Effect of Boundary Layer for Wedge-Induced Attached Oblique Detonations

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Introduction

Studies about an ignition and a stability of detonations have carried out for developments of Oblique Detonation Engine and Ram Accelerator. Suppose that the detonation wave holder is inserted in the supersonic combustible flow, the characteristics of the ignition and stabilization of detonation wave are totally different from the self-sustained detonation waves usually observed in the experiments. The combustion behind the leading shock wave could be sustained by the holders such as the wedge, and the oblique detonation wave is settled at the supersonic combustor.

The elucidation of an onset of the wedge-induced oblique detonation must be necessary for the development of the detonation-based aerospace propulsion system. In our previous study [1], the two-dimensional wave structures of oblique detonation were tried to understand by the one-dimensional piston-supported unsteady detonation wave structures, analogically. All consideration on the analogy was numerically carried out. Our results showed that the wave structure of the onset of the oblique detonation and the reaction intensity on the wedge wall can be predicted by the piston-supported detonation with a little computational cost. The investigation for analogy was studied in inviscid flow. The effects of viscosity and the boundary layer on the wedge have not been fully elucidated. In the present study, the Navier-Stokes simulation and the analogy reveal the effect of the boundary layer for wedge-induced attached oblique detonation.

Computational Setup

The computational objects are the oblique detonations around two-dimensional wedge in viscous and inviscid flow, and the one-dimensional piston-supported detonations. Two-dimensional normalized Navier-Stokes equations are prepared for simulations with one-step chemical reaction model. The coefficient of viscosity is derived by Sutherland's equation. We fix the parameters with the values γ=1.2, and T_0=293 K, μ_0=2.91x10^{-4} kg/(ms). The equations are integrated explicitly, by use of a scheme employing an explicit second order difference in time and in space, based on the non-MUSCL total variation diminishing approach [2]. For the simulations of wedge-induced detonations, the grid is clustered to a triple point and a detonation wave front because of their chemical stiffness. We prepare a grid resolution of at least 10 points in the half-reaction length, $L_{1/2}$. For the simulations of piston-supported detonations, a grid resolution of 100 points/$L_{1/2}$ is prepared in the whole grid. The finer grid is also used to confirm the reliability of the resolutions for current works.

The parameters of main flow conditions of wedge-induced oblique detonation are the main flow speed U, the angle of the wedge θ, the activation energy E, the heat release parameter Q, and frequency factor K. U, E, and Q are normalized by $\sqrt{RT_0}$, RT_0, and RT_0 respectively, where R and T_0 is the gas constant and the initial temperature. The frozen shock strength initiated by the piston is set to be the same as the frozen oblique shock strength by the wedge.

Results and Discussion

The wedge-induced oblique detonations are reproduced by the numerical study of viscous flow and compared with results of Navier-Stokes simulations for inviscid flow. Figure 1 shows the density distributions of the wedge-induced oblique detonations in (a) inviscid flow and (b) viscous flow. In a wedge-induced attached oblique detonation of inviscid case (Fig. 1a), a tip of the wedge initiates an oblique shock, and a reaction occurs behind the oblique shock. Subsequently, the reaction front interacts with the oblique shock and finally develops into the oblique detonation. In the viscous case (Fig. 1b), the tip of the wedge initiates the oblique shock and the boundary layer, and the reaction occurs in the boundary layer. Subsequently, the reaction front interacts with the oblique shock and finally develops into the oblique detonation. The structure of viscous case is basically the same as that of the inviscid flow except for the existence of the boundary layer. Observing Figs. 1a and 1b carefully, you realize that the induction length of the viscous case is shorter than that of the inviscid case. Figure 2 shows the density distributions of the wedge-induced oblique detonations in (a) inviscid flow and (b) viscous flow. The wave structures have the triple points in both flows. The differences between inviscid and viscous flow appear in the boundary layer and the induction length in Figs.1 and 2.

We will explore the possibilities of the utilization of the analogy between the two-dimensional wedge-induced steady detonations and the one-dimensional piston-supported unsteady detonation in viscous case. In our calculation condition, it is able to assume that the effect of the diffusion is small because the Reynolds number is high ($Re \approx 10^7$). Therefore, we suppose that the existence of boundary layer on the wedge wall increase the wedge angle imaginarily. The strength of the oblique shock is measured from the numerical results of the wedge-induced frozen oblique shock simulated by Navier-Stokes equations. The frozen shock strength initiated by the piston is set to be the same as the frozen oblique shock strength by the wedge. Figure 3 shows the *t-x* diagram of the density distributions of the one-dimensional piston-supported unsteady detonation reproduced by one-dimensional Euler equations corresponding to Figs (a) 1b and (b) 2b in viscous simulation. The x in Fig. 3 is the distance from the piston surface. The wave structure in Fig. 3a is the same as the time-evolving distribution in Fig. 1b except for the boundary layer. On the other hand, there is not the analogy of the wave structure between the wedge-induced detonation in Fig. 2b and the one-dimensional piston-supported detonation in Fig. 3b since the triple point does not appear on the piston-supported detonation wave.

In order to compare quantitatively among inviscid flow results, viscous flow results of the wedge-induced detonations and piston-supported detonations, the distance of the wedge-induced detonation has to be converted to the time of the piston-supported detonation. In our previous work [1], the distance is converted to the time by the local fluid speed on the wedge wall behind the wedge-induced oblique shock. This convergence cannot be used in the quantitative comparison since the local fluid speed on the wedge wall is zero in the viscous flow. Accordingly, the main flow speed behind the oblique shock in the viscous flow result wave is utilized as the representative speed instead of the local fluid speed on the wedge wall. Figure 4 shows the velocity distributions corresponding to Figs. (a) 1 and (b) 2. The main flow speed behind the oblique shock wave is almost constant as shown in Fig. 4. Therefore, the utilization of the main flow speed behind the oblique shock is appropriate. In order to reveal the effect of the viscosity and the analogy with viscous flow, we quantitatively compare the results of Figs. 1 and 3a which appear the analogy as shown in Fig. 5. The time in the piston-supported detonation can be converted to the distance from the tip of the wedge by the main flow speed behind the oblique shock as mentioned above. Figure 5 shows the post shock pressure distributions of the inviscid flow results, the viscous flow results of the wedge-induced detonation and the piston-supported detonation corresponding for the inviscid flow and the viscous flow. The shock pressure peaks correspond to the interaction point between the oblique shock and the reaction front behind the shock wave. The distance from the tip of the wedge to the interaction point in the viscous flow result is shorter than that in the inviscid flow. The profile of the shock wave in the piston-supported detonation agrees well with the profile in the wedge-induced detonation in the inviscid and viscous case respectively. Accordingly, the induction length can be predicted by the results of the piston-supported detonation without time-consuming calculation regardless of the presence of the viscosity. Furthermore, the analogy in the viscous flow indicates that the viscosity affects only the existence of the boundary layer and makes the shock angle increase. Li *et al.* [3] reported that combustion generated by thermal dissipation is mainly confined to a thin layer near the wedge surface. Their argument was correct but not proved. Our results proved their argument.

Conclusion

Navier-Stokes simulations of the oblique detonations around the wedge were carried out, and we explored the possibilities of the utilization of the analogy between the wedge-induced steady oblique detonation and the one-dimensional piston-supported unsteady detonation. The simulation results indicated that the boundary layer in the flow field creates the stronger shock at the leading edge and the higher temperature behind the shock. This higher temperature shortens the induction length and causes an earlier onset of the detonation structure. If we know the exact oblique shock strength, the induction length can be predicted by the results of the piston-supported detonation.

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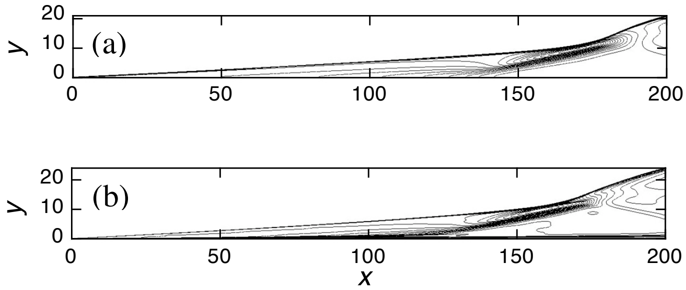

Figure 1 Density distributions of wedge-induced detonations with U=18.051, θ=20°, E=50, Q=50: (a) inviscid flow, (b) viscous flow.

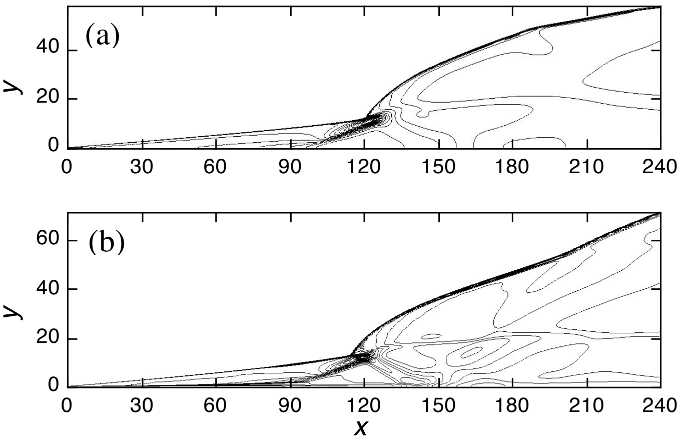

Figure 2 Density distributions of wedge-induced detonations with U=12.035, θ=30°, E=50, Q=50: (a) inviscid flow, (b) viscous flow.

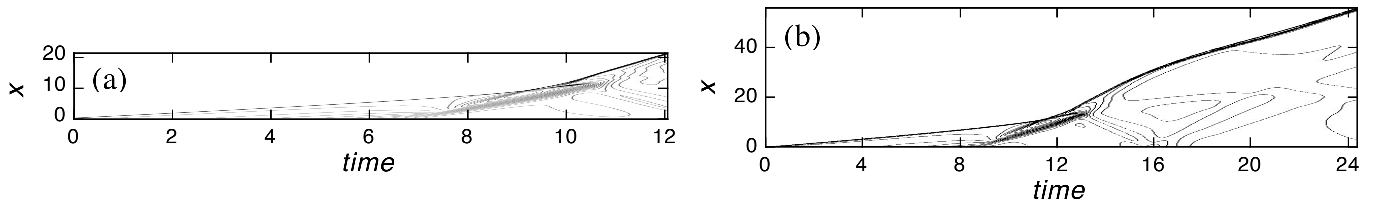

Figure 3 Density distributions of piston-supported detonations corresponding to (a) Fig. 1 and (b) Fig. 2 in viscous flow.

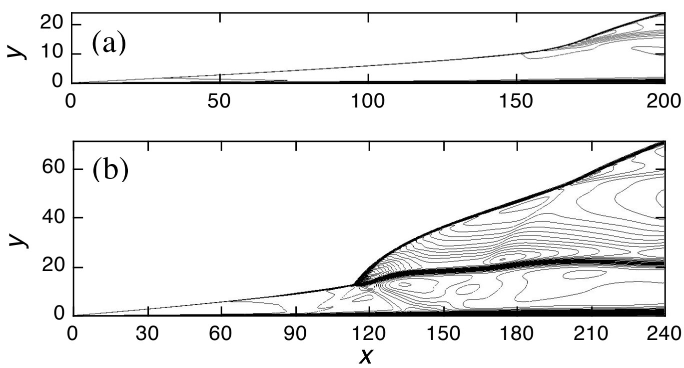

Figure 4 Velocity distributions of wedge-induced detonations with (a) U=18.051, θ=20°, E=50, Q=50 and (b) U=12.035, θ=30°, E=50, Q=50 in viscous flow.

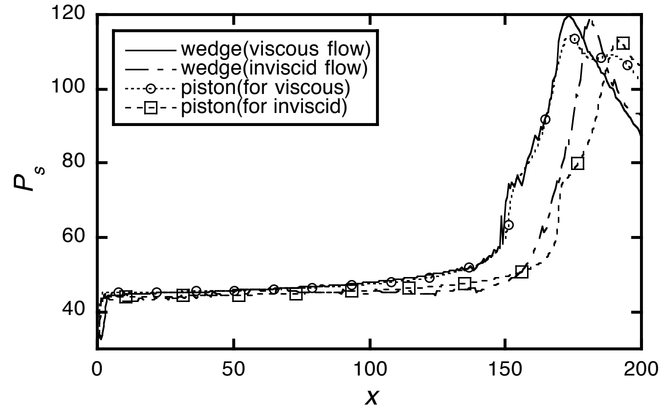

Figure 5 Shock pressure distributions with U=18.051, θ=20°, E=50, Q=50.