Shock Structure of Single Spinning and Two-headed Detonations in a Circular Tube

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Unsteady three-dimensional detonations in both a circular tube and a coaxial tube are simulated in order to reveal characteristics of single spinning and two-headed detonations. The numerical results show a feature of a single spinning detonation which was discovered in 1926. Transverse detonations are observed in both tubes, however, the single spinning mode maintains the complicated Mach reflection whereas the two-headed mode develops periodically from the single Mach reflection to the complex one.

1 Introduction

Spinning detonation and multi-headed detonation in a circular tube have been observed in the past experiments and have been studied in order to reveal their flow structure for over eighty years. The spinning detonation is the lowest mode propagating in a circular tube and it propagates with a helical track on the wall and rotates around the tube axis. Campbell and Woodhead first observed as the reproducible striations produced on high-speed photographic records of detonations in stoichiometric mixture of carbon monoxide and oxygen in 1926 [1, 2, 3]. Bone and co-workers systematically investigated the phenomenon and they concluded that spin was connected with the mode of coupling of the leading shock front and reaction zone[4, 5, 6].

Recent computational fluid dynamics (CFD) has yielded remarkable insight in these problems. One of the simulated results in a circular tube is done by Washizu et al. [7]. They simulated a spinning detonation in a coaxial tube by using a two-step chemical reaction model, however, their results do not mean a pure spinning detonation in a circular tube. We have simulated three-dimensional hydrogen/air detonation with a detailed chemical reaction model in a rectangular and a circular tube for about six years. We computed a cornstarch/oxygen two-phase detonation in a cylindrical tube and revealed a structure made up of a periodic two-headed detonation [8]. We recently simulated a single spinning detonation in a circular tube and begins to reveal its shock structure[9, 10, 11].

In this paper, we presented simulation of a single spinning and two-headed detonations in a circular tube and a coaxial tube in order to reveal their three-dimensional shock structures.

2 Numerical Method

The governing equations are the Euler equations with 9 species ($H_2, O_2, H, O, OH, HO_2, H_2O_2, H_2O$, and N_2) and 18 elementary reactions and they are explicitly integrated by the Strang type fractional step method. The chemical reaction source term is treated in a linearly point-implicit manner. A Harten-Yee non-MUSCL type TVD scheme is used for the numerical flux [12]. The Petersen and Hanson model is used for chemical kinetics to solve detonation problems. This model was proposed by Petersen and Hanson [13] as a new detailed chemical reaction model.

The computational mesh is a cylindrical system with 601x41x213 grid points without an axial insert. Radial grid points decrease with an axial insert to preserve similar resolution. The grid sizes are 5μm in the propagating direction, 10μm near the wall and 20 μm close to the center in the radial direction, and 15μm in the circular direction along the tube wall. Five micrometer corresponds to a resolution of 32 grid points in the theoretical half reaction length which equals 1.6 $\times$ 10^{-4}m for H_2 at atmospheric pressure. Therefore, computational domains are 3mm in length and 1mm in diameter. The present computed domain is small in order to maintain high resolution, however, the three-dimensional propagating structure can be revealed in such a small scale. The present simulation carried out for not only a pure circular tube but also coaxial tube with different diameter of the axial insert. The radius of the cylindrical axial insert in the tubes, r_1, is 0.1 mm and 0.4 mm, respectively. Therefore the ratio of the radius of the axial insert to that of the tube radius, r_1/R, are 0, 0.2, and 0.8, respectively.

The boundary conditions are as follows: the upstream conditions are at pressure of 0.1 MPa and temperature of 300K, and the inflow gas is stoichiometric with H_2/air gas mixture; the wall boundary conditions are adiabatic, slip, and non-catalytic; and the downstream condition is the non-reflected boundary proposed by Gamezo et al.[14].

The initial conditions for the one-dimensional simulations are given in two computational domains with high pressure in the vicinity of a closed end wall and low pressure. In the three-dimensional calculation the results from the one-dimensional simulations are used as an initial condition, and sheets of unburned gas mixture behind the detonation front are artificially created. These sheets are asymmetrically formed on the circular direction. Present simulations requires about 150 hours on 8 processors of a NEC SX-6 to obtain a steady detonation.

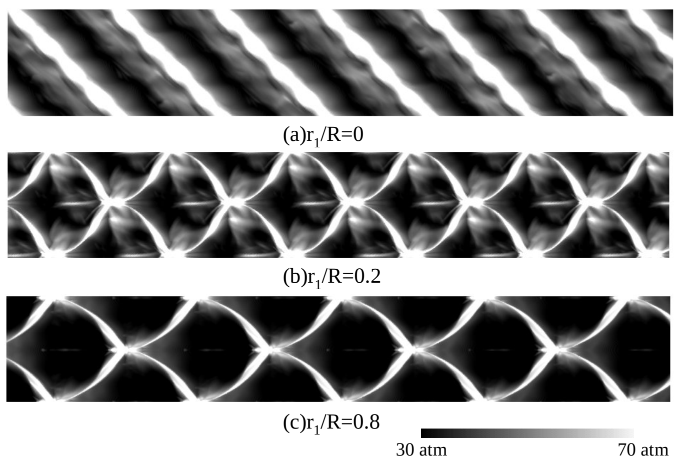

Figure 1: Maximum pressure history on the tube wall. Detonation propagates from left to right.

3 Results and Discussions

Figure 1 shows a comparison of maximum pressure histories on the wall with and without the axial insert. The average detonation velocities for three cases are approximately D=1980 m/s which is Chapman-Jouget value. A spinning detonation pattern which is observed experimentally resembles a "ribbon" wrapped in a loose spiral without the axial insert in Fig.1(a). The ratio of the pitch to the tube diameter in the experiments was approximately 3 and its theoretical value is 3.13[15]. The ratio in the present simulations equals 3.14 and agrees well with the experiments. This implies that the transverse wave velocity is approximately D=1980 m/s. In the cases with the axial insert, periodical two-headed cellular patterns are observed as shown in Fig. 1(b) and (c). The diameter of the axial insert affects on the cell aspect ratio and the cell length for $r_1/R = 0.8$ becomes longer than that for $r_1/R = 0.1$. These results indicate that the transverse wave is weakened as the diameter of the axial insert increases.

Figure 2(a) presents instantaneous detonation front shapes viewed from the front side at various times. A triple line forming a stationary Mach configuration with a strongly developed "leg" is observed near the left side wall. One "whisker", which is obviously together with the Mach leg, weakens rapidly with the increase of the distance from the wall of the tube. The Mach leg stands orthogonal to the tube wall. A transverse detonation, which exists behind the Mach leg and whiskers, rotates synchronistically. The Mach leg rotates in the clockwise direction continuously. Figure 3(a) shows instantaneous pressure

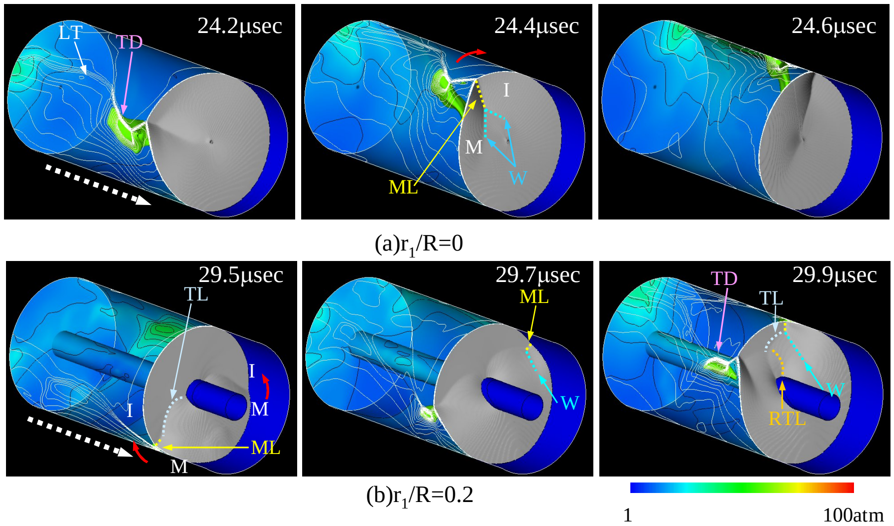

Figure 2: Comparison of instantaneous pressure space isosurfaces and contours in the tube at various times. The lime green space isosurface is pressure of 40atm. The gray space isosurface denotes the detonation front. The white broken arrow denotes the propagating direction of the detonation front, and the red arrow near the detonation front denotes the rotating direction. I - incident shock side, M - Mach stem side, ML - Mach leg, W - "whisker", TD - transverse detonation, LT - long pressure trail, TL - triple line, and RTL - reflected triple line, respectively.

contours on the wall. The stationary shock pattern near the detonation front rotates. The transverse detonation and long pressure trail appear behind the detonation front. The trail is generated by the spin head and follows after the Mach leg. The frequency of rotation of the trail coincides with that of the Mach leg. With increasing distance from the transverse detonation, the trail gradually degenerates into compression waves of finite amplitude.

Figure 2(b) shows instantaneous detonation front shapes with an axial insert of $r_1/R = 0.2$. Some triple lines propagate along the circumference and the other along a radius. This wave system is similar to the figure as shown in Ref.[16], and it is a typical two-headed detonation. Two curved triple lines, which propagate along the tube radius, appear on the detonation front at t=29.5μsec. A Mach leg standing orthogonally on the tube wall connects with the curved triple lines. The Mach leg rotates along the circumference. These two-headed time-dependent detonation fronts in a circular tube were reported in Ref.[8], however, the whiskers are not reproduced. Figure 3(b) shows instantaneous pressure and temperature contours on the tube wall. These results are similar to the two-dimensional detonation propagating in a channel. A single Mach reflection is observed at t=29.5 μsec and it changes a complex Mach reflection with a transverse detonation. This procedure repeats periodically. A pressure trail, which also appears in the spinning detonation, propagates behind the detonation front.

4 Conclusions

Unsteady three-dimensional simulations with a detailed reaction model were performed for hydrogen/air mixtures in both the circular tube and the coaxial tube in order to reveal their characteristics of single spinning and two-headed detonations. The instantaneous shock structures in both modes agree well with those reported in the experimental data. Transverse detonations are observed in both tubes, however, the single spinning mode maintains the complicated Mach reflection whereas the two-headed mode develops periodically from the single Mach reflection to the complex one.

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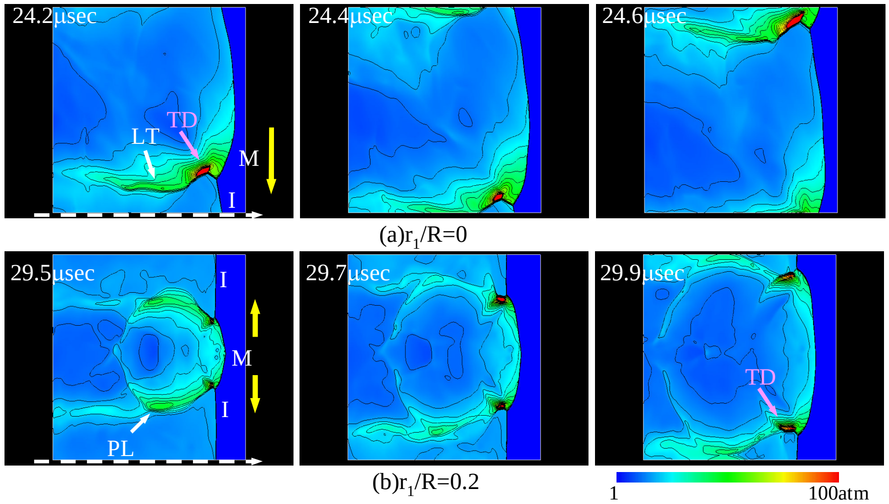

Figure 3: Comparison of instantaneous pressure and temperature contours on the wall. The white broken arrow denotes the propagating direction of the detonation front, and the yellow arrow near the detonation front denotes the rotating direction. I - incident shock side, M - Mach stem side, TD - transverse detonation, LT - long pressure trail, and PT - pressure trail, respectively.

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