INSTABILITY OF OBLIQUE SHOCK WAVES WITH HEAT ADDITION

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후방 발열이 있는 경사 충격파의 불안정성

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A comprehensive numerical study was carried out to identify the on-set condition of the cell structures of oblique detonation waves (ODWs). Mach 7 incoming flow was considered with all other flow variables were fixed except the flow turning angles varying from 35 to 38. For a given flow conditions theoretical maximum turning angle is 38.2° where the oblique detonation wave may be stabilized. The effects of grid resolution were tested using grids from 255×100 to 4,005×1,600. The numerical smoked foil records exhibits the detonation cell structures with dual triple points running opposite directions for the 36 to 38 turning angles. As the turning angle get closer to the maximum angle the cell structures gets finer and the oscillatory behavior of the primary triple point was observed. The thermal occlusion behind the oblique detonation wave was observed for the 38° turning angle.

Key Words : Oblique Shcok Wave, Unsteady Flow, Oblique Detonation Wave, Instability, Cell Structure

1. INTRODUCTION

Oblique detonation waves (ODWs) stabilized over inclined walls have been considered as a promising combustion means for hypersonic propulsion systems such as ODW engines and ram accelerators. A number of studies were carried out to examine the fundamental characteristics of an ODW and its implementation for propulsion systems[1-14]. Among the various issues of ODW studies, the on-set condition self sustaining ODW was one of the key issues, and the presence of cell structure was considered as a proof of that condition. However, littlehas been known about the ODW cell structure either by experimentally or by numerically. In numerical aspect, the great difference in the length scales of the chemical induction behind the oblique shock wave and the ODW was the major obstacle for resolving that problem. Choi et al.[15] captured the unsteadiness ODW frontal structures unveilingthe various source instability mechanisms from pressure wave interactions generated from vortex dynamics originating from the primary triple points. They could capture the detailed wave structures with help of the systematic numerical approach of grid refinement study and chemical induction length estimations behind oblique shock wave(OSW) and ODW. They showed that the ODW instability has a strong dependency on the chemical the activation energy in same way to the normal detonation waves. However, only single-sided triple point was foundfrom their study since they did the studies only for a fixed flow parameters except the activation energy. Recently, Daimon et al.[16] did a variety numerical study of ODW structures over a hemi-spherical blunt body by changing flow conditions. They showed the cellular structures of ODW wave front and discussed about the flow structures about the ODW detonation cells. They also discussed about the onset condition ODW cell structures from the parametric studies on flow speed, body size and initial pressures. However, it is considered that they failed to identify the onset condition of oblique detonation waves since they could not consider the fundamental thermo-fluidic parameters.

The focus of present study is to identify the on-set

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condition of ODW by resolving the ODW cell structures numerically. Since there were various parameters affecting the ODW characteristics, careful attention should be give to isolate the effect of the thermo-chemical parameters. In the present study a comprehensive numerical study was carried out to investigate the unsteady cell structures of oblique detonation waves (ODWs) for a fixed Mach 7 incoming flow as an extension of the previous studies [15].

2. THEORETICAL FORMULATION AND NUMERICAL METHODS

Since the grid requirement for the present study would be significant, a simplest possible formulation is used in this study. Euler equations for compressible inviscid flows and the conservation equation of reaction progress variable are summarized as a following vector form in a two-dimensional coordinate.

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho e\\ \rho Z\end{bmatrix}+\frac{\partial}{\partial x}\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (\rho e+p)u\\ \rho Zu\end{bmatrix}+\frac{\partial}{\partial y}\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ (\rho e+p)v\\ \rho Zv\end{bmatrix}=\begin{bmatrix}0\\ 0\\ 0\\ 0\\ \rho w\end{bmatrix} \qquad (1)$$

where, pressure is defined as,

$$p=(\gamma-1)\rho\left\{e-\frac{1}{2}(u^2+v^2)+Zq\right\} \qquad (2)$$

Here, Z is reaction progress variable that simulates the product mass fraction and varies from 0 to 1. Qis the dimensionless heat addition by combustion. As a combustion mechanism, one-step Arrhenius reaction model is used to simulate the various regimes of detonation phenomena without the complexity and large computing time for dealing with many reaction steps and detailed properties of reacting species. Thus, the reaction rate in Eq. (1) that depends on mixture concentration is defined as follows.

$$w=(1-Z)k\exp(-E\rho/p) \qquad (3)$$

Here, k is reaction constant and E is activation energy. The fluid dynamics equations are discretized by finite volume formulation, and numerical fluxes are calculated by Roe's approximate Riemann solver with interpolated primitives variables by third-order accurate MUSCL-type TVD scheme. The discretized equations were integrated in time by 4thorder accurate 4-stage Runge-Kutta scheme (RK4). Since the details about the theoretical formulation and numerical algorithms for the compressible reactive flows has been discussed thoroughly in the previous studies, [17,18] those will not be discussed further.

3. THERMO-CHEMICAL PARAMETERS FOR THE MORPHOLOGY OF ODW CELL STRUCTURES

Among the various thermo-fluidic parameters for the modeling of ODW, heat release and specific heat ratio is determined by the mixture composition and there is no clue of evidence that they have direct influence on the existence of cell structures. The activation energy is shown to have a strong influence of the degree of instability, but only a single-sided structures were found from the parametric studies of the activation energies[15]. Therefore the only variables that can affect the ODW structures is the flow turning angles regarding from the basic analysis on the morphology of ODW[1] and only the flow turning anglewas considered fro parametric studies for the onset condition of ODW cell structures with all other variables were fixed. The selected thermo-fluidic parameters are dimensionless heat release, Q of 10.0, specific heat ration g of 1.3 and dimensionless activation energy E of 30.0 from the previous study[15]. These flow parameters were selected to weaken the restriction of grid resolution requirements from the chemical induction length scale analyses. The effects of grid resolution have been studied by using grids from 255×100 to 4,005×1,600. The calculation of half reaction length scale behind ZND structure exhibit that the 10 grid points could be included in the half reaction length behind the ODW and more than 80 point behind the oblique shock wave. The comprehensive study on the grid resolutions for the reaction zone is found in the previous study[15].

Fig. 1 is polar diagram for ODW and OSW with parameters of present study. At C-J point Θ is 12.3° and β is 34.5°. At maximum q condition of attached ODW, Θ is 38.2° and β is 67.1°. In the previous study for flow turning angle greater than Θmax [14], it has been shown that the detached detonation is observed for a wedge of infinite length, but periodic oscillation of the primary triple point could be observed over a wedge of finite length due to the repeated thermal occlusion and relaxation. Therefore it is expected that a dual-headed ODW structures of triple

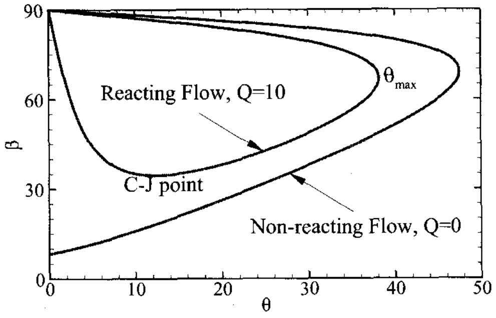

Fig. 1 Polar diagram for Mach number 7 with $\gamma = 1.3$.

points running opposite directions could be existed where the flow is near choked condition since the transverse waves behind the triple points has a propagation speed close to the speed of sound. The reason why the previous study exhibited only the single headed structures is that flow turning angle of 30° is has flow speed quite greater than the speed of sound behind the ODW. Therefore flow turning angles from 35° to 38° were considered for parametric study.

4. RESULTS AND DISCUSSIONS

Figure 2 is the instantaneous density contours from the ODW simulations with different flow turning angles. Similarly to the previous results[15], present results show the irregular ODW front structures are observed with various wave interaction behind. At 35° most of the transverse waves move downstream, but a part of wave front shows dual headed wave front. The primary triple point is stationary for this condition. As the turning angle get larger, existence of the dual-headed triple points structure gets clear. At 38° transverse waves more evenly spaced. Differently from the results of 35° and 36° , the results of 37° and 38° shows a separated or disturbed flow regions along the wall, which reflects the presence of the subsonic flow region. The locations of the primary triple points of 36°, 37° and 38° are not stationary but moves back and forward repeatedly, due to the thermal occlusion behind the ODW.

Figure 3 is the numerical smoked foil record of ODWs that is produced by the tracking of maximum pressure locations along the ODW wave fronts. The maximum pressure locations were traces along the flow directions at each time and piled up along the flow direction. At 35°, the cell structure is not observed at earlier stage, but begins to appear at middle of the computing time. The

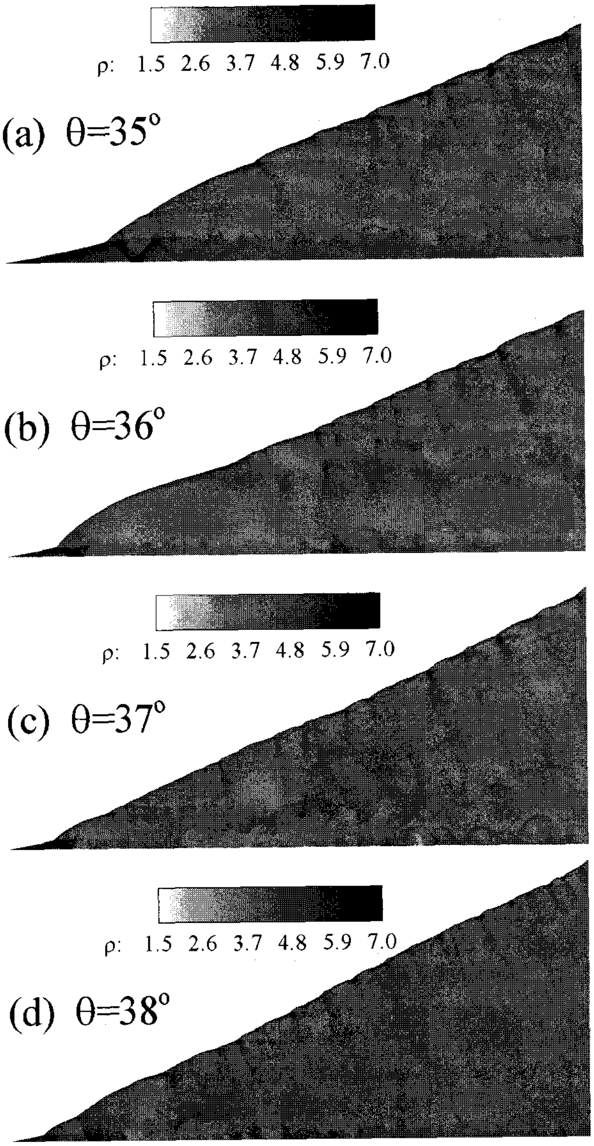

Fig. 2 Instantaneous density contours for flow turning angles from 35° to 38°.

presence of the cellular structureis getting clear as the turning angle get larger. Another important observation is that the periodic motion of the primary triple point. Since the primary triple point is stationary at 35°, the trace of it is plotted as a straight line along the bottom, but shows periodic traces for 36° to 38°. The periodicity gets frequent as the turning angle gets larger. Fig. 4 is the magnified plots of the smoked foil records for each cases at the end of the computations. The presence of the cell

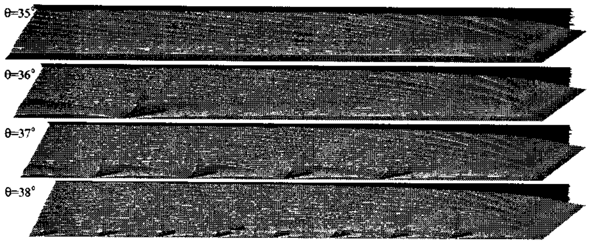

Fig. 3 Numerical smoked-foil records of oblique detonation waves for flow turning angles from 35° to 38°.

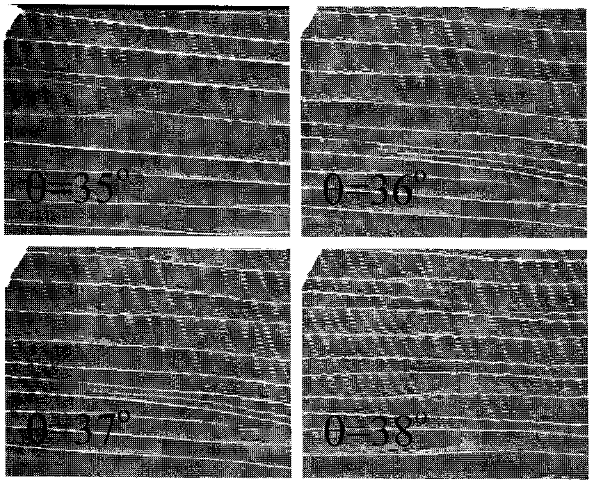

Fig. 4 Magnified plots of numerical smoked-foil records showing cell structures of oblique detonation waves.

structure is more clearly shown. It is also understood that the cell size gets smaller as the turning angle gets larger.

5. CONCLUSIONS

A comprehensive numerical study was carried out to identify the onset condition of the cell structures of ODWs. From the investigation of the morphology of ODW cell structures, flow turning angle was presumed being a key parameter for the onset condition of the dual-headed triple point structures. Since the transverse waves propagate at near sonic speed and the flow speed becomes subsonic beyond the Θmax condition, a parametric study was carried out for the flow turning angles from 35° to 38° those are close to the Θmax. Differently from the previous result of single headed structures at 30°, present results exhibits the dual-headed triple point structures with cellular structures in smoked foil records. The cell structure gets finer as the flown turning angle gets larger. At larger turning angles, thermal occlusion is observed behind the ODW that results in a repeated motion of the primary triple point moving forward and backward, contrary to the results at smaller turning angles having stationary position.

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