A Numerical Simulation of Reflection Processes of a Detonation Wave on a Wedge

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Abstract

A two dimensional numerical simulation has been performed on reflection processes of detonation waves of a stoichiometric oxyhydrogen mixture diluted with argon on a wedge. A numerical scheme adopted is the flux corrected transport scheme and a two-step chemical reaction is assumed. Mach reflection of the detonation wave was simulated and trajectories of a triple point on the wedge are obtained and are compared with those obtained by the numerical soot track records.The results are qualitatively compared with the experimental data.

Introduction

Reflection of detonation waves on a wedge is one of the fundamental problems relating interactions between the detonation waves and structures in the surroundings. From a scientific point of views, the problem has not been studied extensibly compared with that of reflection of shock waves in which a huge amount of researches have been performed. But some pioneering scientists, e.g., Gvozdeva et al.(1969), and Edwards, et al.(1984), have been shown that there exists Mach reflection as well as regular reflection. Recently in the 90's, the problem revived by the work of Meltzer et al.(1993). Using CFD with unstructured adaptive mesh, Yu at al.(1995, 1996) revealed the diffraction process in a good qualitative agreement with the experiment. Recently, Li, et al.(1997) have presented a paper on the theoretical work as an extension of the reflection problem of inert shock waves on this problem. The present study aims at the understanding of the reflection of the gaseous detonation wave on the wedge by a numerical simulation compared with the experimental observations by Ohyagi et al(1998).

Formulation of the problem

In the present simulation, in order to elucidate the reflection processes of the gaseous detonation waves, the following assumptions were made:(1) Flow is two-dimensional. (2) Gas is a perfect gas with constant specific heats. (3) Dissipative effects, such as viscous, heat-conductive and diffusive effect are neglected. (4) Chemical reactions are modeled as a two-step reaction. Under these assumptions, the conservation equations for mass, momentum and energy as well as the two reaction parameters are formulated in the generalized coordinate. These equations are solved with an initial distribution which have been obtained for the one-dimensional Chapman-

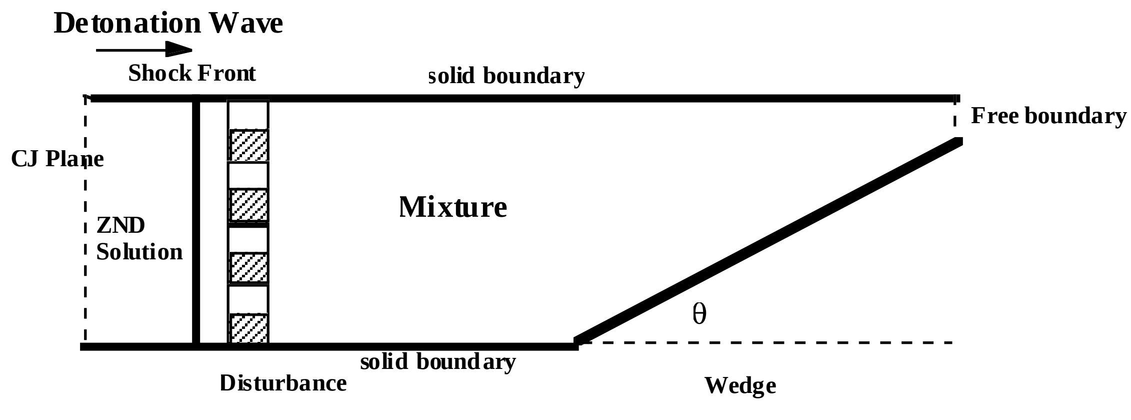

Fig.1 Computational domain of the problem

Jouguet detonation wave by the ZND model. Figure 1 shows a computational domain of the problem. It constitutes a two-dimensional duct with a wedge of angle θ. Ahead of the wave front, some disturbances of the state variable are given artificially. Boundary conditions on solid walls are the slip-surface condition and on the outlet is imposed a free boundary. In the CJ detonation wave, the state behind the CJ plane should not affect upstream so that it is not necessary to be calculated. In the present calculation, only the region upstream of the CJ plane is calculated. Then the inlet condition is fixed by the CJ condition. The approaching straight duct should be long enough to develop to a stable triple-shock structure of the detonation wave.

The present calculation utilizes the Lax-Wendroff scheme with Flux-Corrected Transport algorithm. A time-splitting method was applied for *x* and *y* directions as well as the inhomogeneous terms due to the chemical reactions. Computational grids were generated analytically by solving the Laplace equation.

In the present calculation, a gas is assumed to be $2H_2+O_2+7Ar$ at 101.3kPa and 288K. Following the Korobeinikov model, the reaction parameters are evaluated as are shown in Table 1. The specific heat ratio of the mixture is assumed to be equal to 1.4. From these parameters, the CJ Mach number M_{CJ} and the induction length L_{CJ} are calculated to be 4.8 and 0.387 mm respectively. The wedge angle θ is varied from 0 to 40 deg as are listed with the grid numbers in Table 2. Throughout the present calculation, the grid sizes for the both directions $\Delta\xi$ and $\Delta\eta$ are fixed to be 0.4 (i.e. about 0.15 mm) so that width of the duct is fixed to be $201 \times 0.4 L_{CJ}$=31.1mm which is nearly equal to that of the tube used in the experiment(Ohyagi et al., 1997). The Courant number is fixed to be 0.8 and η_0, η_1 and η_2 for the FCT algorithm are equal to 1/6, 1/3 and -1/6 respectively. The length of initial distribution is $40L_{CJ}$ which is sufficient to reach the equilibrium CJ condition.

Table 1 Non-dimensional reaction parameters

Q/RT_0	52.6
E_α/Q	1.7
E_β/Q	0.35
$k_\alpha\, \rho_0\, L_{CJ}/a_0$	287
$k_\beta\, p_0^2\, L_{CJ}/a_0$	1.43×10^{19}

Table 2 Wedge angle and grid number

Wedge Angle θ(deg)	Grids n_ξ x n_η
0	601 x 201
10	901 x 201
20	501 x 201
30	351 x 201
35	301 x 201
40	301 x 201

Results and Discussions

Figure 2 shows a typical soot track image which is a trace of pressure contours at each time. It shows the case of θ=20 deg in which a region of smaller and distorted cells can be identified. This type of reflection can be called as the Mach reflection as that of inert shock wave. A cell size behind the Mach stem becomes smaller than that behind the incident wave. For inert shock waves, there is no spatial length scale in the problem so that the trajectory angle of the Mach stem is a function of the incident Mach number and the wedge angle only. Then the angle is constant for each condition. For detonation waves, there is a length scale based on the chemical reaction, such as an induction zone length or a cell size. Then the angle of the Mach stem may vary with the distance along which the wave propagates. It is observed from the present numerical result that, in the present computational domain, the trajectory of the triple point of the Mach reflection on the wedge is not a single straight line but it deflects at a distance of about seven cells to a line with a same angle as that of the detonation cells. It cannot say that the angle will be fixed to the cell angle as the wave propagates downstream.

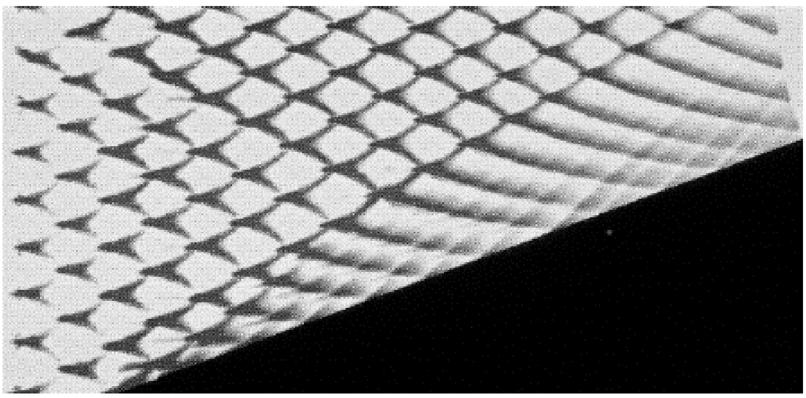

Fig.2. Numerical soot-track image for θ = 20 deg
for a stoichiometric oxyhydrogen mixture diluted with 7 argon at 101.3kPa.

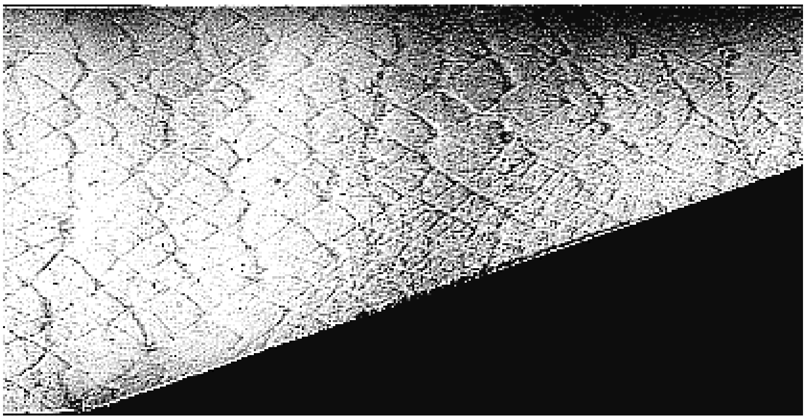

Fig.3 Experimental soot-track image for for θ = 20 deg
for a stoichiometric oxyhydrogen mixture at 40kPa.

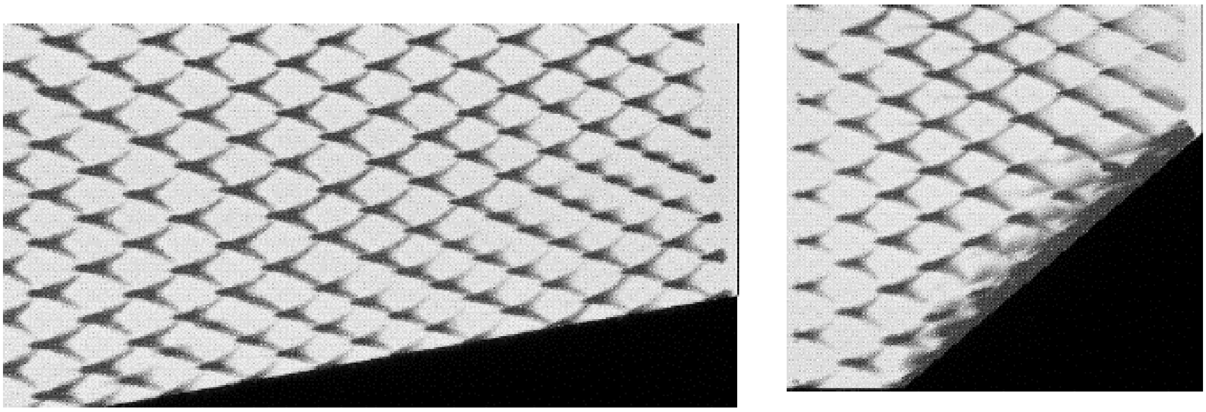

Fig.4. Numerical soot-track images for θ = 10 deg(left) and θ = 40 deg(right)
for a stoichiometric oxyhydrogen mixture diluted with 7 argon at 101.3kPa.

Figure 3 shows the experimental soot-track image for a non-diluted stoichiometric oxyhydrogen mixture at a lower pressure 40kPa (Ohyagi, et al 1998). Although the mixture is different, these soot-track patterns are qualitatively similar. But in the experiments, the phenomenon is three dimensional and irregular. It cannot identify the mechanism of wave interactions clearly from the soot-track. Experiments using the mixtures diluted with argon should be performed(Hoshi, et al. 1999) because it will create more regular structure..

Figures 4 show numerical soot-tracks for θ = 10 deg and θ = 40 deg. A disturbance on the cell pattern created at the apex of the wedge propagates with an angle larger than the cell angle for θ = 10 deg but small cells due to the Mach reflection can be distinguished after the second reflection point on the wedge. Effects of computational cells may affect these subtle phenomena. For θ = 40 deg which is larger than the cell angle, a disturbed high pressure region appears near the wedge surface but no clear structure can be seen in this region.In the experiment for this angle, the Mach stem cannot be observed so that it is clarified as the regular reflection. These high pressure on the surface is, of course, caused by the reflection of the wave.

Detonations in the Mach stem region are overdriven detonation waves so that the pressure and temperature in the wave front are higher that those in the CJ detonation. In the present calculation, a size of the computational cell is fixed to 0.4 of the CJ induction distance. It might be insufficient to use this computational cell size to the overdriven detonation caused by the Mach stem. But it can be said that the results indicate clearly the mechanism to create the Mach stem detonation at least qualitatively.

Conclusions

Numerical simulations of the reflection processes of gaseous detonation waves on a wedge are performed by using the Flux Corrected Transport method and by using the two-step chemistry. The following conclusions are derived:

(1)Structures of the Mach reflection and the regular reflection of the detonation wave on the wedge are simulated successfully at least qualitatively.
(2) A trajectories of the triple point is not a straight line but deflects during the propagation process on the wedge. It coincides with the cell angle of the detonation wave for a certain distance from the apex.
(3)A detailed structure behind the Mach stem detonation should be simulated by using finer computational cells.

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