Numerical Study of Structure and Stability of Oblique Detonation Wave over a 40° Wedge

J.-Y. Choi* , I.-S. Jeung †, Y. Yoon †

*Department of Aerospace Engineering, Pusan National Univesity
30 Changjeon-dong Kumjeong-ku, 609-735, Korea
aerochoi@hyowon.pusan.ac.kr
†Department of Aerospace Engineering, Seoul National Univesity
Shinlim-dong San 56-1, Gwanak-ku, Seoul 151-742, Korea
enjis@plaza.snu.ac.kr, ybyoon@plaza.snu.ac.kr

Abstract

The structure and the stability of oblique detonation waves in $H_2/O_2/N_2$ mixtures were investigated through a numerical simulation of experimental cases. The numerical simuations were performed for expansion tube experiments of oblique detonation waves over a wedge of a turning angle greater than attaching condition. Present results were compared with experimental images and examined for the better understanding of oblique detonation waves. The comparisons not only present the validity of the numerical simulations but also show the details of the structure of oblique detonation wave including the interaction between transverse shock wave and boundary layer. Besides, present unsteady computation predicts some tansient and unstable characters of oblique detonation waves that could not be captured in the experiment due to a limitation of experimental time. A slow dettaching process of oblique detonation was observed for highly sensitive and energetic mixtures, but an attached oscillatory behavior for a less sensitive mixture.

Introduction

Research on oblique detonation wave over a body takes interests for a last decade along with the application to the novel hypersonic propulsion systems such as ram accelerator or oblique detonation wave engine. Thus, the stabilization of the oblique detonation wave is crucially important for stable operation and optimum performance, because an instability of oblique detonation wave results in unstart problem of propulsion system or improper location of stabilization results in a performance degradation. Basically, condition of oblique detonation wave formation was studied Pratt et al.[1] with Rankin-Hugoniot theory and equilibrium chemistry, but following theoretical studies could not present a detailed structure of oblique detonation waves resulting from non-equilibrium chemical kinetics. In actual situation, the chemical kinetic effect induces pre-heating zone behind a oblique shock wave and a coupling of reaction front, and oblique shock wave results triple-point structure of oblique detonation wave at some distance behind a wedge nose. This detailed induction zone structure of oblique detonation wave was first studied by Li et al.[2] with inviscid computational fluid dynamics and Viguier et al.[3] prove the structure in two layer detonation tube with Schlieren images. Recently, Morris et al.[4] also showed similar structure of oblique detonation wave using expansion tube facility with Schlieren and PLIF (Planar Laser Induced Fluorescence) imaging techniques. Their experiment was performed for a wedge angle greater than maximum turning angle of attached ODW predicted by Rankine-Hugoniot theory and equlibrium chemistry, and the presence of induction zone structure at the experimental condition was considred as a result of chemical kinetic effects. A motivation of present sudy comes from here whether the attached ODW is possible at off-attaching condition. For this study computational methods would be a good aid for understanding the detailed flow features, since computational simulation could give a solution to a problem of limited experimental test time.

Numerical Modeling and Computational Procedure

For the simulation of the oblique detonation phenomena over two-dimensional wedge, the coupled form of species conservation equations and Navier-Stokes equations are employed with the detailed combustion mechanism of $H_2/O_2/N_2$. The combustion mechanism used in this study is taken from Jachimowski[14] by ignoring the nitrogen dissociation mechanisms that has a negligible effects on flow field characteristics. This mechanism consists of nine-species and nineteen reaction-steps including HO_2 and H_2O_2 reactions steps that are important in the ignition problems. This combustion mechanism is considered as one of the most widely used ones since it has been used in a number of computational researches on shock-induced combustion and supersonic combustion problems. The governing equations are discretized numerically by a finite volume approach. The convective fluxes are formulated using Roe's FDS method derived for multi-species reacting flow along with MUSCL approach and differentiable limiter for high order accurate shock capturing capability. The discretized equations are temporally integrated by a second order time accurate fully implicit integration method with Newton sub-iteration method for time accuracy and solution stability at large time step. More detailed descriptions of the governing equations and numerical formulations are documented in literatures[5,6] and will not be repeated here. The numerical modeling of governing equations have been validated through a number of steady and unsteady simulations of shock-induced combustion phenomena and shock wave/boundary layer interaction problem.[5,6] The solutions showed remarkable agreements with existing experimental data including the position of shock and reaction front and the oscillation frequency of shock-induced combustion and pressure and friction coefficient data of shock wave/boundary layer interaction problem. An oblique detonation experiment by Viguier et al. was also simulated and comparison with their experimental and numerical results showed reasonable agrreements.

Numerical silmuations were carried out for experimental cases by Morris et al.[4] showing oblique detonation wave and oblique shock-induced combustion of $2H_2$+O_2+$17N_2$ mixture over a 40^o wedge at Mach number 5.8 according to inflow mixture pressures. The different mixture pressures are 0.23bar, 0.18bar and 0.12bar, and these cases are denoted in this study as Case 1, Case 2 and Case 3 respectively. Fig. 1 is the experimental Schlieren and PLIF images for each cases. Inclined wedge length is 1.98 cm and inflow temperature is 290K. Computations were performed using 301×250 computational grid clustered to wegde nose and surface boundary. Although the solution of oblique detonation wave is very sensitive to the grid density, grid refinement study proved that the above grid resolution is sufficient enough for the simulation of experimental cases considered.

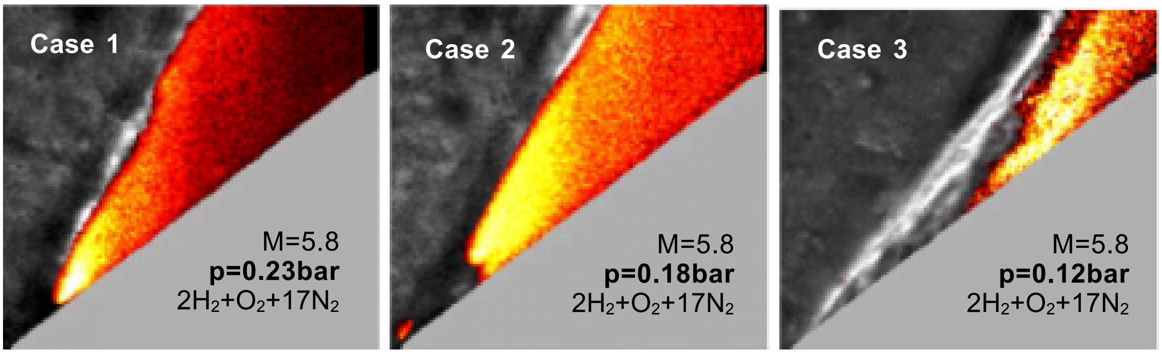

Fig.1 Experimental Schlieren and PLIF images for three experimental cases by Morris et al.[4]

Results

Fig. 3 is the computational results for Case 1 and 2. Although the density contours of Fig. 3 (a) and (b) shows nearly same flow configuration to the experimental images in Fig. 2, those are just snap-shots during the computation process and overall computational result says that the experimental images by Morris et al.[3] are in-progress results. Fig. 3 (c) shows temporal evolution process of detonation ftont and subsonic region for Case 2, and Case 1 shows nearly same evolution process with slight time difference. In this process, after ignition during the passage of mixture over the wedge, burnt gas expands and

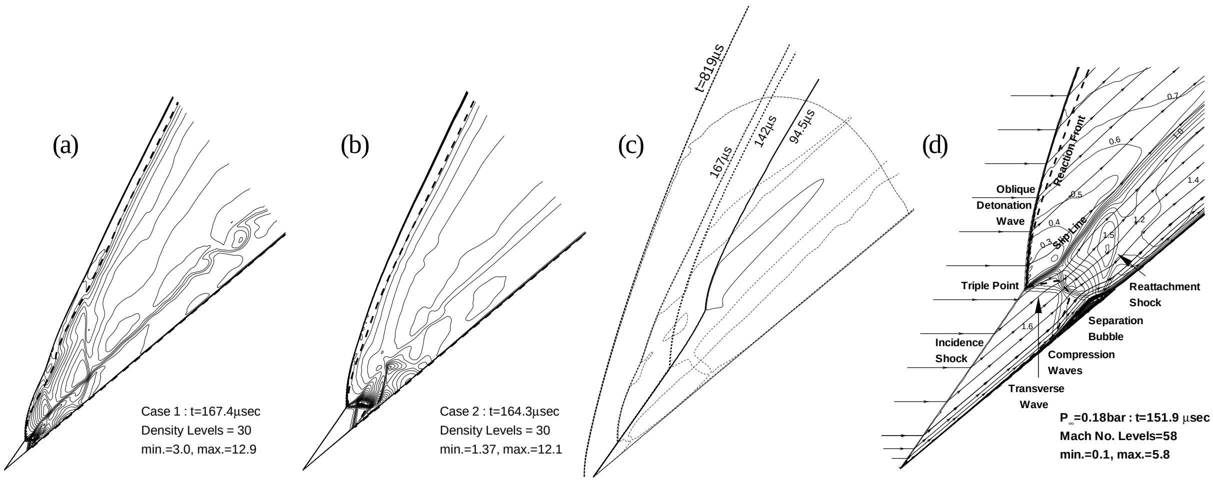

Fig. 2 (a), (b) Density contours and flame fronts (thick dashed line) for case 1 and 2, respectively. (c) Temporal evolution process of detonation front and subsonic region. (d) overlaid Mach number contours and stream lines showing detailed ODW structure near triple point.

couples with shock front. The coupled shock and reaction front develops to a detonation front, but it is not stabilized over a wedge. Understood by the presence of subsonic region behind triple point, thermal choking occurs locally by the flow area occlusion by large wedge angle and the thermal occlusion by heat addition. The choked flow pushes forward the detonation front and oblique detonation wave finally detaches from wedge. Situation is nearly same for Case 1 except slightly fast progress. These detached solutions are not shown in the experiment [4] because the time for the stabilized solution is much longer than experimental test time (about 150 μs). However, latest images by Morris et al.[7] for more sensitive case shows such a detached ODW and the detachment is also justified by reminding that this case is at off-attaching condition in shock-polar diagram[3]. Fig. 2 (d) shows induction zone structure during ODW evolution process. This structure is very similar to the one suggested by Li et al.[1], but shows the separated flow region caused by transverse wave/boundary layer interaction. Also, bifurcation of shock and reaction front is noticed, that is considered as one of the ODW characteristics at off-attaching condition.

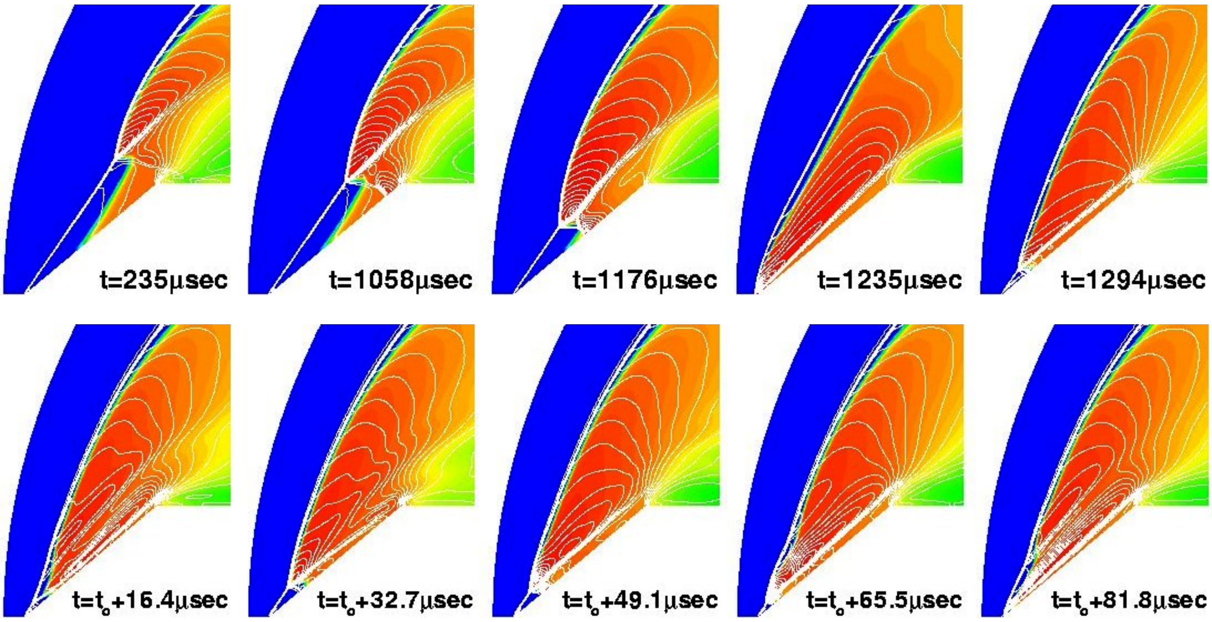

Fig. 3 Overlaid plots of density contours and OH distributions for Case 3 showing evolution process of oblique detonation wave and one-period of oscillation behavior after very long time.

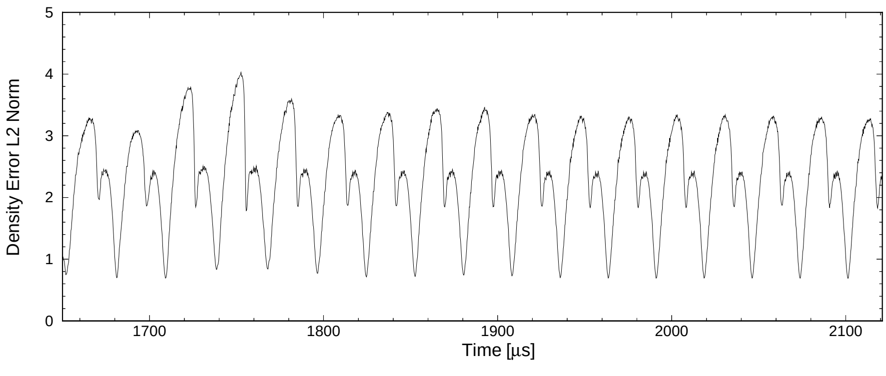

Fig. 4 Convergence history of oscillating oblique detonation wave for the case of p_∞ = 0.12 bar

In contrast to the above results, the results for Case 3 shows different behavior. Since induction time is much longer, coupling of shock and reaction front occurs over wedge turning point and ODW propagates upstream very slowly. Thus, a flow field image of Fig. 3 at t=235μs could be mis-understood as oblique shock-induced combustion if we take into account the location of triple point laying outside the imaging region in Fig. 1. Moreover, t=235μs is much larger one compared with 150μs experimental test time of the expansion tube facility[4]. Time need for the triple point to reach the wedge nose is about 1,200 μs. Differently to the Case 1 and 2, the oblique detonation wave for this case doesn't detach completely from wedge nose and exhibits periodically oscillating flow features after reaching the wedge nose, even though this case also corresponds to off-attaching condition. That is, a triple point is formed downstream and detonation front propagates upstream as was in the case of more sensitive mixtures, but finally decays when it reaches wedge nose. During this process, new triple is formed at downstream shock front and the same process is repeated. Fig. 3 also shows the perodical oscillating behavior of the oblique detonation wave after sufficiently long time, and Fig. 4 is convergence history showing this oscillatory characteristics. This oscillatory behavior is presumed being originated basically by the low heat content of the mixture, but the length of and induction time and chemical charcteristic time for complete combustion have much more crucial role if we consider that this case is also corresponds to a detaching condition obtained from chemical equlibrium calculation assuming infinitely fast chemical reaction.

Conclusion

The structure and the stability of oblique detonation waves in $H_2/O_2/N_2$ mixtures are investigated through a numerical simulation of experimental cases. The results of present computations are conceived to be valid in comparison with previous experimental results. In addition, the results give the details about the structure of oblique detonation including transverse wave/boundary layer interaction detonation wave and its characteristics at off-attaching condition. In this studies, it is understood that oblique detonation waves found in the experiment shows very transient or unstable characterisitcs and they were in-progress result during evolution process. At off-attaching condition where the solution of oblique detonation wave is not given by the theoretical shock polar diagram, the oblique detonation wave seems to be transient and unstable. At this condition, thermal choking caused by the flow area occlusion by the large wedge angle and the thermal occlusion by the heat addition moves the triple point upstream continuously. Finally, the oblique detonation reaches the edge of the wedge and detaches from the wedge nose, as was expected.

However, in some case for less sensitive mixture, it is found that the oblique detonation wave doesn’t detach completely from wedge nose and shows periodical oscillations. This oscillatory behavior is considered as characteristics of a critical off-attaching condition where it is predicted by Rankin-Hugoniot and chemical equlibrium theory but chemical charcteristic time is much long than fluid characteristic time.

Acknowledgemnts

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References

[1] Pratt, D.T., Humphrey, J. W. and Glenn, D. E., “Morphology of Standing Oblique Detonation Wave,” *Journal of Propulsion and Power*, Vol. 7, No. 5, Sept.-Oct. 1991, pp. 837-845.

[2] Li, C., Kailasanath, K. and Oran, E. S., “Stability of Oblique Detonations in Ram Accelerators,” AIAA Paper 92-0089, Jan. 1992, Reno, NV.

[3] Viguier, C., Figueira da Silva, L. F., Desbordes, D and Deshaies, B. “Onset of Oblique Detonation Waves : Comparison between Experimental and Numerical Results for Hydrogen-Air Mixtures,” *Twenty-Sixth Symposium (International) on Combustion*, The Combustion Instotute, Pittsburgh, PA, pp.3023-3031.

[4] Morris, C. I., Kamel, M. R. and Hanson, R. K., “Expansion Tube Investigation of Ram-Accelerator Projectile Flow Fields,”AIAA Paper 96-2680, July 1996, Lake Buena Vista, FL.

[5] Choi, J.Y., Jeung, I.-S. and Yoon, Y., "Numerical Study of SCRam-Accelerator Starting Characteristics," AIAA Journal, Vol. 36, No. 6, 1998, pp. 1029-1038.

[6] Choi, J.Y., Jeung, I.-S. and Yoon, Y., " Validation of CFD Algorithms for Unsteady Shock-Induced Combustion,," AIAA Paper 98-3217, 34^{th} AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 13-15 1998, Cleveland Ohio.

[7] Morris, C. I., Kamel, M. R., Ben-Yakar, A. and Hanson, R. K. “Combined Schlieren and OH PLIF imaging Study of Ram Accelerator Flow Field”, AIAA Paper 98-0244, Jan 1998, Reno, NV.