Mechanisms of Oblique Shock-Induced Combustion Instability

Jeong-Yeol Choi
Department of Aerospace Engineering
Pusan National Uinversity
Pusan 609-735, Korea

In-Seuck Jeung
Department of Aerospace Engineering
Seoul National University
Seoul 151-742, Korea

ABSTRACT

Instability of oblique detonation waves (ODW) at off-attaching condition was investigated through a series of numerical simulations. Two-dimensional wedge of finite length was considered in $H_2/O_2/N_2$ mixtures at superdetonative condition. Numerical simulation was carried out with a compressible fluid dynamics code and a detailed hydrogen-oxygen combustion mechanism. Present result reveals that there is a chemical kinetic limit of the ODW detachment, in addition to the theoretical limit predicted by Rankine-Hugoniot theory with equilibrium chemistry. Result also presents that ODW still attaches at a wedge as an oblique shock-induced flame showing periodically unstable motion, if the Rankine-Hugoniot limit of detachment is satisfied but the chemical kinetic limit is not. Mechanism of the periodic instability is considered as interactions of shock and reaction waves coupled with chemical kinetic effects. From the investigation of characteristic chemical time, condition of the periodic instability is identified as follows; at the detaching condition of the Rankine-Hugoniot theory, (1) flow residence time is smaller than the chemical characteristic time, behind the detached shock wave with heat addition, (2) flow residence time should be greater than the chemical characteristic time, behind an oblique shock wave without heat addition.

Keywords : oblique detonation wave, shock-induced combustion, Rankine-Hugoniot theory, combustion instability, numerical simulation.

INTRODUCTION

An oblique detonation wave (ODW) stabilized over a body was given interests for a last decade, since is it considered as a promising combustion mechanism for novel hypersonic propulsion systems such as a ram accelerator or an oblique detonation wave engine. In these systems, the stabilization of the ODW is crucially important for stable operation and optimum performance, because an improper location of stabilization results in performance degradation or an instability of ODW results in unstart of propulsion system.

Formation of ODW was studied by Pratt[1] with Rankine-Hugoniot theory assuming immediate heat addition behind an oblique shock wave, and Shepherd[2] summarized recent theoretical and experimental results of ODW for propulsion application. Fig. 1 is a polar-diagram of oblique shock wave and ODW from the Rankine-Hugoniot theory assuming frozen flow and equilibrium chemistry. It is understood from the theory that there is a range of flow turning angle for a given Mach number where ODW may be stabilized, although it is narrower than that of frozen oblique shock wave. Here, θ_{CJ} is a physically possible minimum turning angle and $\theta_{det,eq}$ is a maximum allowable turning angle. The stabilized structure of ODW was numerically studied by Li et al.[3], and it has been observed in many experiments using two layer detonation tube.[4,5] In actual situation of stabilized ODW, the chemical kinetic effect induces pre-heating zone behind an oblique shock wave, and combustion initiates at some distance behind the wedge nose. Coupling of the reaction front and the oblique shock wave results in a triple-point structure, and an ODW is formed behind the triple point with a wave angle greater than that of oblique shock wave.

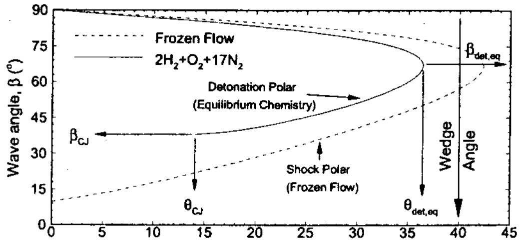

Fig. 1 Shock-Polar diagram showing the range of wave angle and turning angles for H_2-Air mixture at M=6 (T=300K, P=1bar).

Beyond the maximum turning angle $\theta_{det,eq}$, detonation may be detached, as was frozen shock wave. However, detached detonation over wedge is rarely found from experimental results, even though there are many achievements of detached detonation over blunt bodies.[6,7,8] Recently, Morris et al.[9] carrid out an experiment of shock-induced combustion over a wedge in expansion tube. A wedge of 40° flow turning angle was used in their experiment, that is greater than $\theta_{det,eq}$ for the experimental condition. Differently from the theoretical expectation with equilibrium theory, attached shock-induced combustion results were observed in the experiment, although they are coupled or de-coupled according to the level of mixture pressure. Chemical kinetic effect was believed to be a reason of the disagreement between the experiment and the theory. In the continuing studies, Morris et al.[10] also observed attached and detached shock-induced combustion according to different levels of dilution and Mach number. Although their results gave an understanding on ODW or oblique shock-induced combustion at off-attaching condition, stability and steadiness of the results were speculative due to the limitation of experimental test time. Hence, a purpose of present study is to improve the understanding of the stability and steadiness of ODW or oblique shock-induced combustion at off-attaching condition. For this study, computational methods would be a good aid for understanding the detailed flow-features, because it could give a solution to without restrictions such as a test time and a model size.

GOVERNING EQUATIONS AND NUMERICAL METHODS

For the simulation of the oblique detonation phenomena over two-dimensional wedge, the coupled form of species conservation equations and inviscid Euler equations was employed with the detailed combustion mechanism of $H_2/O_2/N_2$. Jachimowski combustion mechanism was used ignoring the nitrogen dissociation mechanisms that have a negligible effect 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. The governing equations were discretized numerically by a finite volume approach. The convective fluxes were formulated using Roe's FDS method derived for multi-species reactive flows along with MUSCL approach and a differentiable limiter function. This spatial discretization strategy satisfies TVD conditions and shows high-resolution shock capturing capability. The discretized equations are temporally integrated by a second order time accurate fully implicit method. A Newton sub-iteration method was also used to preserve the time accuracy and solution stability at large time step. Since the detailed descriptions of the governing equations and numerical formulations are documented in literature [11,12], it will not be recapitulated here.

The numerical modeling of governing equations have been validated through a number of steady and unsteady simulations of shock-induced combustion phenomena and oblique detonation phenomena.[11-13] The solutions showed good agreements with existing experimental data including locations of shock and reaction fronts, oscillation frequency of shock-induced combustion and pressure and friction coefficient data of shock wave/boundary layer interaction problem. Oblique detonation experiments by Viguier et al.[5] and Morris et al.[9] were also simulated and the comparison with their experimental and numerical results showed reasonable agreements. Since the validation of computational algorithms and the accuracy of combustion mechanism had been studied through a number of supersonic combustion studies, it would not be included in detail.

COMPUTATIONAL CONDITIONS

Computational condition of simulation was selected from the experiment by Morris et al.[10] A wedge of 40° angle in $2H_2+O_2+17N_2$ mixture was considered with flow Mach of 5.85. Inflow temperature and pressure is set to 292K and 0.12bar, respectively. Length of wedge is set to 2.44cm for a reference case. Except the smaller size wedge, this case very similar to Case A of experiment using 3.84cm wedge[10] where attached and de-coupled shock-induced combustion is observed due to the high dilution of mixture. Fig. 1 is a detonation polar diagram for this condition, and it is understood that detached detonation may be found even in this highly diluted condition, if chemical reaction is fast relatively. Among the various case of the experiments, the above reference case is selected because it has special characteristics of periodic oscillation. Other cases showing plain developing process to a detached wave had been discussed previously.[13]

The computations were carried out using 301×250 grid clustered to wedge nose and surface boundary. Although the solution of oblique detonation wave is very sensitive to the grid density, previous experience on this kind of calculations suggests the above grid resolution is sufficient enough for the understanding of detailed flow features.[13] For an unsteady state calculation, frozen flow solution was obtained and used as an initial condition of reactive flow calculation with imposed mixture condition on inflow boundary. Although the presence of acceleration gas flow ahead of test gas makes an ambiguity about setting a initial condition for unsteady calculation of expansion tube experiment, previous experiences[12,13] suggest that it is not significant because the settling time of reactive flow is much more longer than that of frozen flow, especially for highly diluted mixtures as was considered in this study.

RESULTS

Unsteady Calculation of Reference Case

At an initial stage of simulation, mixture gas comes from inflow boundary and passes around the wedge forming an incident oblique shock. During the passage of the mixture gas, mixture gas ignites between oblique shock and contact surface due to the shock heating behind the oblique shock wave. After the ignition, burnt gas expands and couples with oblique shock front forming a triple point structure. However, a long ignition delay for this case makes the triple point positioned far above the wedge surface. Therefore, the combustion flow field near wedge surface may be misunderstood as a de-coupled shock induced combustion as shown in the experimental image in reference 10, if a frame of view is confined to near wedge surface. Triple point exists outside the experimental view frame and the coupled waves move forward very slowly to the wedge nose. About 1,200 μs was needed for the triple point to reach the wedge nose. Remind that test time of the expansion tube was only 150μs.[10]. However, the oblique detonation wave does not detach from the wedge after reaching the nose, and shows periodic oscillations of repeated coupling and de-coupling of shock and reaction front, even though this case also corresponds to the detaching condition in detonation polar diagram in Fig. 1. Fig. 2 (a) is a partial history of density error L^2 norm showing periodically oscillating features from the beginning of the oscillation. Fig. 2 (b) is a magnified view of a period showing 45μs of duration. The marked points in this plot are the time of contour plots in Fig. 3. In this fig-

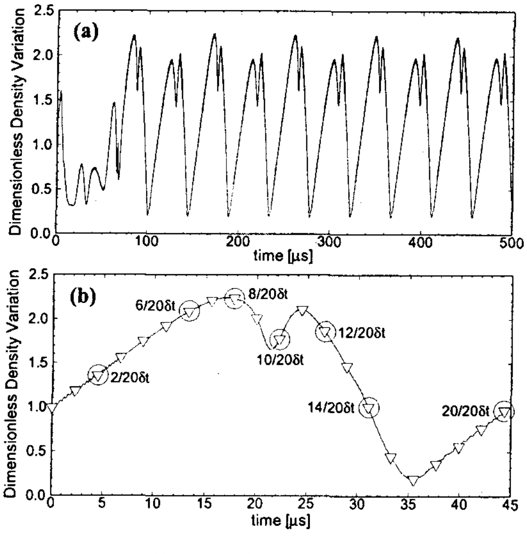

Fig. 2 (a) Part of history of density error L^2 norm showing periodic oscillation, (b) Magnified view of a period of oscillation. Circles designate the instance of plots in Fig. 3.

ure, a triple point moves forward to nose, but finally decays when it reaches wedge nose. During this process, new triple point is formed at downstream shock front and the same process is repeated. As the triple point approaches to nose, overall pressure level decays behind the triple point and the strength of front shock is getting weaker. Accordingly, ignition delay behind a front shock wave and transverse wave is getting longer relatively, and the coupled transverse wave generating high pressure becomes de-coupled. Finally, the triple point structure is broken and the de-coupled oblique shock and reaction front moves backward.

Understanding of Scaling Effect

The oscillatory behavior is presumed being originated basically by the low heat content of the mixture, but the chemical kinetic induction time needed for complete combustion have much more crucial role, since this case is also corresponds to a detaching condition predicted by Rankine-Hugoniot theory with equilibrium chemistry that assumes prompt heat addition behind a shock wave. Therefore, non-equilibrium chemical kinetic effects that introduce a chemical induction time for a sufficient amount of heat addition are considered as playing an crucial role for the oscillatory behavior of the oblique detonation wave.

For the understanding of the scaling effects between flow and chemical time scale, some numerical calculations were carried out by simply adjusting the length of wedge with the other flow conditions fixed. The wedge lengths were changed from 1.16cm to infinity. Considered wedge lengths are 1.16cm, 1.74cm, 2.44cm, 3.84cm, 5.76cm, 6.96cm, 11.5cm, 38.4cm and 384cm. The case of infinity length was also simulated by truncating the expansion corner and imposing extrapolation boundary condition at the exit. Converged results, for each case except these cases from 2.24cm to 5.76cm, are plotted in Fig. 4. The exceptions are intermediate solution during oscillation. Combustion is not observed for very small wedge and oscillating

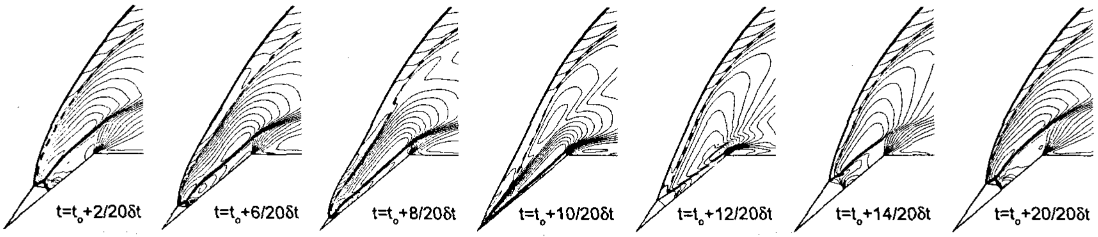

Fig. 3. Overlaid Mach number contour and flame fronts(dashes line) for a period showing oscillating flow field.

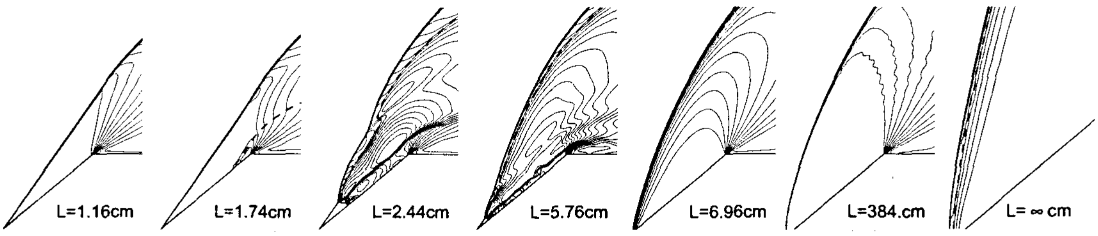

Fig. 4. Overlaid Mach number contour and flame fronts(dashes line) for various scale of wedge length.

combustion is observed for intermediate scales. Beyond the wedge length of 6.96cm, the shock wave is detached from wedge nose. As the size of wedge getting larger, the shock stand-off distance is also getting larger but gradually converges to a equilibrium condition, in dimensionless sense. Practically, the case of 384cm can be considered as a result of equilibrium chemistry having very fast reaction. Case of infinite wedge length plotted in Fig. 4 is an intermediate solution, and the final solution with an assumption of infinite length protrudes forward the inflow boundary, because the shock stand-off is proportional to wedge scale, but cannot be defined (or defined as infinity) in this case.

To measure the scaling effects quantitatively, flow time scale and chemistry time scale are compared for each case. In this study, there are two flow time scales and two chemical time scales: τ^o_f, flow residence time behind an oblique shock wave, τ^n_f, flow residence time behind a detached shock wave that is considered as being locally normal to flow direction, τ^o_c, chemical characteristic time behind an oblique shock wave and τ^n_c chemical characteristic time behind a detached shock wave. Typically, chemical characteristic time is defined as ignition delay behind a shock wave, but is defined as a time when an amount of heat addition is achieved, because induction time is very short for present cases but heat addition takes much longer time than ignition delay. The flow residence time is estimated from flow speed behind shock wave and maximum allowable fluid dynamic length scale. Theory of normal and oblique shock wave is used for simple estimation of flow speed. The wedge length is used as maximum allowable length scale for oblique shock wave, and the shock stand-off distance scaled from equilibrium condition (case of 384cm wedge length) is used for normal shock wave.

With these definition, estimated τ^o_c is 17.5μs and τ^n_c is 10.6μs. Estimated flow residence time for each case is summarized in Table 1. Even though present analysis is a crude one due to the ambiguity of definitions of shock stand-off distance and characteristic chemical time, summarized result give quite an impressive estimation. With this table, time scaling effect on shock-induced combustion mode around a wedge at off-attaching condition is summarized as follows; (1) if the chemical characteristic time is longer than flow residence time behind an oblique shock wave, no combustion or de-coupled shock induced combustion is found, (2) if the chemical characteristic time is shorter than flow residence time behind a detached normal shock wave, shock wave is detached from wedge, (3) Within the intermediate range, shock-induced combustion attaches to wedge, but is not stabilized and exhibits periodical oscillation.

Table 1 Summary of time scales and combustion mode.

L(cm)	τ^o_c	τ^o_f	τ^n_c	τ^n_f	Combustion Mode
1.16	17.5	9.67	10.6	1.97	No Ignition
1.74	17.5	14.5	10.6	2.95	Decoupled SIC
2.44	17.5	20.3	10.6	4.14	Oscillation
5.76	17.5	48.0	10.6	9.76	Oscillation
6.96	17.5	64.0	10.6	11.8	Detached detonation
38.4	17.5	3,200	10.6	651	Detached detonation

[a] Unit of time is μs.

CONCLUSIONS

Through a series of numerical studies, stability of the shock-induced combustion was investigated at off-attaching condition over a two dimensional wedge. From the results of present numerical simulation, various regimes of combustion were observed. With the definition of fluid dynamic and chemical time scales defined above, the combustion regimes are successfully classified into three categories including (1) detached combustion, (2) attached combustion and (3) no combustion or de-coupled combustion. At one extreme, no combustion or de-coupled shock induced combustion is found in case the chemical characteristic time is longer than flow residence time behind an oblique shock wave. At another extreme, detached combustion is found in case the chemical characteristic time is shorter than flow residence time behind a detached normal shock wave.

At an intermediate condition, the unsteady numerical analysis reveals ODW or shock-induced combustion still attached at a wedge but showing periodic motions that was not yet observed due to experiment limitations. So, it is concluded from this result that attached shock-induced combustion may be possible at off-attaching condition, but it is unstable and is oscillating. Close examination of the flow field suggests that the mechanism of the periodic instability should be an interaction of shock and reaction waves coupled with chemical kinetic effects at this intermediate condition.

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