Three-dimensional Wave Structure of Oblique Detonation around a Blunt Body

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1 Introduction

Oblique detonation wave has been studied as a phenomena used for a prospective propulsion system. Kaneshige *et al*. [1, 2] and Kasahara *et al*. [3-5] have reported about initiation and stabilization of oblique detonation induced by a hypersonic velocity projectile in premixed gas. Irregularity on the detonation wave is clearly observed in their instantaneous schlieren pictures. However, wave structure and unsteady combustion for oblique detonation wave are not clarified due to the difficulty of the observation on time-evolving unsteady combustion porcess.

Choi *et al*. [6] have reported numerically that the wave structure of wedge-induced oblique detonation in two-dimension has triple points. In their conditions, overdriven oblique detonations appear. The triple points on the detonation front move downstream and the collision of triple points does not appear. We have calculated CJ oblique detonation wave around blunt body at hypersonic flying speed in axisymmetric simulation [7]. The structure of the oblique detonation wave front and unsteadiness of the triple points are observed in detail. The blunt body flying at over CJ speed creates the strong shock wave attached with reaction front in the front of the projectile. The reaction front interacts with the bow shock in front of the projectile, where the shock angle is much larger than the oblique detonation angle. That area is called overdriven region. The direct interactions between the reaction front and the bow shock are observed on the side of the projectile at a certain interval on the bow shock. The wave structure looks similar to that of a planar detonation, but the transverse detonation wave is always facing upstream. When the detonation occurs, the angle of oblique shock wave is almost constant and equals the angles of theoretical oblique detonation. The collisions of triple points are similar to the planar detonation in that region. On the other hand, when the stabilized oblique detonation is not initiated by the projectile, the final shock angle is much smaller than theoretical oblique detonation angle.

In the present study, three-dimensional wave structure of oblique detonation around a hemispherical blunt body is numerically investigated. A comparison between three-dimensional results and two-dimensional axisymmetric data is conducted on the wave structure and the angle of oblique detonation.

2 Computational Setup

Oblique detonation around a hemispherical projectile with cylindrical afterbody is simulated by three-dimensional Euler equations. For chemical reactions, a simplified two-step chemical reaction model [8] is used. Thanks to this model the treatment of the reaction is easier than handing a realistic chemical system undergoing

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a number of elementary reactions. The basic physics of the flow field can be derived from this model as proved in the previous studies [9-11]. All the parameters in the present simulations come from Ref. 11. The gas is non-diffusive and assumed perfect with adiabatic index of γ=1.4. The equations are solved by finite difference method, and the unsteady solutions are obtained using time marching procedure. A second order in time and in space explicit difference scheme based on the non-MUCL total variation diminishing approach is used [12]. A computational domain is set around the blunt body, as shown in Fig. 1. The vertical span of the computational domain is four times as long as the projectile radius in accordance with the study of Kasahara *et al* [3-5]. The grid distribution is 301x51x301. The outer grid in the ζ direction is adapted along the shock wave. Figure 1 shows the grid distribution on a plane parallel to the flow direction and the outline of the computational domain. The initial pressure and temperature are set to be P_0=0.061 atm and T_0=293 K. The CJ detonation speed is D_{CJ}=1937 m/s under this gas condition. The projectile speed and diameter are V_p=2769.0 m/s and D=60 mm. The oblique detonation has appeared under this condition in the two-dimensional axisymmetric simulation [7]. The initial condition of three-dimensional calculation is taken from the two-dimensional axisymmetric solution of an oblique detonation.

3 Results and Discussion

Three-dimensional simulation features a huge computational cost. The basic features of oblique detonation wave were simulated using a limited number of grid points. Grid resolution study is conducted in order to save a computational cost. The higher resolution simulation with 901x601 grid points in two-dimensional calculation is carried out. This grid has been used in our previous work [7]. The pictures of pressure distributions are piled up shifting the projectile position at the flying speed in Fig. 2. Figures 2a and 2b show the pressure distributions of 901x601 and 301x301 cases. In both cases, the cell formation appears as well as two-dimensional planar detonation in the channel. The oblique detonations are well established in Figs 2a and 2b, where the shock angles reach the theoretical oblique detonation angle. Here, theoretical CJ detonation angle can be obtained from the following equation.

$$\theta_{CJ} = \sin^{-1}\left(\frac{D_{CJ}}{V_p}\right) \tag{1}$$

Equation 1 means that the normal component of projectile velocity to oblique detonation front is equal to CJ detonation speed. At this condition, the theoretical CJ detonation angle is 44.4˚. On the other hand, the cell size is different in Fig. 2a and 2b. The above results show that the coarse grid system makes the cell size bigger but can simulate the basic features of oblique detonation such as the wave angle and structure.

Wave structure and features of the three-dimensional oblique detonation are shown and compared with two-dimensional axisymmetric numerical simulation results. Figure 3a-3d show the time-evolving isosurface of pressure. Those surfaces correspond to shock fronts of oblique detonation. The wrinkled structure of shock front appears in this simulation results as well as the previous experimental study [1-5]. The winkle corresponds to the linear triple point. Figures 4a-4d show the time-evolving isosurface of progress variable β=0.5 of reaction. Those surfaces represent the burned-unburned boundary of oblique detonation wave. Each time of Figs. 4a-4d corresponds to that of pressure distribution of Figs. 3a-3d. The keystone-shaped reaction front, which is shown in the circle, appears in Fig. 4a. Those move in the direction of allow. Those keystone-shaped reaction fronts approach each other in Fig. 4b and collide in Fig. 4c as shown in the circle. These waves can propagate to circumferential direction, unlike two-dimensional axisymmetric numerical simulation results. The oblique detonation wave angle in three-dimensional numerical simulation almost equals that of two-dimensional axisymmetric simulation. The number of cells along the flow direction in three-dimensional simulation is 4. Therefore, the cell sizes between two-dimensional axisymmetric and three-dimensional oblique detonation are same level.

4 Conclusion

Oblique detonation around a spherical projectile flying into the combustible gas at speed higher than CJ detonation speed has been studied by two-dimensional axisymmetric and three-dimensional simulation. The results with 901x601 and 301x301 have been compared in two-dimensional axisymmetric simulation in order to simulate the basic wave structure with low computational cost. The coarse grid can simulate the basic features of oblique detonation such as the wave angle and structure. In three-dimensional simulation results, the wrinkled structure of shock front have appeared as well as the previous experimental studies by Kaneshige *et al.* [1-2] and Kasahara *et al* [3-5]. The winkle consists of the linear triple point. The keystone-shaped reaction front has been observed behind some wrinkle-structured shock. The line of triple point moves in circumferential direction. Three-dimensional simulation result agrees with two-dimensional axsimmetric in the oblique detonation angle and cell size. Further observations on unsteadiness and wave structure of the three-dimensional oblique detonation will be presented at the conference.

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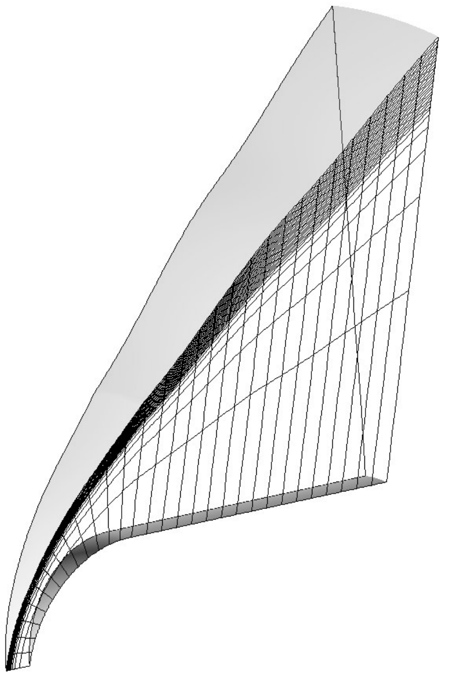

Fig. 1 Every 10th point of three-dimensional computed grid on k=1

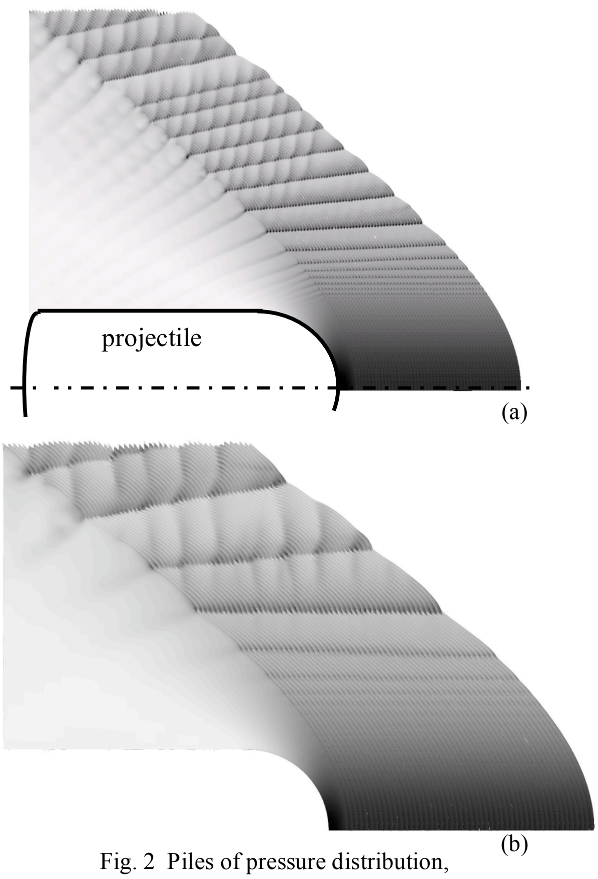

Fig. 2 Piles of pressure distribution, (a) 901x601, (b) 301x301 grid points

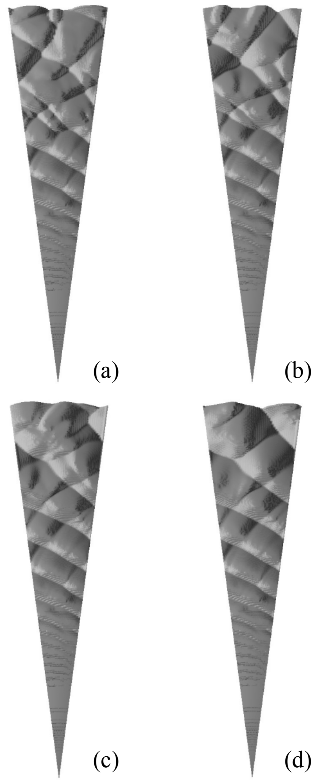

Fig. 3 Time evolving distribution of shock front in 3D calculation.

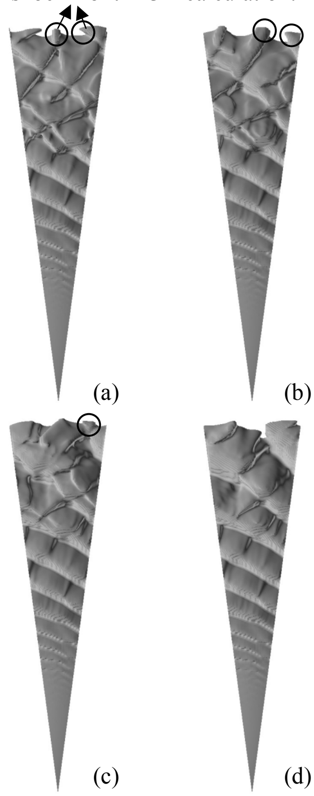

Fig. 4 Time evolving distribution of reaction front (β=0.5) in 3D calculation.