Thrust Performance Estimation on Rotating Detonation Engine Using Two-dimensional Numerical Simulations: Isp under Low-pressure Environment

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1 Introduction

Detonation is a shock-induced combustion wave propagating through a reactive mixture and has been investigated from the safety engineering by past studies. Pulse detonation engine (PDE) is a constant-volume-like combustion engine with a supersonic detonation wave. PDE is recently recognized as one of new propulsive systems for supersonic transportation. The theoretical thermal efficiency of the engine applied detonation is known to be better than the conventional constant-pressure combustion engines. PDE provides a better efficiency than ramjet engines with respect to fuel-based specific impulses (Ispf); however, absolute thrust of PDE is smaller due to its essential pulsed flow.

Recent propulsive research using detonations is focused on a rotating detonation engine (RDE), which obtains a continuous thrust by using rotating detonation in a coaxial cylinder. Producing thrust force continually is the most notable difference with the PDE. RDE is first studied by Voiseknovskii [1] in 1959, and he investigated the spin detonation propagating in the circle. It is known prototype Nicholls et al. [2] in 1966, they concluded that there are many tasks for the injection of combustible gas mixture such as stable operation of rotating detonation due to put the RDE to practical use. Zhdan et al. [3] studied by the experimental and numerical approaches to understand the continuous rotating detonation phenomena and required length of the combustion chamber. Wolanski et al. [4] and Lu et al. [5] are also experimentally studied successfully. As for the numerical approach, Hishida et al. [6] discovered the shock structure of rotating detonation. Yi et al. [7] simulated RDE with some exhaust nozzles to show the possibility of new propulsive engines. Yamada et al. [8] also simulated to understand the mechanism of transverse wave required for the continuous detonation in two-dimensional RDE. These researches, however, three-dimensional shock structure rotating in the coaxial tube with deep chamber depth does not researched well as well as its thrust performance. Although the thrust performance in these researches are performed under the atmospheric pressure such as 0.1 MPa, it is necessary to estimate accurate Isp under a flight environment .

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In this study, thrust performance on the rotating detonation engine by using the two-dimensional numerical simulations are estimated under a low-pressure environment in order to find the effects of the background pressure on the thrust performance.

2 Analytical Methods

2.1 Numerical Methods

The governing equations are the two-dimensional Euler equations with the detail chemical reaction model. The governing equations include 8 species (H_2, O_2, O, H, OH, HO_2, H_2O_2, H_2O) mass conservation equations. The convection term is evaluated by AUSM-DV scheme. In the time integration, Strang-type fractional step method is applied. The chemical reaction model is Petersen & Hanson model. The integration of the source term is the point implicit method.

2.2 Computational Domain

In this study, 2D computational domain on the outer surface of the 3D coaxial tube is used as shown in Fig. 1. The periodic boundary condition is applied on the top and bottom boundaries. 1D detonation results are put to start the rotating detonation. There are two boundary condition systems for gas injection; one is the supersonic inlet condition and another is the subsonic inlet condition. The supersonic inlet condition is used since the inlet nozzles for fuel usually have a choked condition at the exit of small nozzles. However the most of real cases may have a subsonic inlet condition. The subsonic inlet condition is discussed by Zhdan et al. [3]. The exit boundary conditions are given by two patterns as not to flow backward from the downstream to upstream as follows;

(1) The exit pressure is extrapolated from the ambient pressure at the cases that the exhaust speed is subsonic. The other variables are extrapolated and the temperature is calculated by the equation of gas state.

(2) All variables at the boundary are extrapolated from the upstream values when the exhaust speed is supersonic.

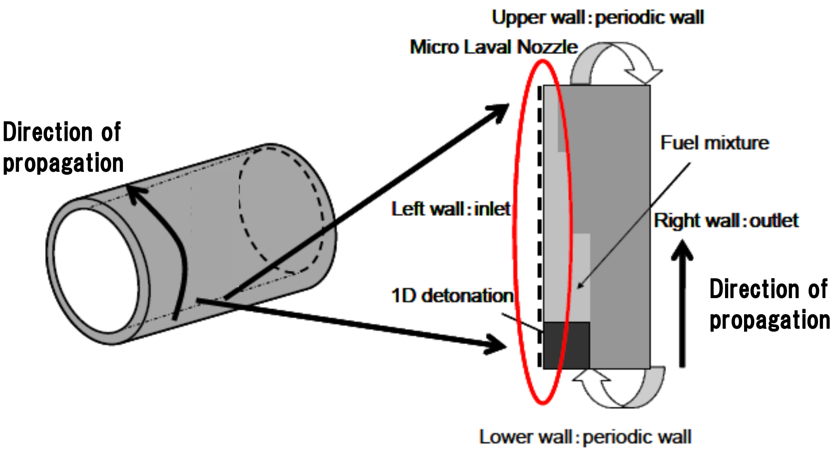


Figure 1. 2D calculation domain.

2.3 Grid System and Simulation Conditions

The simulation conditions and grid system used in this study are shown in Table 1. In the two-dimensional simulations, orthogonal grid system clustering near the inlet is employed. The ambient conditions behind the exit are the pressure p_e of 0.1 and 0.01 MPa, the temperature of 300 K. The present simulation conditions in the stagnation chamber are the pressure p_0 of 4, 5, and 6 MPa. The micro nozzle area ratios of throat to nozzle exit, At/Ae, are 0.0657 and 0.1. The stoichiometric H_2/O_2 gas mixture is supplied from the micro nozzles.

Table 1. Computational domain

2D calculation domain	
The number of grid points	301x601
Grid size in x and y directions	5 μm

3. Results and Discussions

3.1 Comparison between 2D and 3D simulation

At first, the comparison of Isp between 2D and 3D simulations is shown in Fig. 2 because 3D simulations require computational cost. Some important parameters are selected by 2D simulations then some cases in 3D simulations will be simulated in the future. This figure shows the effect of stagnation pressure p_0 on Isp between 2D and 3D simulations. Isp of 2D simulations is 10~15 second higher than that of 3D simulations. These differences are approximately 5%. This is because detonation velocity along the inner wall is approximately 15% lower than CJ velocity [8]. Although there exist dimensional effects, Isp changes of 2D and 3D show the same tendency.

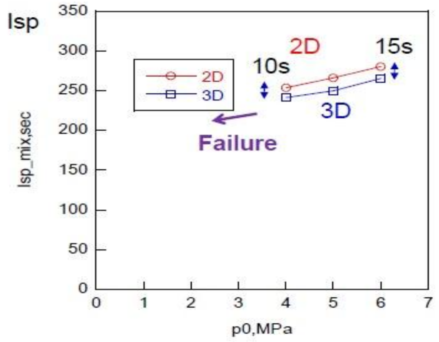


Figure 2. Dimensional effects on Isp.

3.2 Effects of Ambient Pressure on Isp

First, comparison of flow structure in RDE is carried out. The result shows structure of the detonation wave flow in RDE is shown in Fig. 3. The red area is high pressure region due to the rotating detonation. Figure 4 shows the instantaneous temperature contours during the cyclic detonation wave propagating in RDE in Fig. 4. In the simulation condition, the ambient pressure, p_e, is 0.1 MPa at case(a) and 0.01 MPa at case (b). The stagnation pressure, p_0, is 4 MPa and the micro-nozzle area ratio, At/Ae, is 0.0657 at both cases. The difference between them is small. Therefore, ambient pressure does not affect propagating detonation wave. Figure 5 shows the effects of ambient pressure on Isp. The simulation conditions are similar to Fig. 4. At the inlet section in Fig. 5(a), overall features between them coincide. This means that the rotating detonation head does not affected by the ambient pressure. At the exit section, similar feature between them is shown in Fig. 5(b) and the flow speed at the exit is supersonic.

The effects of ambient pressure on Isp are shown in Fig. 6. The simulation conditions are A_t/A_e=0.0657 and 0.1, and p_e= 0.01 and 0.1 MPa, respectively. This figure shows that Isp increases as the stagnation pressure increase and Isp also increase as the ambient pressure decrease. The difference of Isp between p_e=0.01 and 0.1 MPa is approximately 20-30 s. This is because the pressure thrust caused by the difference between inside section of RDE and ambient region.

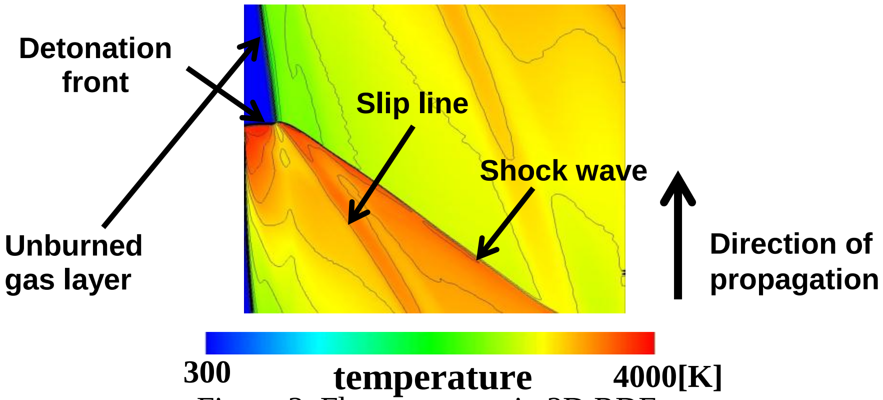
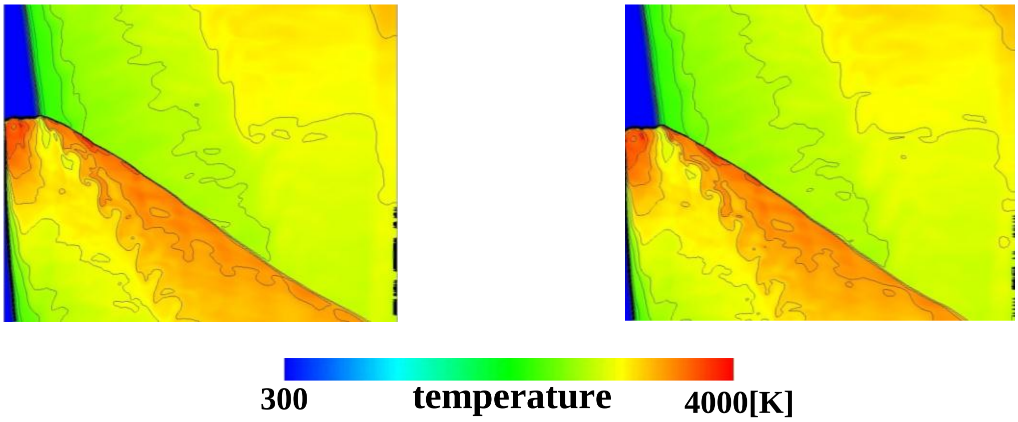
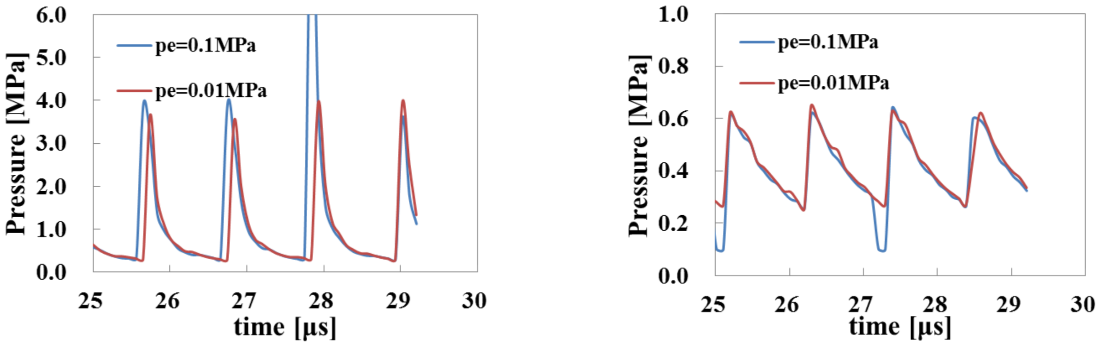


Figure 3. Flow structure in 2D RDE.



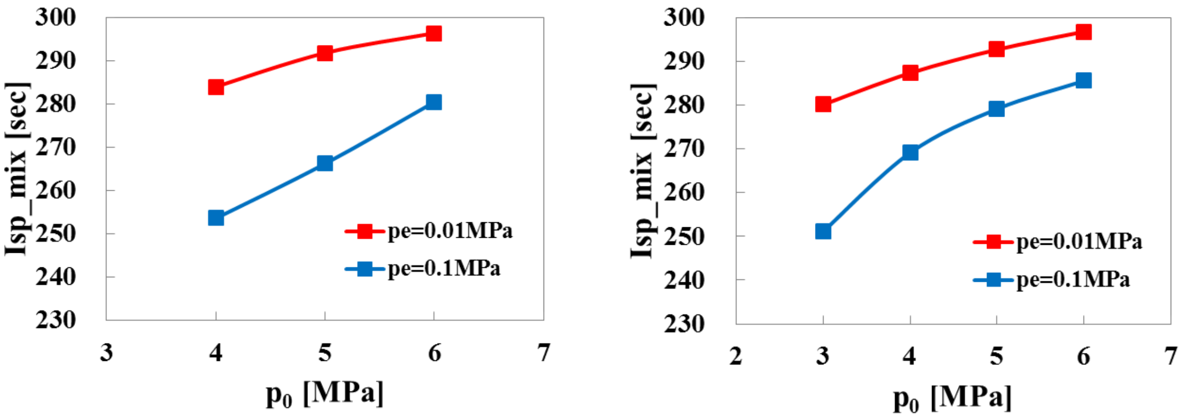
(a) p_e=0.1MPa (b) p_e=0.01MPa

Figure 4. Instantaneous temperature contours in RDE.



(a) inlet section (b) exit section

Figure 5. Comparison of instantaneous pressures profiles.



(a) A_t/A_e =0.0657 (b) A_t/A_e =0.1

Figure 6. Effects of ambient pressure on Isp.

4. Conclusions

The effect of the ambient pressure on the thrust performance of two-dimensional RDE is numerically investigated estimated. The shock structure of RDE and the instantaneous pressure at the exit section are independent of the background pressure, however, the difference of Isp between the ambient pressure of 0.01 and 0.1 MPa is approximately 20-30 s. This difference increases as the ambient pressure decreases. The difference of Isp between these conditions is due to the pressure thrust at the exit section of RDE.

Acknowledgements
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