1 Introduction

Shock induced combustion (SIC) and oblique detonation wave (ODW) stabilized over a body have been considered as a promising combustion means for hypersonic propulsion systems for a long time. There were a lot of studies on the fundamental aspects of SIC and ODW for last two decades along with some conceptual studies for propulsion system applications. A lot of new findings and understandings on the underlying physics were attained through the studies with the help of advances in CFD and high speed visualization techniques. Recently, Maeda et al.[1] showed the various regimes of combustion around the projectile and revealed the unsteadiness of Straw–hat detonation. Among the various regimes of combustion, a lot of efforts were given to comprehend the instability regimes for its interesting nature of physics, and it is known that the combustion regime is dependent on projectile length scale relative to the detonation cell size. Ju et al.[2] suggested a criterion on the classification of SIC and ODW as energetic limit and kinetic limit. Verrault and Higgins applied the criterion to classify the SIC and ODW regimes initiated by conical projectiles.[3]

The purpose of present study is to apply the same criterion to SIC/ODW initiated by a spherical projectile though the CFD estimation of the drag coefficient, which is a crucial parameter of the criterion. It is believed that the application of the criterion to the blunt-body initiated SIC/ODW will further enhance the understanding of its underlying physics. The drag coefficients of a spherical body is well known for a long time, but there is a questionnaire whether it can be applied for the present case. Since, present case involves strong overdriven detonation ahead of projectile surrounded by hot burned gas, but the known drag coefficients of the spherical body is for the hypersonic projectiles in non-reacting or dissociating flows. The prediction of drag coefficient of a projectile in detonable media has another practical importance where gas phase detonation envelos the particle dispersion. The gas phase detonation accelerates the projectile, but the accelerated particle catches up the wave front, finally leading a bow shock or an overdriven detonation wave ahead depending on the criterion.
Theoretical Modeling and Computational Methods

For the reasonable drag prediction of the projectile initiating detonation, viscous flow model with a turbulence model is considered for axi-symmetric configuration. The coupled form of the multi-component chemically reactive system, fluid dynamic equations and turbulent transport equations can be summarized in a conservative vector form as follows.

\[
\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} = \frac{\partial E_v}{\partial x} + \frac{\partial F_v}{\partial y} + W
\]

where,

\[
Q = \begin{bmatrix}
\rho_l \\
\rho u_l \\
\rho v_l \\
\rho c_l \\
\rho k_l \\
\rho \omega_l
\end{bmatrix}, \quad \mathbf{E} = \begin{bmatrix}
\rho_j u_j \\
\rho_j u_j^2 + p \\
\rho_j v_j u_j \\
\rho_j v_j (e + p) u_j \\
\rho_j v_j k_j \\
\rho_j v_j \omega_l
\end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix}
\omega_j \\
\tau_{xx} \\
\tau_{xy} \\
\beta_x \\
\mu_k \partial k / \partial x \\
\mu_k \partial \omega / \partial x
\end{bmatrix}, \quad \mathbf{W} = \begin{bmatrix}
-\rho_j u_j^d \\
\tau_{xy} \\
\tau_{yy} \\
\beta_y \\
\mu_k \partial k / \partial y \\
\mu_k \partial \omega / \partial y
\end{bmatrix}
\]

3 Results and Discussions

Figure 2 is the CFD results for the experimetal cases. CFD results reproduce the overall structure of the experimental results. Although the resolution of computational simulation is not enough to catch the detailed cell structure of ODW, agreement is quite reasonable to interpret overall flow physics and the criterion of detonation initiation by a projectile. In present case of hypersonic blunt body, temperature rise across the bow shock was similar or greater than than the adiabatic flame temperature. Thus, the chemical reaction result in the heat loss by dissociation rather than combustion heating. The burned gas behind the bow shock expands outward displacing the unburned gas mixture. The expanding burned gas enhances the strength of the oblique shock wave that compresses the unburned mixture. That is, the expanding burned gas works as a gasdynamic cone. At critical condition the oblique detonation wave is initiated in the form of so called straw-hat detonation. This results is obtained by using the results of direct detonation initiation by larger projectile as an initial condition. However, this case of straw-hat detonation is quite unstable and moving back ward as observed experimentally.[1] The case returns back to the case of shock-induced combustion similarly to the case (b), if the computation is carry out much longer. Beyond the critical condition direct initiation of ODW is established. The case (d) and (e) are predicted quite well in the present study where case (e) exhibits larger wave angles due to the higher pressure and lower speed conditions.
Distributed of pressure coefficients are plotted in Fig. 3. Pressure around the projectile is always higher in the case of combustion than the case of non-reacting flow. The combustion has both positive and negative effects on drag because pressure on both fore-half and rear-half of the sphere is higher than that of non-reacting case. Thus, the overall drag coefficient maintained slightly smaller than 1.0, similarly to that of non-reacting flow.

Computed results of the drag coefficients are listed in Table 1 for each case. It is noted that the pressure drag dominates the overall drag, but the viscous friction drag is negligible while its dependency on the Reynolds number seems to be quite reasonable. The $d/\lambda$ initiation criterion suggested by Ju et al.\cite{4} and verified through experiment by Verreault and Higgins\cite{5} is also listed in Table 1, computed with the drag coefficients predicted by CFD.

$$\left( \frac{d}{\lambda} \right)_{\text{crit}} = \left( \frac{80}{\pi C_D^2} \right)^{1/2} \left( \frac{M_{\text{ CJ}}}{M_{\text{ proj}}} \right)$$ \hspace{1cm} (3)

The criterion works reasonably well with the visualization result. The case (b) of shock-induced combustion is below the criterion. The case (c) of unstable straw-hat detonation with a little bit smaller critical value agrees with the experimental computational observations that transition position is moving backward and finally restored to the shock-induced combustion. The case (d) is slightly above and the case (e) is much higher than the critical condition, which results in the direct initiation.

![Figure 1](image1.png)

Figure 1. The snap-shots of observed moving image with various mixture initial pressure [1]

![Figure 2](image2.png)

Figure 2 Temperature and pressure distributions overlaid with streamlines from CFD simulations for the experimental cases.
Choi, J.-Y.

Drag Coefficient of Sphere Initiating ODW

Figure 3 Pressure coefficients distributions

Table 1: Flow conditions and computed parameters[1]

<table>
<thead>
<tr>
<th>Case</th>
<th>Gas</th>
<th>$p_0$ (kPa)</th>
<th>$T_0$ (K)</th>
<th>$V_p$ (m/s)</th>
<th>$V_p/D_{CJ}$</th>
<th>$d_\lambda$</th>
<th>$Re_0$</th>
<th>$D_\lambda/D$ (%)</th>
<th>$C_D (d_\lambda)_{crit}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Ar</td>
<td>60.8</td>
<td>282.3</td>
<td>2,318</td>
<td></td>
<td>155,355</td>
<td>0.167</td>
<td>0.862</td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td>$2C_2H_2 + 5O_2 + 7$Ar</td>
<td>21.1</td>
<td>286.4</td>
<td>2,340</td>
<td>1.20</td>
<td>44,619</td>
<td>0.468</td>
<td>0.897</td>
<td>4.44</td>
</tr>
<tr>
<td>(c)</td>
<td>$2C_2H_2 + 5O_2 + 7$Ar</td>
<td>31.4</td>
<td>281.4</td>
<td>2,333</td>
<td>1.19</td>
<td>68,058</td>
<td>0.104</td>
<td>0.899</td>
<td>4.47</td>
</tr>
<tr>
<td>(d)</td>
<td>$2C_2H_2 + 5O_2 + 7$Ar</td>
<td>40.5</td>
<td>283.4</td>
<td>2,386</td>
<td>1.21</td>
<td>88,784</td>
<td>0.084</td>
<td>0.837</td>
<td>4.56</td>
</tr>
<tr>
<td>(e)</td>
<td>$2C_2H_2 + 5O_2 + 7$Ar</td>
<td>60.7</td>
<td>282.3</td>
<td>2,133</td>
<td>1.07</td>
<td>119,685</td>
<td>0.073</td>
<td>0.722</td>
<td>5.55</td>
</tr>
</tbody>
</table>

4 Conclusions

CFD simulation is carried out for hypersonic projectile initiating SIC or ODW based with multispecies reacting flow model and SST turbulence model. The experimental visualization results were reproduced quite well CFD and shows good agreements with observations. The drag coefficients predicted from the CFD seems to be in the reasonable range, and the detonation initiation criterion estimated with the drag coefficient classify the SIC/ODW regimes initiated by hypersonic spherical projectile in detonable media.

References