Three-Dimensional Numerical Simulation of Shock-Induced Combustion Around a Blunt Body

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1 Introduction

As a fundamental research of supersonic combustion, shock-induced combustion around a hypervelocity projectile has been investigated by means of many ballistic range experiments. Lehr performed one of the most famous experiments in 1972 [1]. He caught the unsteady shock-induced combustion on shadowgraph pictures at the specific conditions, in which periodic oscillation of reaction front is clearly recognized.

The oscillation pattern of unsteady shock-induced combustion is classified into two regimes —— regular regime and large-disturbance regime, depending on the manner of the oscillation. The regular regime, which was observed in Lehr's experiment, has a high-frequency oscillation, and the formation of the reaction front is very periodic. On the other hand, the large-disturbance regime has a low-frequency and less regular oscillation. In this regime, the variation of the reaction front is significant and the front part of the bow shock is distorted apparently.

Shock-induced combustion has been also investigated by numerical simulations. Matsuo and Fujii [2] carried out the two-dimensional simulation under the axisymmetric assumption for the regular regime of Lehr's experimental conditions. Their results well agree with the experimental ones.

The instability, which causes such a shock-induced combustion of regular regime, has not been investigated with three-dimensional computational space around a blunt body. In the present study, the instability in front of the projectile is clarified with the time-evolving three-dimensional data. Furthermore, the validity of the previous numerical works under the axisymmetric assumption is confirmed by the comparison with the simulation results including three-dimensional effects.

2 Analysis Object and Numerical Method

We simulated one of Lehr's experimental conditions [1] in three-dimensional computational space; a blunt body projectile of 15mm diameter flying into the stoichiometric hydrogen-air mixture at 1931m/sec. The computational domain is shown in Fig. 1, which is limited around the hemispherical blunt body. The number of grid points is 161x161x241, and grid points are equally distributed in each direction.

Two-dimensional axisymmetrical computational procedure by Matsuo and Fujii [2] is expanded to three-dimensional one. The governing equations are three-dimensional Euler equations with two-step chemical reaction model. Yee's non-MUSCL type 2nd order total variation diminishing (TVD) explicit scheme is used to solve the equations, in which the source term is treated in a point-implicit manner. Two-step chemical reaction model proposed by Korobeinikov et al. [3] represents the reaction mechanism with two phases — induction and exothermic period, based on the ZND model. In this model, induction progress variable α changes from 1 to 0 (exothermic progress variable β is constant with 1) in the induction period, and β changes from 1 to β_{eq} (α is constant with 0) in the exothermic period. This simplified model help reduce the computational load.

3 Results and Discussion

Figure 2 shows the isosurfaces of induction progress variable $\alpha = 0.98$ and exothermic progress variable $\beta = 0.9$, which are approximately corresponding to the positions of the bow shock and the reaction front, respectively. The oscillation pattern of the reaction front is almost axisymmetric in the side view of Fig. 2 (a), but the front view of Fig. 2 (b) indicates that the oscillation is not completely uniform around the projectile. Figure 3 shows the time evolution of the reaction front and the reaction progressing region, which is represented by source term of the governing equations $\rho\omega_\beta$, where ρ denotes the density and $\omega_\beta = d\beta/dt$. As shown in the figures, formation of the new reaction front is not occurring on the axis. Consequently, oscillation cannot be axisymmetric completely. However, formations of new reaction fronts are occurring adjacent to the axis and the distribution of the exothermic region is almost axisymmetric. Therefore, it will be appropriate to consider the regular regime to be an axisymmtric phenomenon. The shadowgraph image of the flow field in Fig. 4 (a) is generated from the three-dimensional computational result by the post processor to compare with experimental outputs directly. In this image, the vertical lines are clearly observed inside the corrugated reaction boundary as well as that of Lehr's experimental shadowgraph picture.

In order to confirm the validity of the previous computational works using the axisymmetric assumption, the result of the three-dimensional (3D) simulation is compared with the two-dimensional (2D) axisymmetrical one. Shadowgraph images, density contour distributions on the stagnation streamline, and shock front pressure histories are used for the comparison. Figure 5 show the shadowgraph image of the axial cross-section at arbitrary moment; (a) is from 2D simulation and (b) is from 3D simulation, which is obtained by the average of the simulation data of all axial cross-sections in the circumferential direction. Two images in Fig. 5 well agree in overall flow field. Both density contour distributions on the stagnation streamline in Fig. 6 (a) and (b) show the typical wave interaction mechanism of the regular regime suggested by Matsuo and Fujiwara [4]. The periods of oscillation estimated from the figures are about 1.42μs for the 2D and 1.49μs for the 3D. These values are nearly equal to the measured value by Lehr (1.405μs). Figure 7 shows the history of the shock front pressure, normalized by the steady shock pressure of the flight mach number. The periods and the amplitudes of the oscillation of the shock pressure in two simulations behave in the same manner. The comparison indicates that the axisymmetric assumption is a reasonable simplification to reproduce the shock-induced combustion of the regular regime.

4 Conclusions

Three-dimensional simulation of the shock-induced combustion of a regular regime was performed. The calculated flow field was almost axisymetric and well agreed with Lehr's experimental result qualitatively. The result of the 3D simulation was compared with the 2D axisymmetrical simulation. The comparison indicated that the axisymmetric assumption was a reasonable simplification to reproduce the shock-induced combustion of the regular regime.

References

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[3] V. P. Korobeinikov, V. A. Levin, V. V. Markov and G. G. Chernyi, "Propagation of Blast Waves in a Combustible Gas", Astronautica Acta, Vol. 17, pp529-537, 1972

[4] Akiko Matsuo and Toshi Fujiwara (1993). Numerical Investigation of Oscillatory Instability in Shock-Induced Combustion around a Blunt Body. AIAA Journal. Vol. 31. No10.

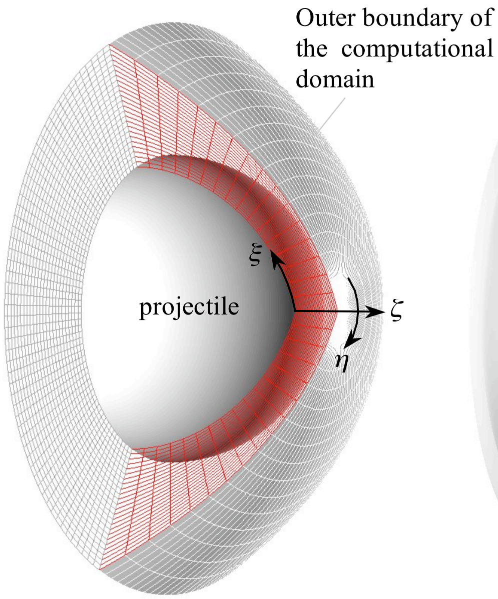

Fig. 1 Computational domain (grid points are displayed every 10, 1, and 10 points for each direction).

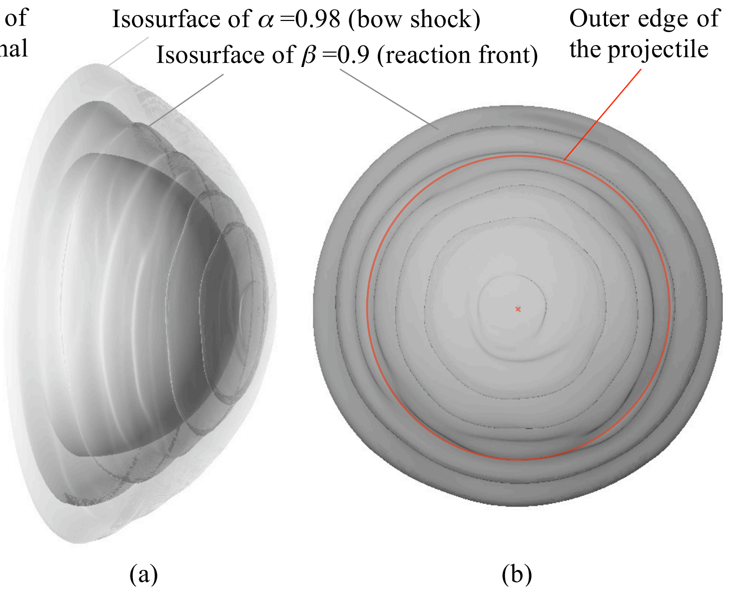

Fig. 2 Calculated flow field. (a) Side view, (b) Front view.

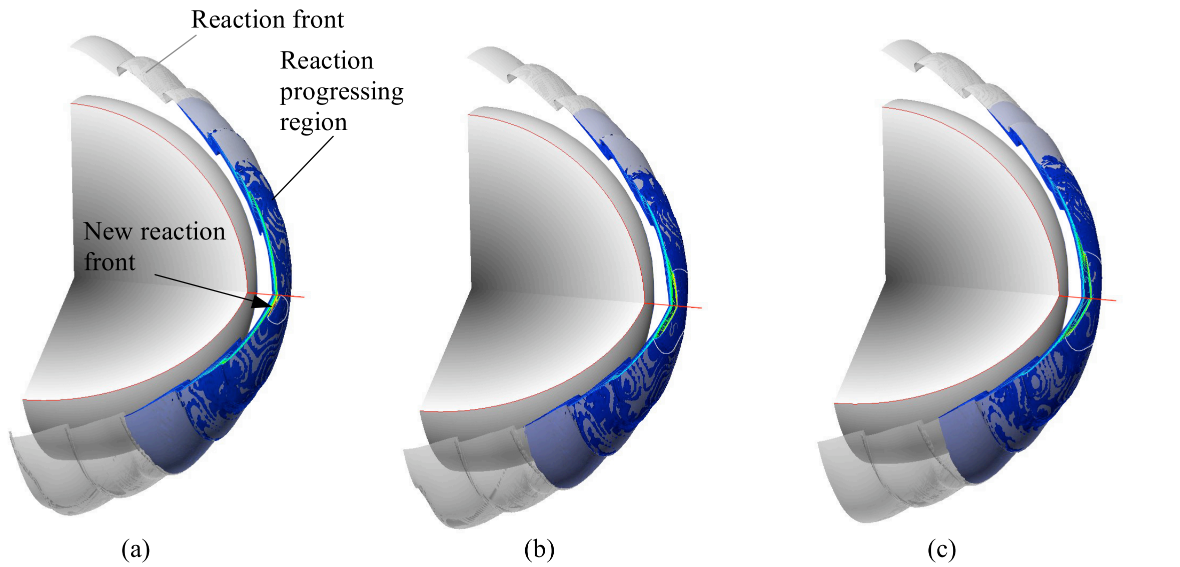

Fig. 3 Time evolution of the reaction front and the reaction progressing region. (a) Time = 0.0μs, (b) Time = 0.2μs, (c) Time = 0.4μs.

Progress of the exothermic reaction
Moderate Intensive

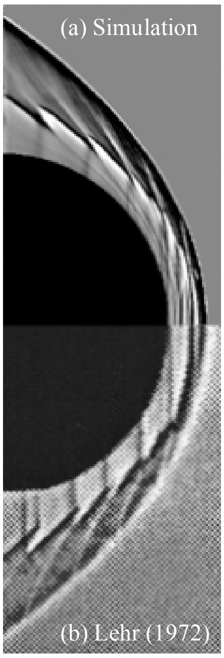

Fig. 4 Three-dimensional shadowgraph image.

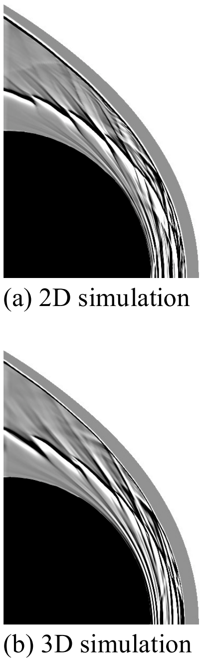

Fig. 5 Shadowgraph image of the axial cross-section.

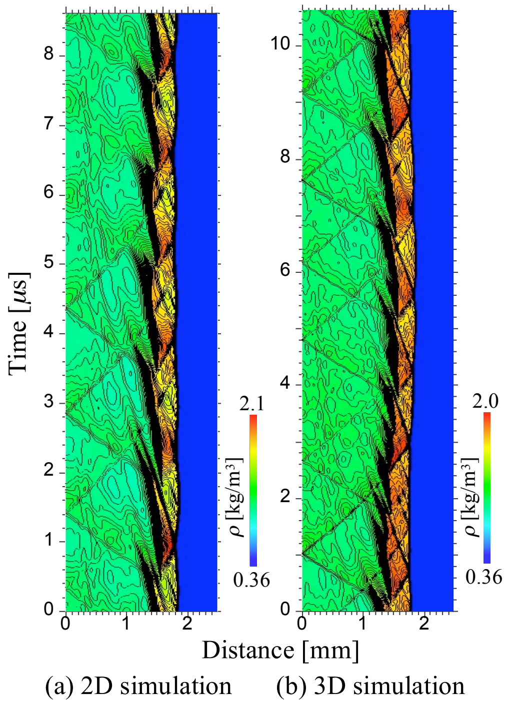

Fig. 6 Density contour distributions on the stagnation streamline.

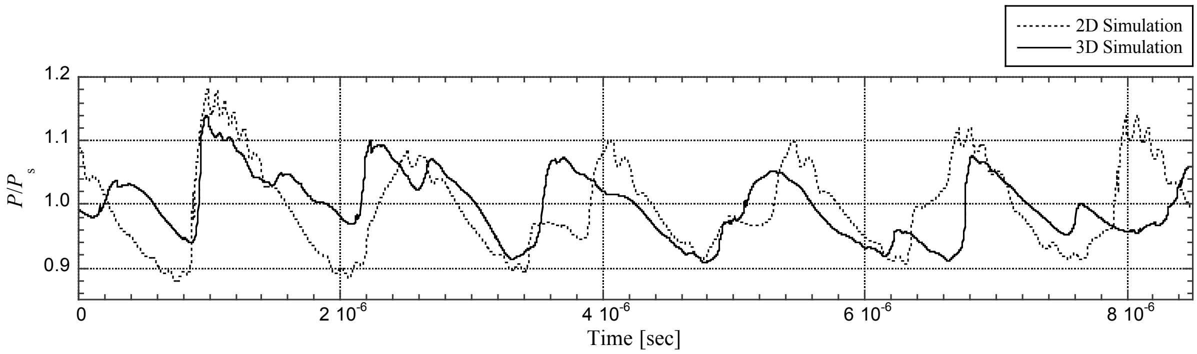

Fig. 7 History of the shock front pressure on the stagnation streamline.