

# Investigation of the Onset Condition of Oblique Detonation Wave Cell Structures

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## 1 Introductions

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.[1-11] 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, little has 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.[10] captured the unsteadiness ODW frontal structures unveiling the 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 found from their study since they did the studies only for a fixed flow parameters except the activation energy. Recently, Daimon et al.[11] 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 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[10].

## 2 Numerical formulations

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 vector form in a two-dimensional coordinate. 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. 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 4th order 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,[12,13] those will not be discussed further.

### 3 Thermo-chemical parameter

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.[10] 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 angle was considered from 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 ratio  $\gamma$  of 1.3 and dimensionless activation energy  $E$  of 30.0 from the previous study.[10]. 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  $255 \times 100$  to  $4,005 \times 1,600$ . 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.[10]

Fig. 1 is polar diagram for ODW and OSW with parameters of present study. At C-J point  $\theta$  is  $12.3^\circ$  and  $\beta$  is  $34.5^\circ$ . At maximum  $\theta$  condition of attached ODW,  $\theta$  is  $38.2^\circ$  and  $\beta$  is  $67.1^\circ$ . In the previous study for flow turning angle greater than  $\theta_{\max}$ [7], 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 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  $30^\circ$  is has flow speed quite greater than the speed of sound behind the ODW. Therefore flow turning angles from  $35^\circ$  to  $38^\circ$  were considered for parametric study.

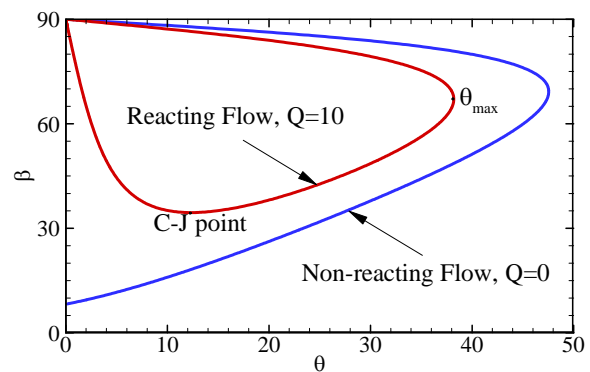


Figure 1. Detonation polar diagram for  $M=7$  with  $\gamma=1.3$

### 4 Results

Figure 2 is the instantaneous density contours from the ODW simulations with different flow turning angles. Similarly to the previous results[10], present results show the irregular ODW front structures are observed with various wave interaction behind. At  $35^\circ$  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  $38^\circ$  transverse waves more evenly spaced. Differently from the results of  $35^\circ$  and  $36^\circ$ , the results of  $37^\circ$  and  $38^\circ$  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  $36^\circ$ ,  $37^\circ$  and  $38^\circ$  are not stationary but moves back and forward repeatedly, due to the thermal occlusion behind the ODW.

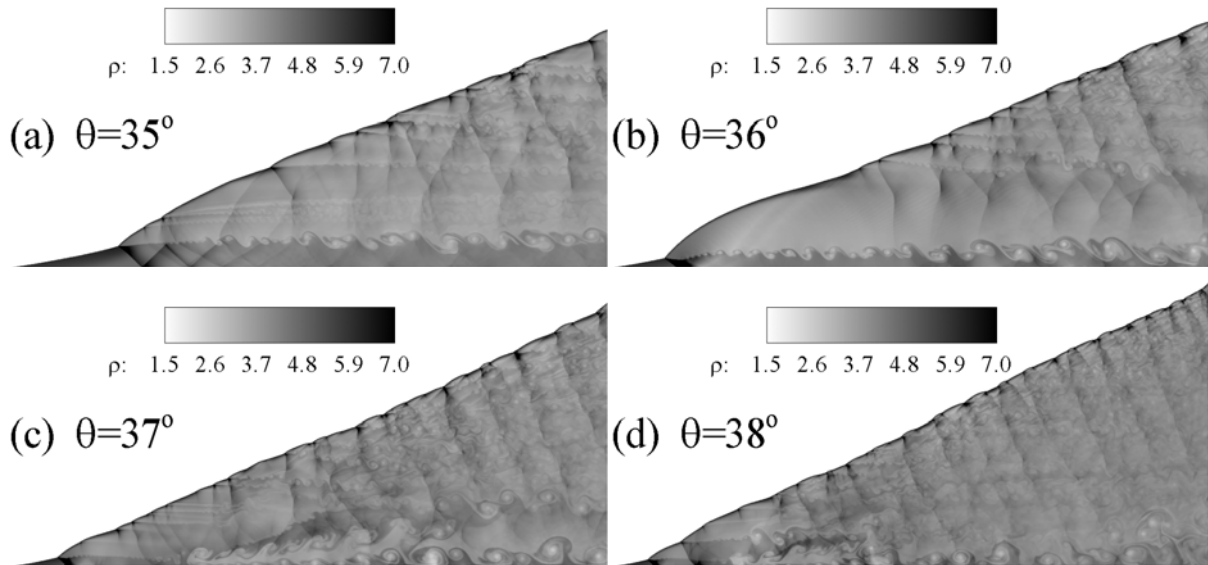


Figure 2. Instantaneous density contours for flow turning angles from  $35^\circ$  to  $38^\circ$ .

Figure 3 exhibits the detailed flow structures of the dual-headed detonation wave front. Fig. 4 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  $35^\circ$ , the cell structure is not observed at earlier stage, but begins to appear at middle of the computing time. The presence of the cellular structure is 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  $35^\circ$ , the trace of it is plotted as a straight line along the bottom, but shows periodic traces for  $36^\circ$  to  $38^\circ$ . The periodicity gets frequent as the turning angle gets larger. Fig. 5 is the magnified plots of the smoked foil records for each cases at the end of the computations. The presence of the cell structure is more clearly shown. It is also understood that the cell size gets smaller as the turning angle gets larger.

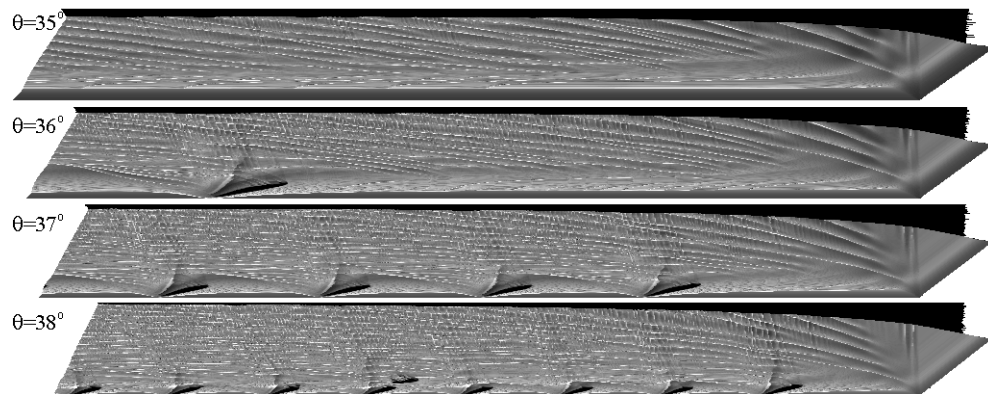


Figure 3. Numerical smoked-foil records of oblique detonation waves for flow turning angles from  $35^\circ$  to  $38^\circ$ .

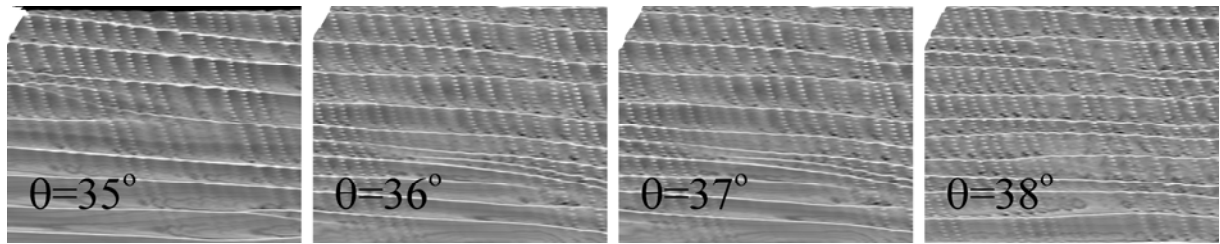


Figure 4. Magnified plots of numerical smoked-foil records showing cell structures of oblique detonation waves.

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