3D Numerical Simulation on Rotating Detonation Engine : Effects of Converging-Diverging-Nozzle on Thrust Performance

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1. Introduction

Detonation is a shock-induced combustion wave propagating through a reactive mixture and it has been investigated for the safety engineering. Pulse detonation engine (PDE) is a constant-volume-like combustion engine with a supersonic detonation wave. PDE has recently been recognized as one of new propulsion systems for supersonic transportation. The theoretical thermal efficiency of the detonation engines is known to be better than the conventional constant-pressure combustion engines [1]. PDE provides a better efficiency than the ramjet engines with respect to fuel-based specific impulses (Ispf); however, the thrust under the high frequency becomes small because of the pulsed-flow operation [1].

Recent researches about propulsion using the detonation are focused on the rotating detonation engine (RDE), which obtains a continuous thrust by using a rotating detonation in a coaxial chamber. The continuous thrust force of RDE is the most notable different from PDE. RDE was first studied by Voiseknovskii [2], and he investigated the spin detonation propagating in the cylinder. Nicholls et al. [3] concluded that there are many tasks for the injection of the combustible gas mixture in order to stabilize the rotating detonation. Zhdan et al.[4] studied by the experimental and numerical approaches to understand the continuous rotating detonation phenomena and they estimated the suitable length of the combustion chamber. Wolanski et al.[5] and Lu et al.[6] had also experimentally studied. As for the numerical approach, Hishida et al.[7] estimated the detailed shock structure of the rotating detonation. Yi et al.[8] simulated RDE with some exhaust nozzles to show the possibility of new propulsive engines. Yamada et al.[9] also simulated the 2D RDE to understand the mechanism of transverse wave required for the continuous detonation. Nordeen et al.[10] and Schwer et al.[11],[12] simulated RDE in hydrogen/air mixture. Zhou et al.[13] simulated hydrogen/oxygen RDE, however, they did not show the value of Isp. The authors simulated the 3D RDE to show that Isp of RDE is larger than the conventional rocket engine [14].

Recently, RDE with the nozzle is researched in order to improve the thrust performance. Brent et al. [15] had experimental study of RDE with the converging-diverging(CD) nozzle to reduce the oscillation in the exhaust flow. This is because the exhaust oscillation is one of the major disadvantages to apply to a gas turbine engine. However, there are many unclear phenomena, such as the details of the flow structure in the internal flow, the effect of the nozzle geometry, and the effects

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of the mass flow ratio on the thrust performance. In the present study, the 3D simulations for RDE with the CD nozzle are performed to find the effect of nozzle geometry on Isp and exhaust oscillation.

2. Computational method

2.1 Numerical Methods

The governing equations are the three-dimensional Euler equations with the detail chemical reaction model. The governing equations include 9 species (H_2, O_2, O, H, OH, HO_2, H_2O_2, H_2O, N_2) mass conservation equations. A second-order AUSMDV [16] is used for the numerical flux in the convective terms. In the time integration, the third-order TVD Runge-Kutta method is applied. UT-JAXA[17] model is used for chemical kinetics to solve the detonation problems. The chemical reaction source terms are treated in a linearly point-implicit manner to avoid the stiffness problem.

2.2 Computational Domain

The computational domain of the 3D simulation is the coaxial chamber attached with the CD nozzle. 1D detonation results are pasted along the circumferential direction to start the rotating detonation.

There are two boundary condition systems for the mixture injection: the supersonic and subsonic inlets. The supersonic inlet condition is used for most of the simulations because the inlet nozzles for premixed gas typically have a choked condition at the exits of small nozzles. However, many real cases should use a subsonic inlet condition because of the high pressure in the combustion chamber. The subsonic inlet condition is proposed by Zhdan et al [4]. The outlet boundary conditions are given at the exit of the RDE by two patterns, but the flow cannot go backwards from the downstream to the upstream:

(1) The exit pressure of the RDE sets the ambient pressure when the exhaust gas speed is subsonic.

(2) The exit pressure of the RDE is extrapolated from the values in the combustion chamber when the exhaust gas speed is supersonic.

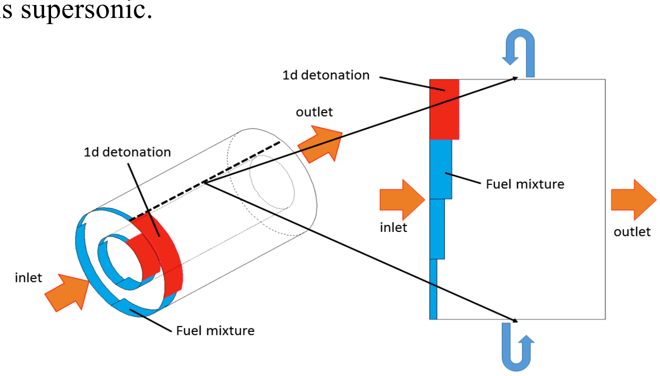

Figure 1. Modeling of 3D RDE.

2.3 Grid System and Simulation Condition

The three-dimensional grid system of the RDE with the CD nozzle is shown in Fig.2. The computational grid points are 241(axial) x11(radial) x601(circumferential). The minimum grid widths near the rotating detonation area are 5 μm for the axial direction, 9.4 μm for the radial direction, 3.93 and 4.95 μm for the inner and outer circumferential directions, respectively. Therefore, the radius ratio R_{outer}/R_{inner} is 1.25. The fine grid system is adopted near the rotating detonation head and the coarse grid system is adopted in another region. The nozzle geometry is designed based on the nozzle in the reference of Brent et al.[14] The nozzle consists of the long constant cross-section area, the short converging section, and the diverging section. In the conical nozzle section, the area ratio of the exit to the throat sets 1.98 to produce supersonic flow with Mach number of approximately 2.2 under the isentropic condition.

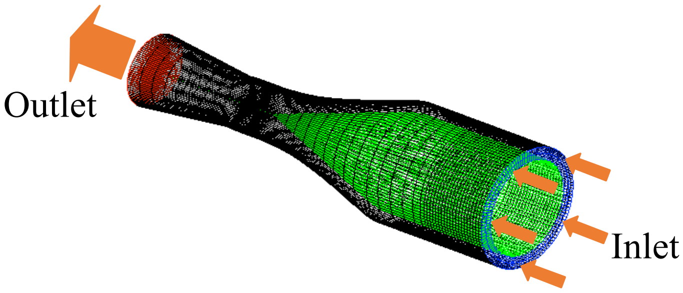

Figure 2. 3D grid of RDE with C-D nozzle (241x11x601).

The ambient conditions behind the nozzle exit are the pressure p_e of 0.01 MPa, and the temperature of 300 K, respectively. The present simulation conditions in the stagnation chamber are the pressure p_0 of 5 MPa and the temperature T_0 of 300 K. The micro nozzle area ratio of throat to nozzle exit at the injection port, A*/A, is 0.1. The stoichiometric H_2/O_2 gas mixture is supplied through the micro-nozzles.

3. Results and discussions

3.1 Effects of the nozzle on exhaust oscillation

Figure 3 shows the time history of the averaged pressure at the nozzle exit section. The exhaust oscillation is considerably reduced by the present CD nozzle in Fig.3. The variation of the time-averaged pressure is approximately 0.01 MPa and the ratio to the time-averaged value (approximately 0.34 MPa) is 3%. The exit Mach number profile in Fig.4 is similar to the pressure profiles. In this figure, the variation is approximately 0.02 and the ratio to the time-averaged value (approximately 2.00) is 1%. This is because the flow is choked at the throat of the CD nozzle. As the above reason, the present CD nozzle can reduce the exhaust oscillation as shown in Ref. 14.

Figure 6 shows the instantaneous Mach number contours at the exit section. Figure 6(a) and (b) are the contours at the chamber exit plane with and without the CD nozzle, respectively. At the chamber exit, the averaged Mach number becomes subsonic in the case with the CD nozzle, however, that is supersonic without the CD nozzle. In the case of the CD nozzle, the shock wave disappears at the nozzle exit although the shock wave due to the rotating detonation appears at the chamber exit section.

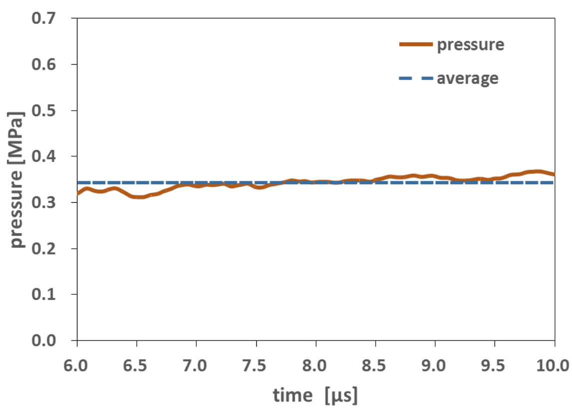

Figure 3. Effect of nozzle on exit pressure.

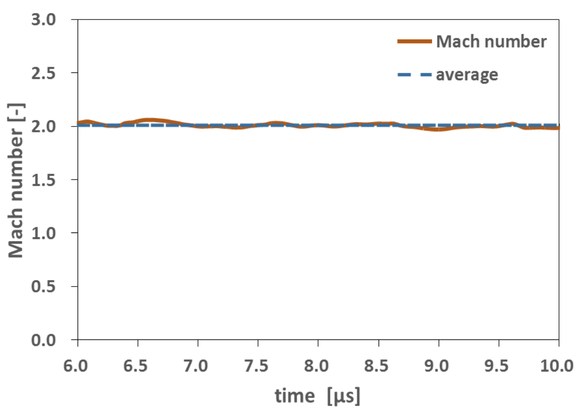

Figure 4. Effect of nozzle on exit Mach number.

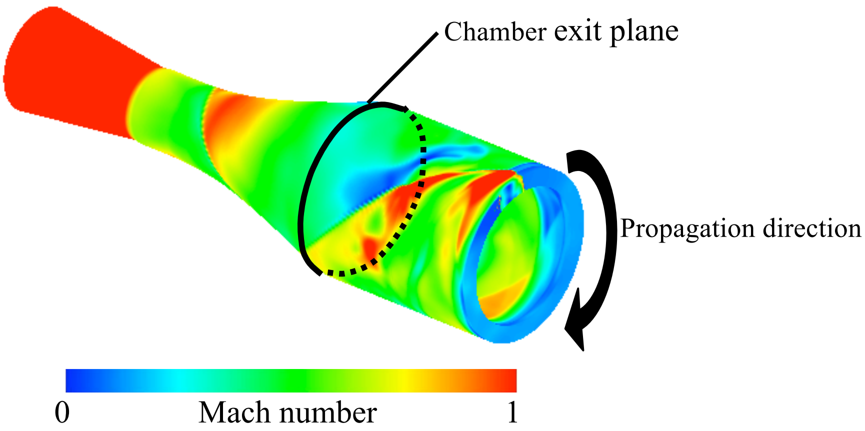

Figure 5. Instantaneous Mach contours of 3D RDE.

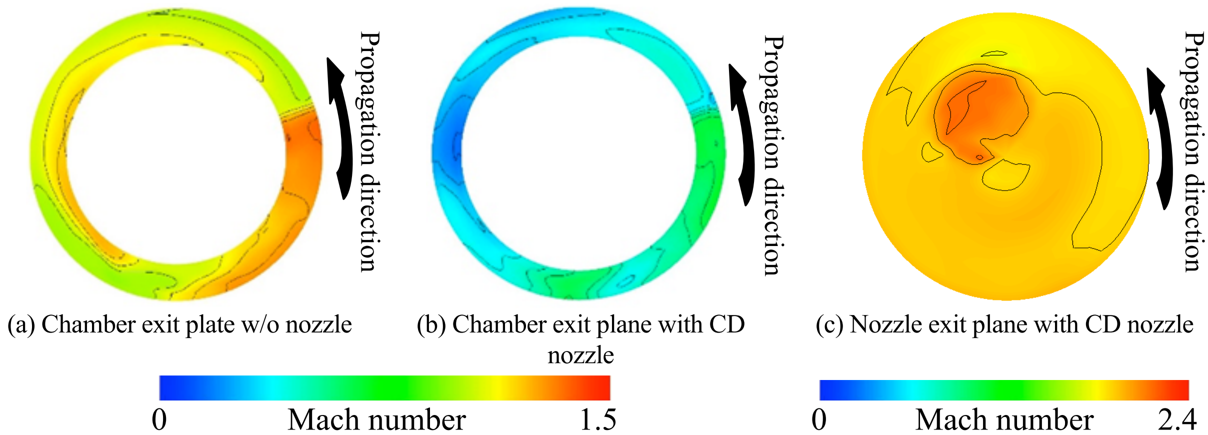

Figure 6. Instantaneous Mach contours at various sections.

3.2 Effect of the nozzle on Isp

Table 1 shows the comparison of averaged Isp during five cycles after the steady RDE is obtained. This table also includes the calculated Isp for a H_2/O_2 rocket engine with and without the nozzle, assuming a chemical equilibrium state under a vacuum environment. This value is calculated using the Gordon and McBride method [18]. Isp is based on the premixed gas mixture. The CD nozzle improves Isp for approximately 90 sec. (33%) larger than that without the CD nozzle. Isp for RDE with the CD nozzle is actually greater than Isp of a conventional rocket engine.

Table 1. The comparison of I_{sp} between w/ and w/o nozzle.

	w/o nozzle	w/ nozzle
3D RDE	275.7 [sec]	363.2 [sec]
Chemical equilibrium	274.3 [sec]	328.6 [sec]

4 Conclusions

Three-dimensional numerical simulation of the 3D RDE with the CD nozzle is performed using the H_2/O_2 detailed chemistry model. The conclusions are as follows:

- The present CD nozzle reduces the pressure oscillation at the nozzle exit. The amount of the variation of the pressure from the time-averaged value is approximately 3% and that of Mach number is approximately 1%.

- The present CD nozzle affects Isp and the improved value is approximately 33%.

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