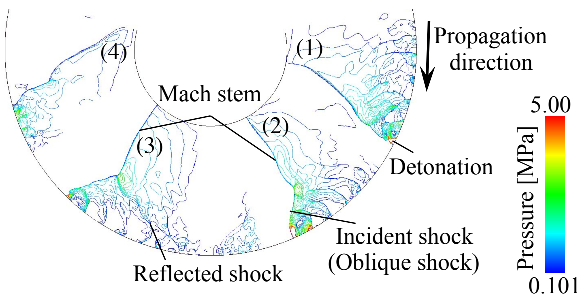


Figure 9 Transition of detonation wave propagation for case Fig.4-8 (b)

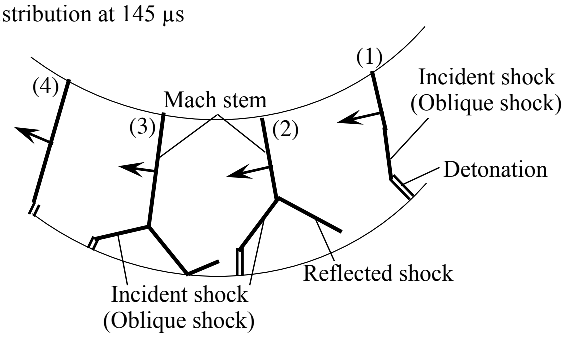


Figure 10 Schematic of transition of detonation wave propagation for case Fig.4-8 (b)