Numerical Study on Detonation Propagation in Pulse Detonation Engine with Expanded Cross-section Area

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1. Introduction

A Pulse Detonation Engine (PDE) is expected as an engine for next generation aerospace vehicles. The PDE is engine which obtains a high thrust by generating a detonation wave intermittently. The study on the PDE includes the flow of basic research development of detonation and must be quickly proceeded towards application. Shortening of deflagration-to-detonation transition (DDT) distance is mentioned to one of the PDE subjects. Pre-detonator has as one trial of the DDT process shortening and the basic researches have been experimentally and numerically done by some researchers [1, 2, 3]. This pre-detonator is that detonation generates within a small tube, and it propagates to combustion chamber. The detailed propagation mechanism of the detonation wave in the tube accompanied by this cross-section area change and the effects of equivalence ratio is not clarified. The purpose of the present study is to investigate the detailed propagation mechanism and to estimate specific impulse I_{sp} for the combustion chamber with the pre-detonator by using numerical simulations with a detailed chemical reaction model.

2. Numerical Method

The governing equations are the Euler equations with 9 species (H_2, O_2, H, O, OH, HO_2, H_2O_2, H_2O, N_2) and 19 elementary reactions. The governing equations are explicitly integrated by the Strang type fractional step method. The chemical reaction source terms are treated in a linearly point-implicit manner. A Harten-Yee non-MUSCL type TVD scheme is used for the numerical flux. In the present simulation, the Nagoya model proposed by Hishida and Hayashi [4] is used for chemical kinetics. Initial conditions in the combustion chamber (zone 2) are pressure of 1.0 bar, temperature of 300K and equivalence ratio, ϕ, changes from 0.5 to 1.5. Results of two-dimensional simulations are used as the initial conditions for the present simulations. The two-dimensional results in the pre-detonator (zone 1) are CJ detonation. Equivalence ratio is fixed to 1.0 in zone 1. The right (downstream) boundary in zone 2 treats as outflow boundary, and other boundaries in zone 1 and 2 are wall boundary. The wall boundary conditions are adiabatic, slip and non-catalytic. The outflow boundary conditions are that pressure is fixed at the ambient pressure of 1 atm and other variables are extrapolated for subsonic outflow case, and that all variables are extrapolated for supersonic outflow case. The grid size is 5 μm. This corresponds to a resolution of 32 grid points in the theoretical half reaction length which for H_2 at atmospheric pressure equals 1.6×10^{-4}m. Width of zone 1, D_1, is 2.0 mm and that of zone 2, D_2, is 3.0, 4.0 and 6.0, respectively. Therefore the width ratios of zone 2 to zone 1 are 1.5, 2.0 and 3.0.

3. Results and Discussions

Figure 1 shows initial conditions in zone 1. Figure 1(a) is pressure contours, and figure 1(b) is maximum pressure history. For the CJ detonation simulations, the present results show significantly irregular cells because of the reaction model. The feature of the present detailed reaction model is discussed in Ref.[5].

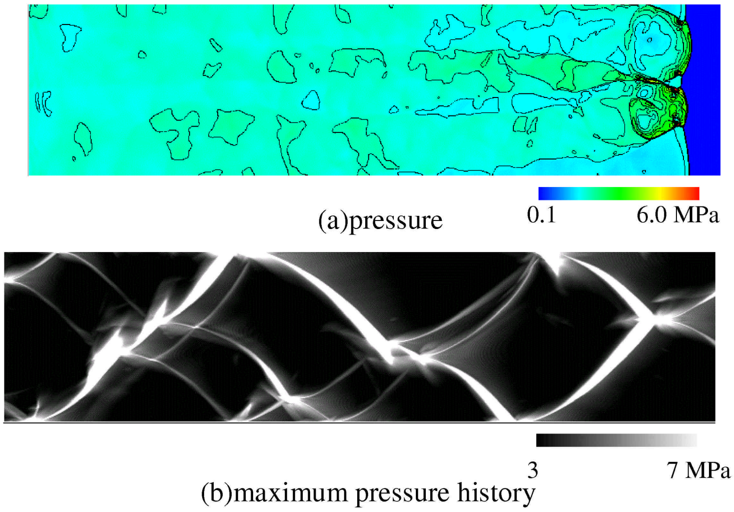

Figure 1. Initial conditions of zone 1.

3.1. Effects of width ratio

Figure 2 shows pressure contours at various times for D_2/D_1=1.5, $\phi = 1.0$. The detonation expanded from zone 1 maintains with a reconstruction of the cellular pattern in zone 2. Figure 3 shows maximum pressure history for various width ratios. For D_2/D_1=1.5, two cellular pattern is observed in zone 1 and the detonation propagates in zone 2 with a reconstruction of cellular pattern. However, for D_2/D_1=2.0, the detonation quenches in zone 2 once, then an explosion on the wall occurs and an initiated detonation propagates. For D_2/D_1=3.0, the detonation completely quenched in zone 2. In this simulations, the detonation is maintained in zone 2 for D_2/D_1=1.5 and 2.0 whereas disappears for D_2/D_1=3.0.

Figure 4 show the effects of width ratios on impulse and I_{sp}. Impulse and I_{sp} are measured as the single cycle PDE. For the re-initiation cases (D_2/D_1 = 1.0 - 2.0), impulse decrease and I_{sp} has a constant values as the width ratio increases. However, for the quenching cases ($D_2/D_1 = 2.5 - 3.0$), impulse decreases suddenly and I_{sp} has approximately 20% lower value than that for the re-initiation cases. Therefore it is concluded that I_{sp} has a constant value (approximately 4000 sec.) for the re-initiation cases and it becomes 20% descent for the quenching cases.

3.2. Effects of equivalence ratio

Figure 5 shows the effects of equivalence ratio on the detonation propagation. The effects of equivalence ratio have been simulated for a non-predetonator case in Ref.[6] and it is shown that I_{sp} decreases as the equivalence ratio increases. So the effects on the present configuration have to be estimated in order to compare the non-predetonator configuration. The detonation completely disappears in zone 2 for ϕ=0.5 whereas the other cases maintain the detonation with a minor reconstruction. Therefore, the equivalence ratio significantly

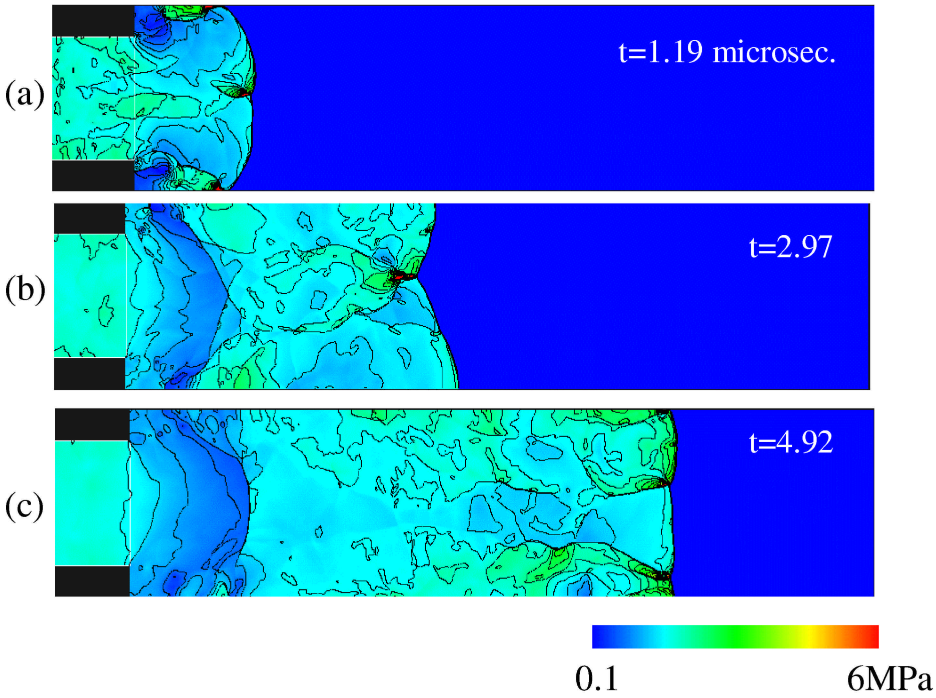

Figure 2. Pressure contours at various times for D_2/D_1=1.5, $\phi = 1.0$.

affects on the propagation in the present simulations.

Figure 6 show the effects of equivalence ratios on impulse and I_{sp} performance. Impulse has a maximum value at ϕ=1.0, and I_{sp} has a monotone descent for the equivalence ratio. Though the detonation disappears for $\phi = 0.5$ as shown in Fig. 5(a), there is no effects on the performance.

4. Conclusions

Unsteady two-dimensional simulations with hydrogen/air CJ detonations were performed in a combustion chamber with a pre-detonator. With regard to the effects of width ratio, the detonation for D_2/D_1=1.5 and 2.0 is maintained in zone 2 whereas disappears for D_2/D_1=3.0. The effects of equivalence ratio on the detonation propagation are also estimated and it is shown that the detonation completely disappears in combustion chamber for ϕ=0.5, however, the other cases maintain the detonation with a minor reconstruction. Impulse and I_{sp} performance was estimated for width ratio and equivalence ratio. They significantly depend on the detonation propagation such as re-initiation or disappearance for the width effects, and I_{sp} maintains approximately 20% loss for quenching cases comparing with the re-initiation cases.

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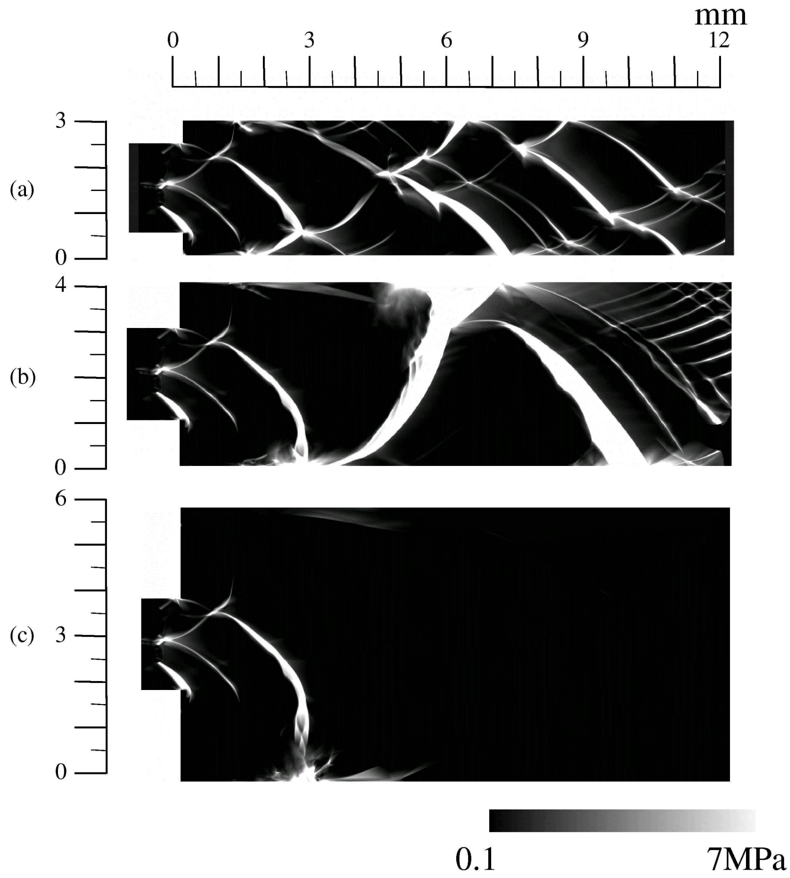

Figure 3. Maximum pressure history for various width ratio, $\phi = 1.0$. (a)D_2/D_1=1.5, (b)D_2/D_1=2.0, (c)D_2/D_1=3.0.

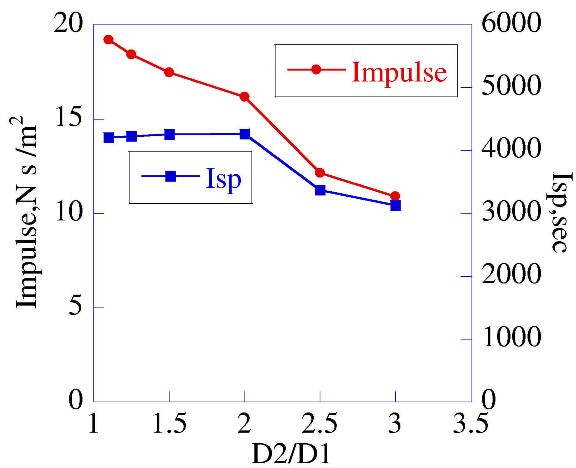

Figure 4. Impulse and I_{sp} performance for various width ratios.

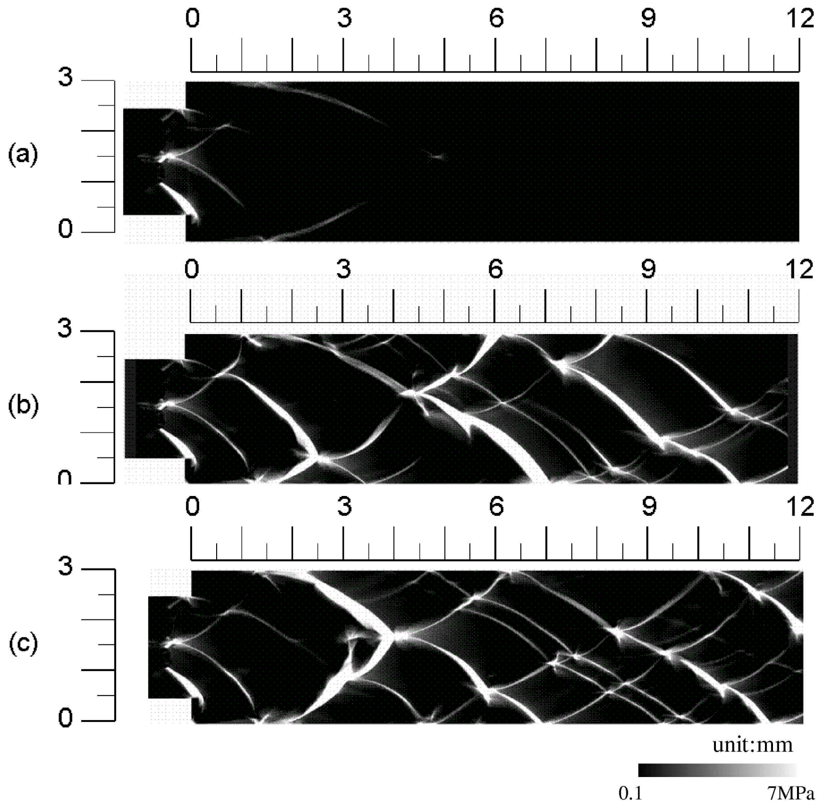

Figure 5. Maximum pressure history for various equivalence ratio for D_2/D_1=1.5. (a)$\phi = 0.5$, (b)ϕ=1.0, (c)ϕ=1.5.

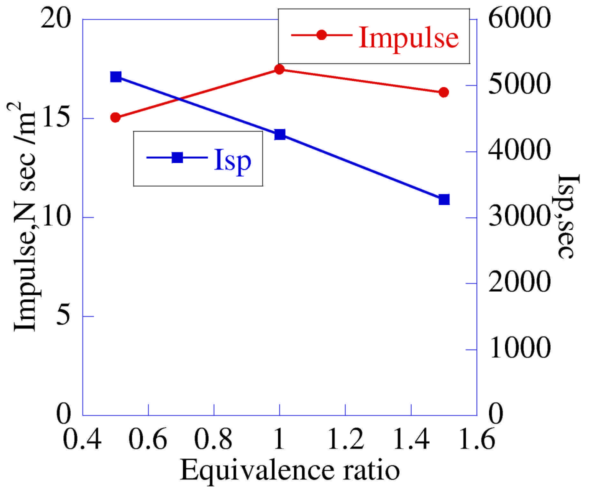

Figure 6. Impulse and I_{sp} performance for various equivalence ratios.

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