Numerical Simulation of the Oblique Detonation Waves in Different Regimes Initiated by Conical Projectile

Jeong-Yeol Choi
Pusan National University
Busan, Korea

and

Jimmy Verreault, Andrew J Higgins
McGill University
Montreal, Quebec, Canada

1 Introduction

Oblique detonation waves (ODWs) and shock induced combustion (SIC) stabilized over a body have been considered as a promising combustion means for hypersonic propulsion systems such as ODW engines and ram accelerators. A number of studies have been carried out to examine the fundamental characteristics of an ODW and its implementation for propulsion systems. A intersting point from the previous studies are there are varities of different ODW regimes depending on the flow conditions and configuration. Recently Verreault and Higgins [1] showed the different regimes of combustion with aeroballistic experiment and high speed visualization. They classified the different regimes of the ODW based on the energetic and kinetic limits of the detonation initiation by high speed projectiles.[2] Presently, computational fluid dynamcis simulation is carried out to understand the flow structure of the different regimes of the combustion shown experimentally.

2 Theoretical Modeling and Computational Methods

As a mathematical model governing ODW/SIC phenomena a coupled form of species conservation equations with momentum and energy equations are used for axi-symmetric configuration. It has been used to study ODW/SIC phenomena around spherical and conical bodies.[3,4] Viscous terms are neglected since it is known to be not important in the previous studies. The coupled form of the equations is summarized as follws in a conservative vector form.

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} + \mathbf{H} = \mathbf{W} \quad (1)$$

where,

Correspondence to: aerochoi@pusan.ac.kr

$$\mathbf{Q}=\begin{bmatrix}\rho_k\\ \rho u\\ \rho v\\ e\end{bmatrix},\ \mathbf{E}=\begin{bmatrix}\rho_k u\\ \rho u^2+p\\ \rho uv\\ \left(e+p\right)u\end{bmatrix},\ \mathbf{F}=\begin{bmatrix}\rho_k v\\ \rho uv\\ \rho v^2+p\\ \left(e+p\right)v\end{bmatrix},\ \mathbf{H}=\frac{1}{y}\begin{bmatrix}\rho_k v\\ \rho uv\\ \rho v^2+p\\ \left(e+p\right)v\end{bmatrix},\ \mathbf{W}=\begin{bmatrix}w_k\\ 0\\ 0\\ 0\end{bmatrix} \tag{2}$$

Jachimowski detailed mechanism for hydrogen combustion is used in the present study that successfully reproduced the ODW/SIC flow field in the previous studies. In this study argon (Ar) is used as inert gas instead on nitrogen. The code has been parallelized by OpenMP for multi-core SMP machines. Further details on the computational methodologies are addressed in the previous studies.

3 Flow Conditions and Configurations

The flow conditions for the computational simulations has been adopted from the experimental data and summarized in Table 1. Projectile diameter is 1.27 cm used as fluid dynamic length scale in CFD simulation. More details in the experimental condition is found in Ref. 1 [1]. Index of each case is taken same as Ref [1]. Initial gas temperature is assumed as standard state except for the case (b). 202×250 grid is used as a baseline grid, but further refined grids, as listed in Table 1, are used for the case of instabilities. The simualtion was carried out with third order spatial accuracy and second order accuracy in time with sub-iterations. CFL number of 2 to 4 is used in ordinary cases.

Table 1: Flow conditions and configurations[1] for CFD simulation.

Case	Gas	p_0 (kPa)	T_0 (K)	V_p (m/s)	θ_c	Regime	Grid
(a)	$2H_2 + O_2 + 7Ar$	101.0	*298*	2,180	40^o	Prompt ODW	402×500
(b)	$2H_2 + O_2 + 7Ar$	120.0	*700*	1,740	25^o	Delayed ODW	202×250
(d)	$2H_2 + O_2 + 7Ar$	96.0	*298*	1,780	45^o	Instabilities	1,602x1,000
(e)	$2H_2 + O_2 + 7Ar$	67.9	*298*	1,930	30^o	Wave splitting	202×250
(f)	$2H_2 + O_2 + 7Ar$	124.0	*298*	1,920	15^o	Inert shock	202×250

3 Results and Discussions

Figure 2 is the experimental results compared with present CFD results. The case (a) corresponds to the prompt ODW regime, in which overdriven ODW is present over the conical part later transit to the CJ ODW. The CFD results agrees well with the experimental results in overall, though the CFD results does not shows the detonation cell structures due to the coarse grid resolution. Some instabilities are shown around the nose of the cone where grid density is higher than other region. The cell sturtcure of the overdriven ODW has been shown previously [5], in which single head (triple point) is the dominent flow structure moving continuosly to the nose. Choi has been shown that dual head structure is the dominent structure of CJ ODW, which exhibits the cell structure similarly to the ordinary noraml detonation waves[5]. It is considered that the CJ ODW can be maintained without any flow turning object becasue the hot combustion gas by the overdriven region expands and works as a gasdynamic wedge. Also, it is considered that CJ speed is maintained by the pressure balance between the burned gas behind CJ ODW and the expanding burned gas behind the overdriven ODW. Therefore streamlines at the exit of the computational domain is not parallel to the incoming flow but is goidng outward.

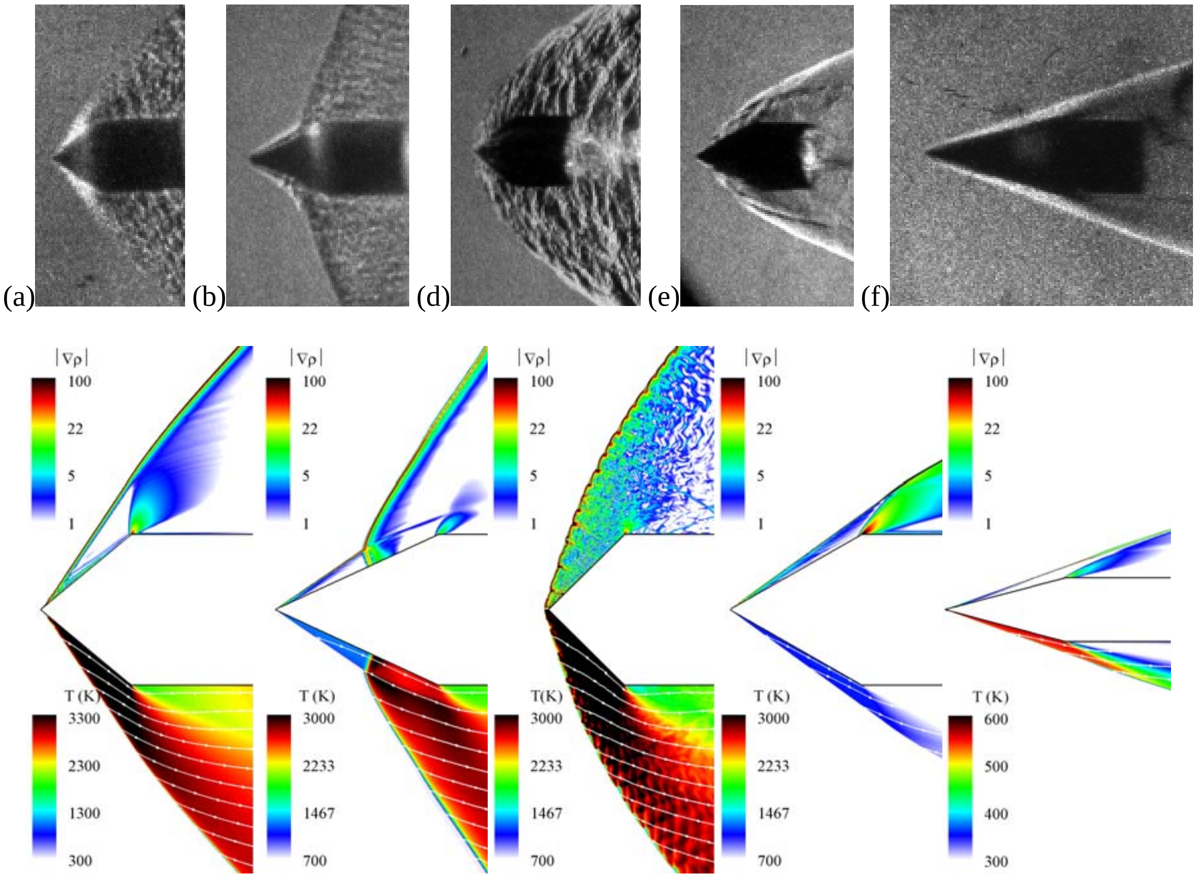

Figure 1. Experimental Schlieren images [1] (upper row) and corresponding CFD results of density gradient and temperature distributions overlaid with streamlines (lower row).

In case of the delayed ODW, for which many CFD work has been done previously, normal detonation wave is present over the wall which forms the primary triple point with the incident shock and ODW. The present CFD results is obtained with an elevated initial temperature resulting reduced amount of heat addition, and consequently smaller ODW angle. The wave front is believe to have same cell structures as CJ ODW, but the fine details of the ODW is not shown because of the coarse grid resolution.. It is considered that the normal detonation wave having CJ detonation speed of the compressed gas over the cone is balanced by chemical induction of the gas, and the location of the triple point is determined accordingly. It should be noted that the experimental result is harldy reproduced with the experimental flow conditions parlty because of the sensitivity of the kinetics mechanism. Coarse grid resolution and numerical stiffness could be other sources of deviation and further study is necessary to elucidate further details of the delayed ODW structures.

The case of the instabilities regime were quite sensitive to grid resolution, while the prompt ODW regimes could be simulated with coarse grid with overall agreement. A coarse grid simualtion of this case results in differenent regimes corresponding to the prompt ODW. Thus, the present level of grid resolution is considered as coase one that may caputre the wave instabilities with qualitative agreement with experimental results. This case has been further smulated with reduced projectile diameter of 0.635 cm to have better resolution, relatively. The structures of the ODW instability ccould understood better with the result plotted in Fig. 2. Distinguished feature of this case is that the instability structures are classified into two single head (triple-point) sturctures. Dual head detonation structure is present over the expansion corner where flow speed changed from subsonic to supersonic.

Overdriven region over the conical surface is occupied by subsonic pocket where the single head structure continuously is moving toward the nose of the cone. Since the cone angle is greater than the maximum value where ODW can be attached, wave deatching and attaching is repeated continuously as observed by Choi et al.[4] A small CFL number has to be used for numerical stability at the nose of the cone where mathematical singularity occurs. Since axi-symmetric configuration is considered, differently from previous study of wedge case [4], the shock focuing at the nose is a sort of implosion phenomena that makes very strong gradients and extremely high temperature pressure. In overall, flow structures and dynamics of the this former part is quite same to that of over driven detonation wave. Rear part of the flow structure is the supersonic flow region where single head structure going downstream. The triple point structure finally decouples and the regimes changes to the unstable shock-induced combustion. Differently to the CJ ODW for which dual head structure is maintained, the amount of the burned gas from overdriven region is not sufficient enough to balance the pressure behind the CJ ODW, since this case is below the energetic limit of the ODW initiation.

The regime of splitting waves has been observed partly in the previous studies, but the case is quite sensitive and cannot be reproduced presently. Fig. 2 shows a result of inert shock regime, but a result of delayed ODW regime has been obtained at same condition with different initial condition. Coarse grid resolution, uncertainties in kinetics and the viscous effect are considered as possbile sources of the error. Further study of this case is considered to investigate the underlying physics.

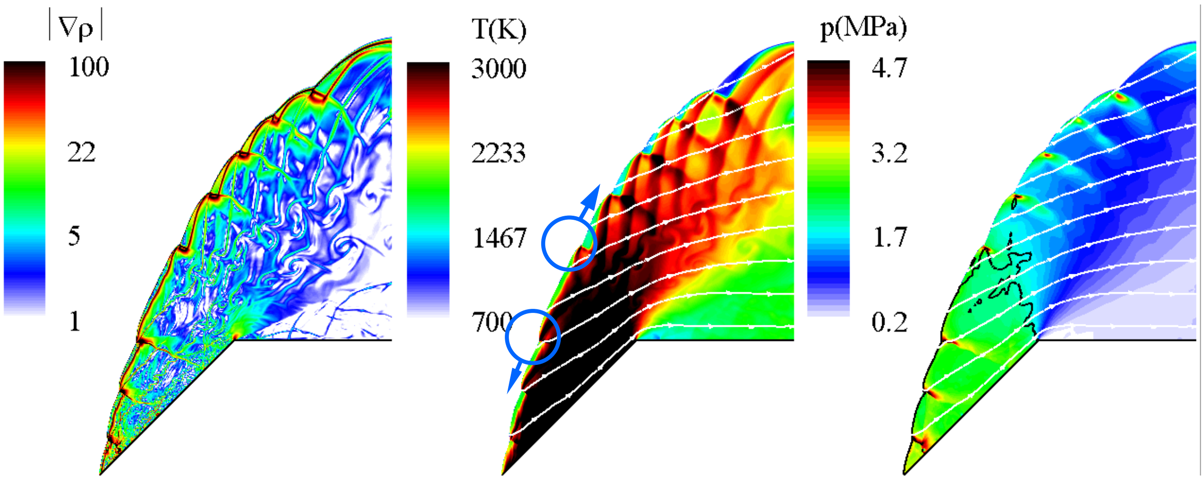

Figure 2. CFD results for case (d): from left density gradient, temperature distribution overlaid with streamlines and pressure distribution overlaid with sonic pocket marked by a black curve.

References

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