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

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1 Introduction

Detonation waves is a kind of combustion waves propagating at supersonic speed with a shock wave. Recently, the application of the detonation to engines has attracted attention [1]. An advantage of detonation engines, compared with conventional deflagration engines, is high thermal efficiency owing to high temperature at a start of chemical reactions. In addition, it is possible to make the size of a combustor small because supersonic combustion is completed immediately. One of the detonation engines is a Rotating Detonation Engine (RDE). The RDE generally has a double-cylindrical combustor and detonation waves continue to propagate in the azimuthal direction. Therefore, the RDE can generate thrust or power stably. In recent years, a number of studies have paid attention to applying the RDE to gas turbine engines as well as rocket engines. Nagoya University [2] conducts experimental research for self-operation of a disk-shaped Rotating Detonation Turbine Engine (RDTE), which has a centrifugal compressor, a combustor, and a radial turbine on the same disk. Figure 1 shows (a) experimental equipment and (b) the disk. The air taken from the axial direction is compressed by the compressor and the flow direction is changed in the radial and azimuthal direction. Flame holders are located in circumference at the upstream of the combustor. The fuel is injected at the upstream of flame holders and mixed with the compressed air. The fuel/oxidizer is combusted by rotating detonation waves, and the burned gas flows into the turbine, and then discharged outside. The flow field of the disk-shaped RDTE is complex and unknown because detonation waves propagate on the disk-shaped rotating combustor, whose shape is not conventional double cylinder.

The objective of this study is to clarify the flow field of a disk-shaped rotating combustor and focuses on the following points by neglecting the turbine for simplicity. First, the effects of the combustor shape are investigated. Most of the two-dimensional numerical analysis of the RDE is conducted in rectangular computational domain because the RDE generally has a double-cylindrical combustor [3]. On the other hand, the present RDTE has the annular combustor on the disk. Characteristics of the flow field in the annular combustor are investigated by the comparison between the annular domain and the rectangular domain. Second, the effects of the disk rotation on the flow field are investigated. The analysis is conducted in a rotating reference frame whose angular velocity is the same as that of the disk.

2 Numerical setups

The governing equations are the two-dimensional compressive Navier-Stokes equation considering the conservation of 9 species (H_2, O_2, H, O, OH, H_2O, HO_2, H_2, O_2, and N_2). For the analysis in a rotating reference frame, the centrifugal force and the Coriolis force are added to the source term of the governing equations. The ideal gas law is employed as the equation of state and it is assumed that gases are thermally perfect. The convection term is discretized by Yee's Non-MUSCL Type 2nd-order upwind scheme [4] and the diffusion term is discretized by the 2nd-order central differential scheme. As a chemical reaction model for H_2/air combustion, the model that treats the 9 species and 25 elementally reactions proposed by Hong *et al*. [5] is used. Time integration of the chemical source term is conducted by MTS method [6].

It is assumed that 4 detonation waves exist in the combustor and the flow field inside the combustor is periodic every 90˚. Thus, the computational region is a quarter of the combustor. The existence of the turbine is neglected for simplicity. It is also assumed that the fuel/oxidizer are completely mixed at the upstream of flame holders. The upstream of the flame holders is treated as a plenum, which is filled with premixed gas. The total pressure p_0 and the total temperature T_0 of the premixed gas is 10 atm and 288 K respectively. The grids used for (a) the rectangular domain and (b) the annular domain are shown in Fig. 2. The length of the lower end of the computational region, which corresponds to a quarter circumference of the row of the flame holders, is 101 mm in both domains. The interval of flame holders is the same as the disk-shaped RDTE in the experiment. The lengths of an injection slit and a flame holder are 3 mm and 2 mm respectively, and 20 pairs are set on the lower end. The boundary condition for the injection slit depends on the relation between p_0 and ambient pressure, which is defined at one point away from the lower end. Adiabatic non-slip wall condition is applied for the surface of the flame holder. The left and right ends of the computational region are treated as periodic boundary conditions. At the upper end, outflow boundary condition that depends on the Mach number is applied. The minimum grid width is 50 µm, and about 3–4 grid points are set in the half-reaction length for the state ahead of detonation waves.

As shown in Table 1, calculations in both the rectangular domain and the annular domain are carried out. For the annular domain, calculations are conducted both with and without the rotation of the disk. Whether the rotating directions of the detonation and the disk are the same or not has not yet been clarified in the experiment. In this paper, the detonation rotating direction is counterclockwise and the rotating direction of the disk is set to be both clockwise and counterclockwise. The rotating speed is set to 20000 rpm, 40000 rpm and 70000 rpm corresponding to 6.6 seconds, 9 seconds and steady state after the Disk-shaped RDTE starts to operate respectively. The flow fields shown in this paper are confirmed as a quasi-steady state by total mass flow rate of injection slits and detonation propagation velocity.

3 Results and Discussions

3.1 The effects of the combustor shape

In this section, the effects of the combustor shape are examined. Results of the following two cases are compared here: the rectangular domain and the annular domain without the disk rotation. Figure 3 shows temperature distributions and streamlines relative to the detonation wave in each case. The burned gas remains between unburned premixed jet pillars. This is because the interval of injection slits is relatively large as reported in the previous work [3]. The temperature of the annular cases is lower than that of the rectangular case in the whole region, especially far from the injection boundary. Figure 4 shows pressure distributions. The pressure of the annular case is lower than that of the rectangular case through the whole region as well as the temperature. From behind the detonation wave, strong compression waves propagate in the opposite direction to the detonation wave. These compression waves are generated whenever the detonation wave enters the contact surface between an unburned jet and burned gas.

Table 1 shows detonation wave height h_{det}, detonation propagation angular velocity ω_{det}, detonation propagation velocity normalized by theoretical CJ velocity D/D_{CJ}, and normalized mass flow rate $\dot{m}/\dot{m}_{max}$. h_{det} in the annular domain is about 1.36 times larger than that in the rectangular domain. D is 1980 m/s for the rectangular domain. By using AISTJAN (the detonation characteristic analysis code) [7] for the average pressure and temperature ahead of the detonation wave, D_{CJ} = 2010 m/s can be obtained. The detonation wave propagates at almost the same as D_{CJ} in the rectangular domain. For the annular domain, ω_{det} is 2.65×10^4 rad/s and D at the lower and upper end of the detonation wave is 1760 and 2110 m/s respectively. D_{CJ} = 2000 m/s is within this range. The annular domains have higher $\dot{m}/\dot{m}_{max}$ than the rectangular domain by 5.9 %.

The reason why the pressure and temperature in the annular cases are lower is considered here. As shown in Fig. 3, the streamlines relative to the detonation wave diverge more when the computational domain is annulus. This indicates that the burned gas more accelerates and expands than for the rectangular domain because the velocities relative to the detonation wave are supersonic. Figure 5 shows Mach number distributions, and Mach number in the white region is approximately 1.0. Differences can be observed in y, η > 15 mm. For the rectangular domain, almost whole areas in y > 15 mm are subsonic except for behind the oblique shock wave. On the other hand, almost all the regions in η > 15 mm are supersonic in the annular case. Therefore, the pressure and temperature are lower in the annular case. The reason why h_{det} and $\dot{m}/\dot{m}_{max}$ are large in the annular cases is considered. Figure 6 shows the mass flow rate histories per unit depth for 5 each injection slit for (a) the rectangular domain and (b) the annular domain. t = 0 on the horizontal axis indicates the moment when the injection of the premixed gas stops. For the annular domain, the lower pressure behind the detonation wave makes the reinjection time earlier. In addition, the period between the time when the mass flow rate becomes almost constant and the time when the injection stops becomes longer in the annular case.

3.2 The effects of the disk rotation

In this section, the effects of the disk rotation are examined. Figure 7 shows distributions of temperature and velocity vectors relative to the disk in (a) a stationary case, (b) a clockwise case at 70000 rpm, and (c) a counterclockwise case at 70000 rpm. Jet pillars tilt to the left in the clockwise case and to the right in the counterclockwise case compared with the stationary case by the Coriolis force. Thus, ω_{det} relative to the disk becomes higher in the clockwise cases and lower in the counterclockwise cases. This trend becomes strong when the rotating speed is large as shown in Table 1. h_{det} and $\dot{m}/\dot{m}_{max}$ tend to be larger in the rotating conditions because of the centrifugal force. Figure 8 shows pressure distributions. The shape of the detonation wave is planner in the stationary and clockwise cases, but uneven in the counterclockwise case. This is because the detonation wave enters premixed jet pillars almost vertically in the stationary case and the clockwise case, but obliquely in the counterclockwise case. The red line in Fig. 7 indicates the turbine inlet of the actual disk-shaped RDTE. Figure 9 shows the angle of the velocity vector to the radial direction on this red line. The positive sign means that the velocity vector tilts clockwise. The turbine inlet angle becomes smaller in the clockwise case and becomes larger in the counterclockwise case compared with the stationary case. It would be preferable that the turbine inlet angle is small because the turbine is designed for flow to come in radial direction. Therefore, from the viewpoint of inflow into the turbine, the rotating direction of the disk and detonation should be opposite.

4 Conclusion

Two-dimensional numerical investigation on the behavior of detonation waves in a disk-shaped rotating combustor is carried out. First, the effect of the combustor shape of and the disk rotation are examined. The values of pressure and temperature of the annular domains are lower than those of the rectangular domain because the flow fields are more influenced by expansion. The detonation propagation velocity is almost the same as the CJ velocity both for the rectangular and annular domains. The detonation wave height and the injection rate are higher in the annular cases. This is because the reinjection time becomes earlier and the period when the premixed gas is injected at an almost constant value becomes longer for the annular domains. Second, the effect of the rotating speed and the rotating directions are investigated. Premixed jet pillars tilt to the left in the clockwise cases and to the right in the counterclockwise cases compared with the stationary case because of the Coriolis force. Therefore, the detonation propagation angular velocity relative to the disk becomes higher in the clockwise cases and lower in the counterclockwise cases. The detonation wave height and normalized mass flow rate becomes higher in the rotating conditions. The turbine inlet angle is smaller when the rotating direction of the disk and detonation is opposite and it would be preferable for the turbine.

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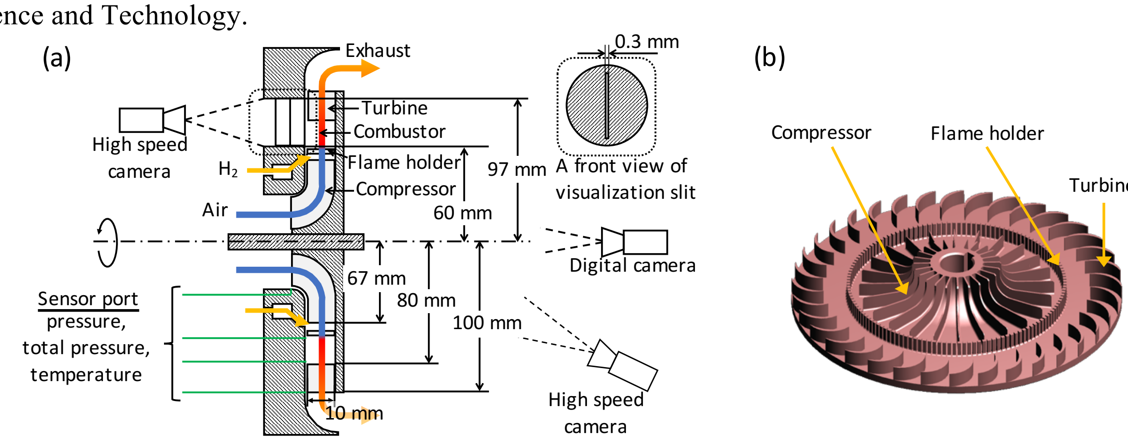

Figure 1. (a) Experimental equipment and (b) the disk that has a compressor, a combustor, and a turbine

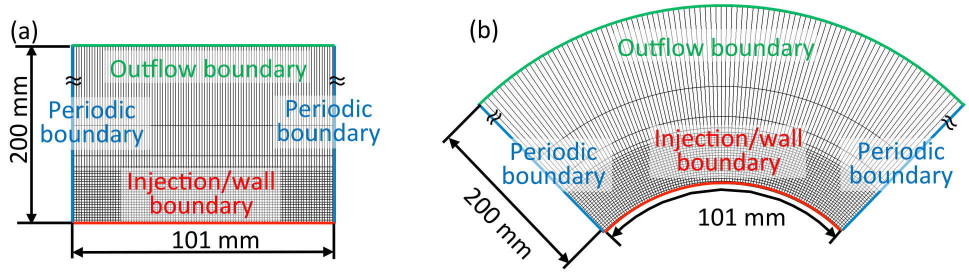

Figure 2. Computational grids for (a) the rectangular domain and (b) the annular domain

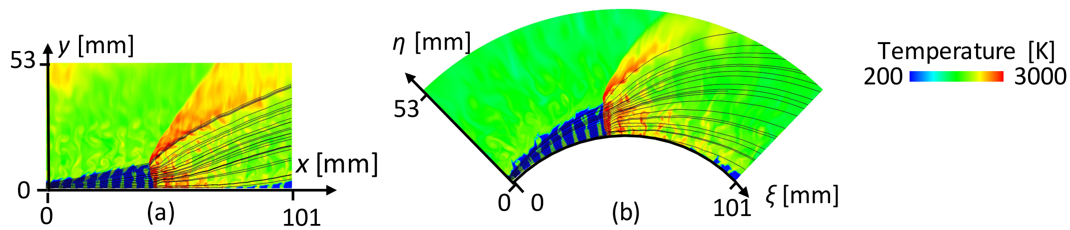

Figure 3. Temperature distributions and streamlines relative to the detonation wave for (a) the rectangular domain and (b) the annular domain

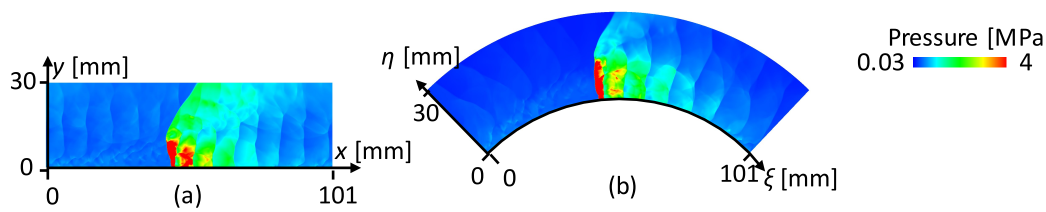

Figure 4. Pressure distributions for (a) the rectangular domain and (b) the annular domain

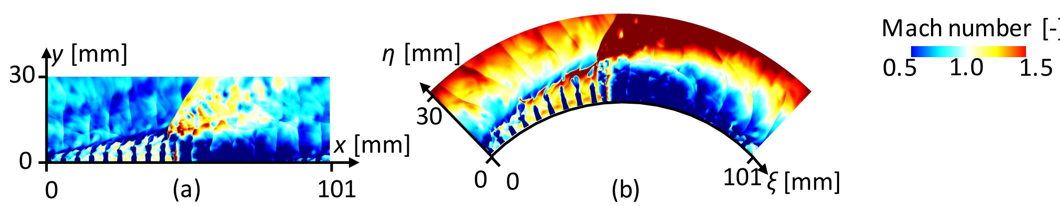

Figure 5. Mach number distributions relative to the disk for (a) the rectangular domain and (b) the annular domain. Mach number in the white region is approximately 1.0.

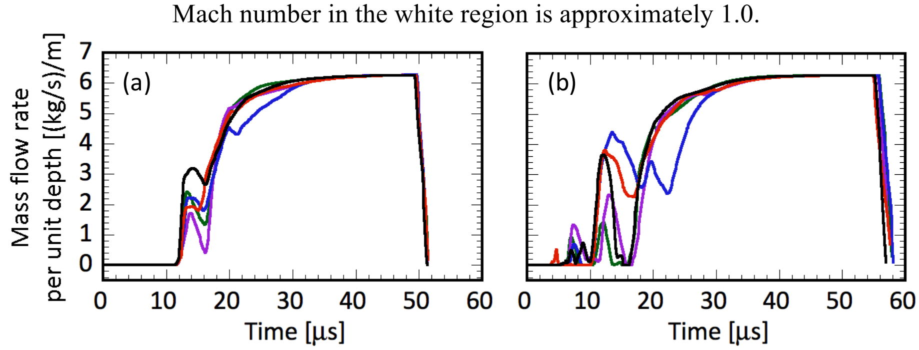

Figure 6. The mass flow rate histories per unit depth of 5 each injection slit for (a) the rectangular domain and (b) the annular domain

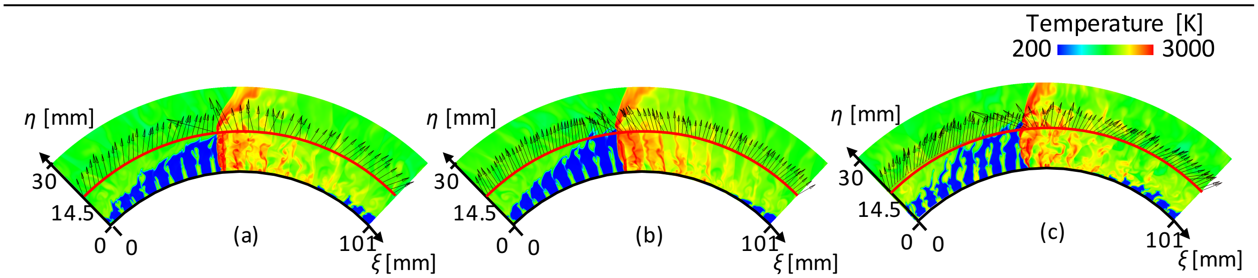

Figure 7. Distributions of temperature and velocity vectors relative to the disk in (a) a stationary case, (b) a clockwise case at 70000 rpm, and (c) a counterclockwise case at 70000 rpm

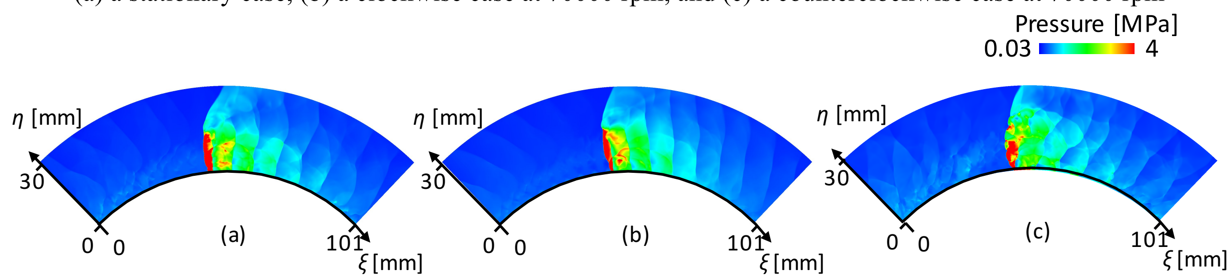

Figure 8. Pressure distributions in (a) a stationary case, (b) a clockwise case at 70000 rpm, and (c) a counterclockwise case at 70000 rpm

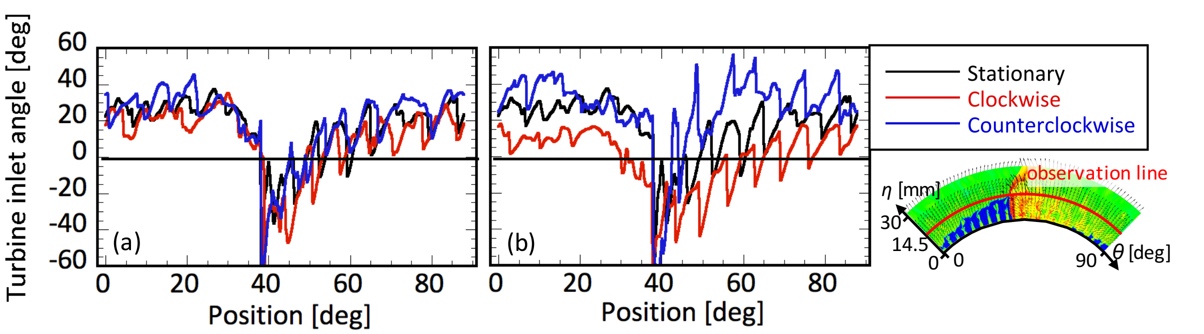

Figure 9. The angle of the velocity vector to the radial direction at (a) 20000 rpm and (b) 70000 rpm on the red line shown in Fig. 7. The positive sign means that the velocity vector tilts clockwise.

Table 1: Detonation wave height h_{det}, detonation propagation angular velocity relative to the disk ω_{det}, detonation propagation velocity normalized by CJ velocity D/D_{CJ} (the range means the values at the lower and upper end of the detonation wave), and normalized mass flow rate $\dot{m}/\dot{m}_{max}$ at all calculation conditions. The positive sign of ω_{disk} means that the rotating direction is counterclockwise.

Calculation condition		h_{det} [mm]	ω_{det} [rad/s]	D/D_{CJ}	$\dot{m}/\dot{m}_{max}$
Computational domain	ω_{disk} [rpm (rad/s)]				
Rectangle	—	10.4	—	0.989	0.628
Annulus	0	14.1	26500	0.880–1.05	0.665
	-20000 (-2090)	14.2	26800	0.891–1.08	0.671
	-40000 (-4189)	14.5	27000	0.896–1.09	0.672
	-70000(-7330)	15.3	27200	0.904–1.11	0.674
	20000 (2090)	14.1	26000	0.852–1.03	0.673
	40000 (4189)	14.6	25700	0.853–1.04	0.679
	70000(7330)	16.2	24600	0.816–1.02	0.709