Extended Abstract submitted to
19th ICDERS, July 27 - August 1, 2003 Hakone Prince Hotel, Hakone, Kanagawa, Japan

Combustion Wave Oscillation behind Oblique and Conical Shock Waves

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Introduction

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. Pratt[1] et al. summarized the classical theory of ODW with Rankine-Hugoniot theory 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 assuming frozen flow and immediate heat addition by equilibrium chemistry. It is known that there is a range of flow turning angle for a given Mach number where ODW may be stabilized, which is narrower than that of frozen oblique shock wave. 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 the stabilized ODW 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.

Beyond the maximum turning angle the overdriven detonation may be detached, as was frozen shock wave. However, the detached detonation over wedge is rarely found, even though there were many observations of detached overdriven oblique detonation wave over blunt bodies.[6,7,8] An example of the detached overdriven detonation wave over a conical projectile is presented by Kasahara *et al.*[9] Another interesting result at the off-attaching condition is the experiment by Morris *et al.*[10] They observed the attached shock-induced combustion results were observed in the experiment, differently from the theoretical expectation with equilibrium theory, although detached shock-induced combustion was observed in their continuing studies.[11] Some numerical calculations have been carried out by the authors[12] for the experimental results by Morris *et al*, and it is understood that the attached solutions are transient phenomena and the detached overdriven detonation waves are final solutions after a sufficiently long time beyond the experimental test time. However, an attached shock-induced combustion was still observed at the

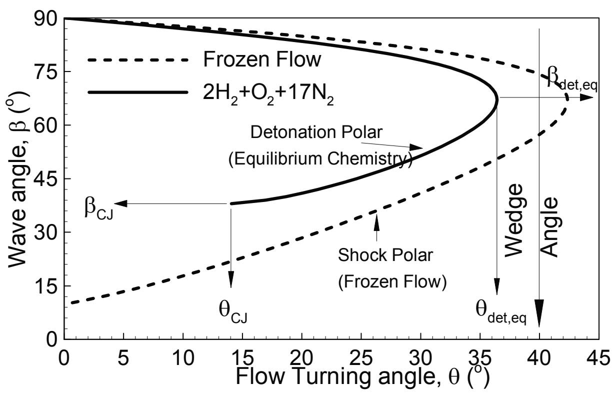

Fig. 1 Shock-polar diagram showing the range of wave angle and flow turning angles for the experimental condition by Morris et al[10]: $2H_2+O_2+17N_2$ mixture, M_∞=5.85, T_∞=292K and P_∞=0.12bar. θ_{CJ} is a physically possible minimum turning angle and $\theta_{det,eq}$ is a maximum allowable turning angle.

off-attaching condition for a case of less sensitive mixture, which is unstable and oscillates periodically.

Actually, the periodical oscillation of combustion induced by oblique shock wave is not a new observation. Behrens *et al*[13,14] observed both steady and oscillatory combustion over cone-cylinder models, but no firm conclusions were made. Jain[14] showed two distinctive regimes of oscillatory combustion and found that the case of oscillatory combustion has an imaginary number of heat addition parameter. Toong summarized the previous studies in his text book[13] with experimental figures by Jain[14]. However, there has not been an intensive or extensive study on the oblique shock-induced combustion, even though numerous studies have been made for the shock-induced combustion around blunt bodies. The mechanism of the periodic oscillation of the oblique shock-induced combustion was not explained clearly but was considered simply as a coupling between gas dynamics and chemical kinetics similarly to the oscillatory combustion around a blunt body. Moreover the condition of oscillatory combustion found by Jain is a sufficient condition but is not a necessary condition. Because, their theoretical derivation is equivalent to the off-attaching condition of standing oblique detonation[1] which implies only the steady oblique detonation wave does not exists and a detached overdriven detonation wave may be a solution in which condition. Hence, a purpose of present study is to clarify the condition of the oscillatory combustion and to improve the understanding of the mechanism of the periodic oscillation of oblique shock-induced combustion at the off-attaching condition of oblique detonation wave.

Numerical Formulation and Computational Setup

For the simulation of the oblique shock-induced combustion/detonation phenomena over two-dimensional wedge, the coupled form of species conservation equations and Euler equations was employed with the detailed combustion mechanism of $H_2/O_2/N_2$.

$$\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{F}}{\partial \xi}+\frac{\partial \mathbf{G}}{\partial \eta}=\mathbf{W}, \quad \mathbf{Q}=\frac{1}{J}\left[\rho_k \quad \rho u \quad \rho v \quad e\right]^T, k=1,\cdots,N \tag{1}$$

Here, $\mathbf{Q}$ is conservation variable vector, $\mathbf{F}$ and $\mathbf{G}$ are convective and viscous flux vectors in (ξ,η) direction respectively, and $\mathbf{W}$ is the vector of chemical production terms. The chemical production terms are modeled using Jachimowski's combustion mechanism. This mechanism consists of nine-species and nineteen reaction-steps including HO_2 and H_2O_2 reaction 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. Since the detailed descriptions of the governing equations and numerical formulations are documented in the previous literature [12,15-16], it will not be recapitulated here. The numerical modeling of governing equations has been validated through a number of steady and unsteady simulations of shock-induced combustion phenomena that showed good agreements with existing experimental data.[12,15]

Computational condition of simulation was selected from the experiment by Morris *et al.*[10] A wedge of 40^o 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. Fig. 1, a detonation polar diagram for this condition, presents that attached solution is not exist for this condition if chemical reaction is sufficiently fast. Among the various cases of the experiment, the above reference case is selected because it has special characteristics of periodic oscillation.[12] Other cases that resulted in a detached wave as a steady state solution had been discussed previously.[12] A large variation of wedge length including the experimental case of 3.84cm were computed as a means of understanding the influence of the relative time scales between the chemical kinetics and fluid dynamics on the condition of periodical oscillation. This way of changing the relative time scale has been used to understand the regimes of shock-induced combustion around a blunt body.[16] For axi-symmetric shock-induced combustion, a H_2+$2O_2$+$2Ar$ mixture was considered at Mach number was 5.0 with initial temperature 288 K and initial pressure of 200 mmHg. The flow conditions were based on the conditions of similar experiments and numerical studies.[13] A same computational domain over 40 degree half-angle was considered for two-dimensional and axi-symmetric shock-induced combustion phenomena.

The computations were carried out using 401×500 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 for the understanding of detailed flow features.[12] For an unsteady state calculation, frozen flow solution was obtained and used as an initial condition of reactive flow calculation by imposing 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] also 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.

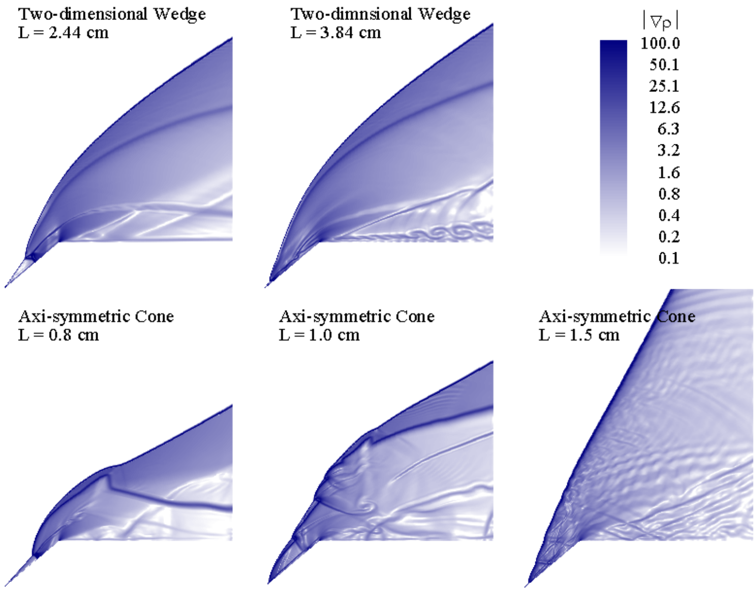

Fig. 2 Instantaneous density gradient plots for shock–induced combustion over two- dimensional wedges and axi-symmetric cones. (L is the length of the inclined portion of the wedge)

Results and Discussions

Periodic oscillation mechanism of shock-induced combustion over a two-dimensional wedges and axi-symmetric cones were investigated through numerical simulations at off-attaching condition of oblique detonation waves (ODW). A series of calculations were carried out by changing the fluid dynamic time scale. The wedge length is varied as a simplest way of changing the fluid dynamic time scale. Result reveals that there is a chemical kinetic limit of the detached overdriven detonation wave, in addition to the theoretical limit predicted by Rankine-Hugoniot theory with equilibrium chemistry. At the off-attaching condition of ODW the shock and reaction waves still attach at a wedge as a periodically oscillating oblique shock-induced combustion, if the Rankine-Hugoniot limit of detachment is satisfied but the chemical kinetic limit is not.

Mechanism of the periodic oscillation is considered as interactions between shock and reaction waves coupled with chemical kinetic effects. There were various regimes of the periodic motion depending on the fluid dynamic time scales. The difference between the two-dimensional and axi-symmetric simulations were distinct because the flow path is parallel and uniform behind the oblique shock waves, but is not behind the conical shock waves. The shock-induced combustion behind the conical shock waves showed much more violent and irregular characteristics.

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.

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