Self-Sustained Oblique Detonation in a Non-uniform Mixture

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1 Introduction

There has been a potential concept of using oblique detonation wave (ODW) for a hypersonic air-breathing propulsion [1]. It can reduce the size and weight of the combustor due to its short flame region. Thus, fundamental characteristics of ODW have been studied in abundance of previous researches [2-4]. Almost all of them consider a perfectly premixed mixture as an incoming flow. Even though effects of the non-uniform composition have been worked on in a few studies, the ranges of the concentration gradients were limited [5-7]. This has motivated us to study ODW in a non-uniform mixture flow from a numerical approach, and we have so far revealed some peculiar behaviors which have never been observed [8-10]. In this study, we focus on self-sustained Chapman-Jouguet (C-J) ODW, which is useful in a practical use because of its minimum entropy generation, with a specific interest in its wave structure and correspondence to the one-dimensional analysis.

2 Numerical Methods

$H_2/O_2/Ar$ mixture was considered in this study with a composition of the oxidizer O_2+3Ar. H_2 mole fraction X_{fuel} was varied normal to the inflow direction H following the Gaussian distribution given by

$$X_{fuel} = \begin{cases} X_0 \exp\left(-aH^2\right) \\ 1 - X_0 \exp\left(-aH^2\right) \end{cases} \tag{1}$$

The non-uniform mixture described above comes onto a spherical projectile with a diameter 4.76 mm at a speed 2188 m/s. Static pressure is 100 kPa and static temperature is 297 K, which were all uniform and unchanged in the fuel concentration gradients. The above configuration was matched to that of the experiment done by Maeda et al [4]. Computational domain is located around the projectile with a grid number of 750×999, extending to the radial and downstream directions. Boundary layer on the projectile was neglected since its effect is always limited close to the projectile, far from ODW front.
Axisymmetric two-dimensional Navier-Stokes equations were solved with a chemical kinetics including 9 species and 27 elementary reactions proposed by Konnov [11]. AUSM$^+$ up 2nd order scheme [12] was applied to convection terms, and 2nd order central difference to viscous terms. Time integration was implemented with TVD 2nd order Runge-Kutta method [13].

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First, we simulated ODW structure in the uniformly stoichiometric condition without any gradients. Figure 1 illustrates the simulated ODW structure as an overlaid contour of pressure (black lines) and water mass fraction (red-yellow-white color map) to illuminate the shock and flame fronts respectively. It can be first noted that ODW front soon reduces to a nearly constant angle behind the projectile. The shock and flame front are strongly coupled so that complete combustion is promised soon behind the shock front. There appear transverse wave structures near the projectile, and weak unsteadiness also occurs close to the outlet boundary. Absence of them in the middle region resulting in a planar front can be attributed to the coarser resolution in the outside region. Since the discretization for convection is second order, a higher order scheme will be needed for a more sophisticated discussion on these transverse waves. This study only discusses the primal ODW front structures without need for a detailed resolution of these secondary dynamic structures.
Figure 2 compares the profile of the observed ODW angles with C-J angle predicted by CEA program on the assumption of one-dimensional flow with a sonic outflow [14]. The black line in the figure denotes the actual profile obtained in this study, and the red horizontal line corresponds to the CEA prediction. Overdriven detonation close to the projectile converges to C-J angle after falling slightly below it, although the coarser resolution and unsteadiness outside generate fluctuating behavior. The above result shows that C-J detonation is stabilized behind the projectile, and validates that the present numerical method including the grid well resolves C-J properties of ODW in the whole region.

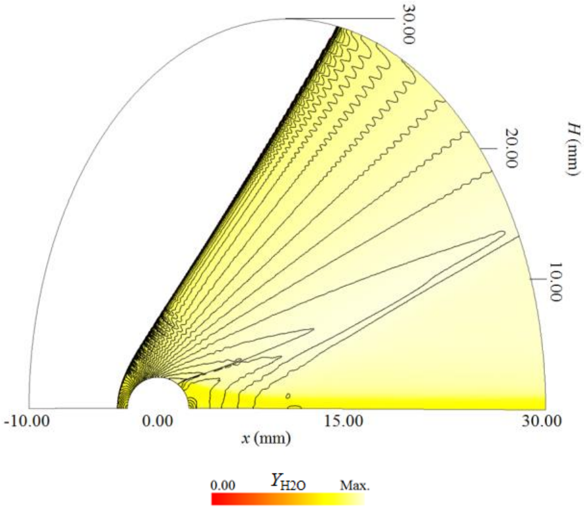

Figure 1. Overlaid contours of ODW structure in a uniform flow

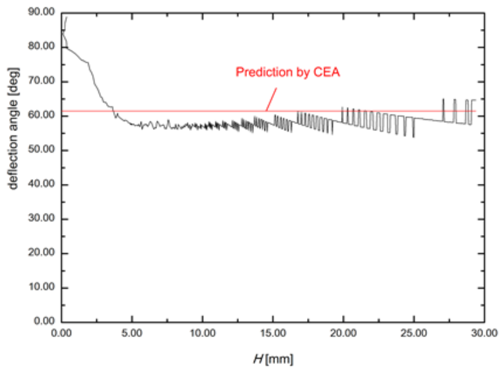

Figure 2. Profile of ODW front angle in the uniformly premixed condition

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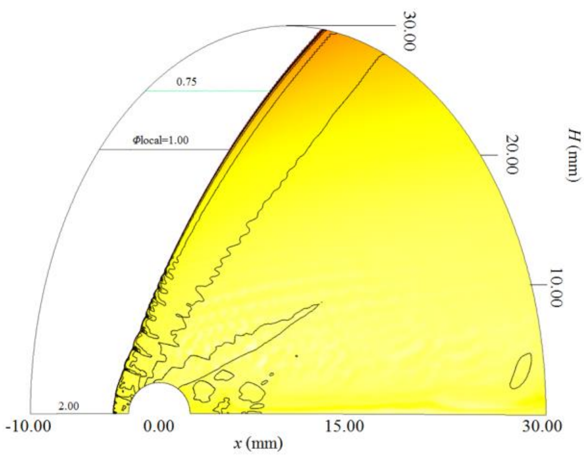
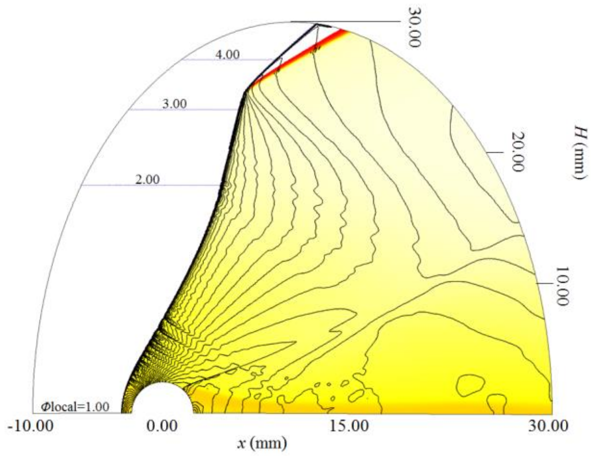
The hydrogen concentration gradient given by Eq. (1) was then introduced to the incoming mixture. The computational results obtained in three conditions simulated were illustrated in Figure 3 in the same way as was done in Figure 1. Several incoming streamlines were shown with their local equivalence ratio in each figure. The case in Figure 1(a) specifies the centerline equivalence ratio $\Phi_{℄}$ with the limitation of the total equivalence ratio Φ_{total} in the computational domain kept unity. The other two cases specify the outermost local equivalence ratio Φ_{out}, imposing $\Phi_{℄}$=1.00.

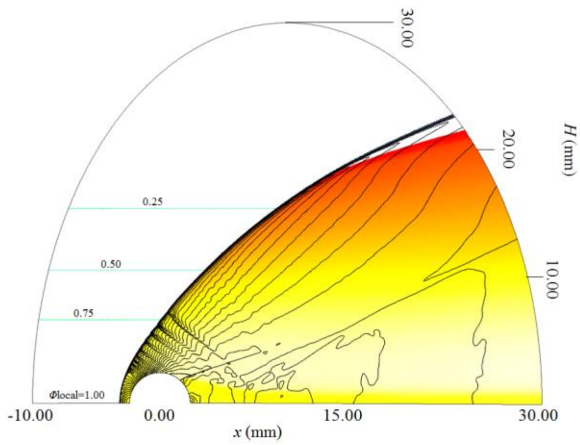
Some fundamental changes occurred to ODW fronts in the non-uniformity: Common to each case in the figure, ODW front deformed into a curved shape. In Figure 3(b) and (c), the shock and flame front decoupled in the outside region to exhibit shock-induced combustion without apparent interaction between them. The decoupling in the Φ_{out}=5.00 case (Figure 3(b)) is accompanied by a discontinuous drop in the shock angle, while it is not in the Φ_{out}=0.01 case (Figure 3(c)). These features, which can never be observed in uniform mixtures, are attributed to the two different effects: A constant incoming speed with different sound speed results in the different shock strength due to variable Mach number, and variable equivalence ratio can lead to longer induction length influenced by chemical kinetic speed.



(a)$\Phi_{℄}$=2.00 with limitation Φ_{total}=1.00



(b)$\Phi_{℄}$=1.00, Φ_{out}=5.00



(c) $\Phi_{℄}$=1.00, Φ_{out}=0.01

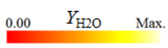


Figure 3. Overlaid contours of ODW structures in the non-uniform flows.

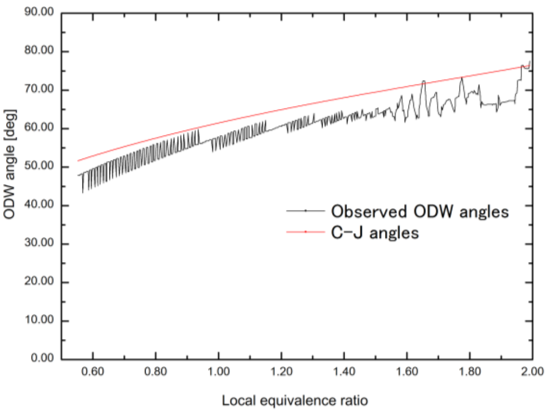
5 C-J Angles of Oblique Detonations

We next conducted one-dimensional analysis on the ODW fronts obtained in Figure 3 to investigate correspondence of the local wave angle to incoming local equivalence ratio. C-J angle β_{CJ}, which is an unique value to each equivalence ratio, was calculated from the ratio of one-dimensional C-J velocity D_{CJ} to the speed of the projectile V_{p}

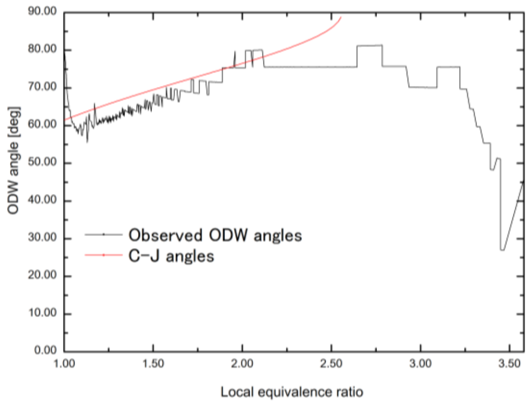
$$\beta_{\mathrm{CJ}} = \sin^{-1}\left(D_{\mathrm{CJ}}/V_p\right) \tag{2}$$

where D_{CJ} was calculated by CEA program against each local equivalence ratio. The calculated value was then compared to the actual wave angle obtained in Figure 3. The results were shown in Figure 4 as the relationship of ODW angle with the local equivalence ratio. The black lines are the observed profiles, and the red lines denote the values obtained from Eq. (2).

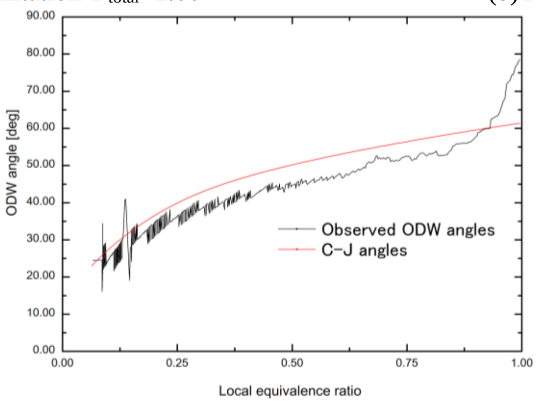
Fluctuation and discrete change are observed in every figure, but the wave angles in Figure 4(a) and (c) apparently change along C-J angles lines, although they are always a little lower. This is also true for Figure 4(b) in the range $\Phi < 2.00$. This clearly indicates that the self-sustanined oblique detonation behind an obstacle stabilizes at C-J angle even in the non-uniform mixture. However, the lower values observed in every case including the uniform conditions (Figure 2) imply that unsteady process of ODW converging to C-J angle has some influence [15].



(a)$\Phi_{℄}$=2.00 with limitation Φ_{total}=1.00



(b)$\Phi_{℄}$=1.00, Φ_{out}=5.00



(c) $\Phi_{℄}$=1.00, Φ_{out}=0.01

Figure 4. Overlaid contours of ODW structures in the non-uniform flows.

It is as important to note that ODW angle in Figure 4(b) starts to deviate from C-J value in the range $\Phi > 2.00$, ceasing to increase in the more fuel-rich region. Since ODW is apparently sustained in the range $2.00 < \Phi < 3.00$ as shown in Figure 3(b), the decoupling, which occurs around $\Phi \sim 3.50$ (Figure 3(b)) with a sudden drop in ODW angle, cannot explain this flat tendency. This can be partly attributed to a weaker interaction of the shock and flame front resulting from larger induction length: induction length in the fuel-rich region is so large that exothermic flow behind the shock is no longer one-dimensional and does not reach the sonic velocity, interrupted by two-dimensional expansion/compression wave. This effect weakens C-J ODW preventing its angle from increasing along C-J angle tendency, subsequently into decoupled shock-induced combustion. Therefore, the flat region observed here can be regarded as the intermediate region just being about to decouple. On the other hand, there is neither a discontinous drop nor a flat region of the wave angle in the Φ_{out}=0.01 case (Figure 4(c)). This is due to a minor difference of the shock angle of ODW and inert oblique shock in the fuel-lean mixture, resulting in a continous change along C-J values even in the decoupled region.

6 Conclusion

Self-sustained Chapman-Jouguet oblique detonation behind a hypersonic spherical projectile situated in a fuel concentration gradient was investigated through axisymmetric two-dimensional numerical simulation, using Navier-Stokes equations involving a detailed chemical kinetic mechanism. The concentration gradient was artificially given by the Gaussian distribution.

As the results, oblique detonation front in the non-uniformity had a curved shape, with its local angle changing along the analytical C-J value. However, when the strongly fuel-rich or fuel-lean around $\Phi \sim$ 3.50 or 0.10 occurs in the outer region, the decoulpling of the shock and flame front into shock-induced combustion occurred. When the decoupling happens in the fuel-rich region, a sudden drop in the wave angle is observed, while it is not in the fuel-lean region because of a minor difference of the angle of the detonation and the inert shock. Weakening of interaction between the shock and flame front in the strongly fuel-rich region prevented the wave front from increasing accordingly to the tendency of C-J angle, resulting in a relatively flat portion of the wave front just before reaching the decoupling location.

From the results and discussion above, it was newly revealed that the self-sustained oblique detonation retains its local C-J angle even in the concentration gradient, but that too large induction length in the fuel-rich/fuel-lean region can result in the decoupling of oblique detonation into shock-induced combustion, which is also a newly observed wave phenomena.

Our future works will be devoted to numerical study with a higher resolution or a uniform grid distribution to remove probable grid dependency of the wave phenomena. Transverse wave structures in the non-uniformity will be also our major interest. To investigate them, a higher order convective scheme will be required.

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