NUMERICAL INVESTIGATION OF SUPERSONIC COMBUSTION OF THE HYSHOT II IN THE SHOCK TUNNEL

Chih-Peng Chen¹, Dun C. Liu¹, Guan-Bang Chen² and Ruey-Hung Chen³

¹MRSRD, Chung-Shan Institute of Science and Technology, Taoyuan, 325, Taiwan, Republic of China
²Research Center of Energy Technology and Strategy
National Cheng-Kung University
³Department of Mechanical, Materials and Aerospace Engineering
University of Central Florida

I. INTRODUCTION

Recent interests in scramjet engine have attracted efforts from numerous researchers to the topic of supersonic combustion. The University of Queensland devised a ballistic re-entry vehicle called HyShot to achieve supersonic combustion conditions for a flight mach number of approximately $M = 8$. A double wedge intake and two back-to-back combustors constituted the HyShot engine. It was supplied with hydrogen fuel and air mixture at an equivalence ratio of 0.3 [1]. The aerodynamic test of the HyShot configuration was carried out in the High Enthalpy Shock Tunnel Göettingen, HEG, of the German Aerospace Center. Because of the complexity of the air-breathing engine, computational fluid dynamics was used to support the experimental design and the analysis of the experimental data of supersonic combustion [2-5].

Recent development of computer hardware has improved the effectiveness of computational fluid dynamics (CFD) tools in supersonic combusting flows. Karl et al. [5] have successfully simulated the intake flow field and revealed that the flow in this region was highly two-dimensional and the assumption of uniform inflow conditions in spanwise direction at the combustor entrance plane were justified. This allows the use of the existing symmetries in the combustor flow field to reduce the size of the computational domain to one eighth of the original span. The domain is then bounded by two symmetry planes, one at the center of an injector and the other between two injectors. They assumed a Probability-Density-Function (PDF) model to study the influence of turbulent fluctuations on the species source terms in detailed chemistry schemes.

Boyce et al. [6] employed the Baldwin-Lomax turbulence model and the 12-species 25-reaction hydrogen-air chemistry model in the HyShot II calculations. Their 2D intake studies indicated that at low angles of attack the configuration was well behaved, but at high angles of attack the cowl shock caused the boundary layer to separate from the main intake ramp. This resulted in a separation shock that extended into the combustion chamber. On the other hand, their 3D combustion chamber simulations consistently predicted that supersonic combustion had been obtained. At higher altitudes, reasonable agreement between the measured and predicted pressures was found, although the fuel-off pressures are under-predicted by approximately 15%. At lower altitudes (corresponding to the later stages of the flight experiment), the CFD results well under-predicted the flight data.

Won et al. [7] carried out numerical investigations of combustion characteristics of HyShot scramjet combustor, where gaseous hydrogen was transversely injected into a supersonic cross flow. The altitude, the angle of attack, and the equivalence ratio were specified as 35-23 km, $0^\circ$, and 0.426, respectively. The simulated $H_2$ and $OH$ mass fractions showed that the upstream recirculation region generated by the fuel injection had flame-holding effects. Their two-dimensional simulations predicted combustor inner pressure distribution that agreed well with experimental results and revealed periodic combustion characteristics of the HyShot scramjet combustor. Effects of altitude were also investigated and the strength of flow instability and subsonic boundary layer thickness
C.-P. Chen

Supersonic combustion of the hyshot

Affect the combustion efficiency according to altitudes. Frequency analyses revealed the effects of flow instability on the turbulent combustion in the HyShot scramjet combustor.

Kindler et al. [8] applied an assumed multivariate PDF together with finite-rate chemistry to the simulation of the HyShot supersonic combustion. The experiments of the HyShot supersonic combustion configuration performed at the High Enthalpy Shock Tunnel of DLR in Göttingen (HEG) were investigated numerically. Different reaction mechanisms for hydrogen combustion and the effect of the assumed PDF on the combustion process were investigated. It showed that fluctuations of temperature and species mass fractions had a great influence on the combustion process in the HyShot combustor. They were able to predict the ignition delay experimentally observed at the HEG shot 663.

Another study by Won et al. [9] simulated the complex unsteady flow field of a supersonic combustor environment with the DES turbulence approach. The main objective of their study was to gain further insight into the turbulent mixing and reacting flow physics in the HyShot-II scramjet combustor. The detail and global flow features were captured with the instantaneous flow visualization methods. The unsteady simulation with finite-rate chemistry provided the qualitative flow physics in a realistic scramjet combustor environment.

In a study by Ingenito et al. [10], a 3-D LES of the HyShot scramjet combustor was done by means of a hybrid numerical scheme, consisting of highly refined grids and a detailed kinetic scheme. The results suggested very efficient combustion: the flame anchored within the recirculation zone between the bow shock and the fuel injection and the bow shock was located about 10 mm from the H₂ orifices. The mixing was also found to be very fast, with contra-rotating vortices within the H₂ core flow enhancing the turbulent diffusion of H₂ while eddies between the separate fuel streams were responsible for the fast air/H₂ mixing. The flame structure was shown to be driven by large scale eddies, suggesting a possible “flame in eddies” structure.

In summary, one of the primary issues about predicting performance of the scramjet combustor is to choose an appropriate turbulence model and chemical reaction mechanisms. An important follow-up issue is the closure problems for the interaction of turbulence and chemistry under supersonic conditions. This paper examines the effects of specifying different turbulence models and chemical reaction steps on the scramjet combustor flow fields. The commercial software, FLUENT, is employed to solve the supersonic reacting flow. Three turbulence models are considered to demonstrate their effects on simulating the HyShot-II problems. The effects of applying single-step reaction and multi-step reaction mechanisms are also examined.

II. SETUP

Two cases with different inlet conditions are considered. Their geometries and dimensions are the same as those of the HyShot II shown in Figure 1. Only one eighth of the full domain is modeled due to the geometrical symmetry. The height and width of the full domain are 9.8 mm and 75 mm respectively. The overall length in flow direction of the computational domain is 410 mm, and an expanding nozzle begins at x = 300 mm. The hydrogen fuel is injected through four circular ports each with 2 mm in diameter. The fuel ports are located at x = 58 mm downstream from the inlet of the combustor. A 3-D unstructured hexahedral grid system with 486,864 nodes is used to discretize this supersonic combustion flow field. The distribution of the grids is shown in the Figure 2. There are 828, 21 and 28 nodes in streamwise, spanwise and vertical directions, respectively, and the minimum grid size is 0.1mm.

The discretized governing equations were solved with a control volume formulation in accordance with the Roe-FDS algorithm. Symmetry boundary conditions were applied at the two spanwise planes. One was located at the center of a round injector and the other was the vertical center-plane of the combustor; they were the top and bottom boundaries of the hashed region in Figure 1, respectively. Two different chemical reaction mechanisms were adopted to model the supersonic combustion behaviors. One was the single-step reaction mechanism:

\[ \text{H}_2 + 0.5\text{O}_2 \rightarrow \text{H}_2\text{O}, \quad k_f = A e^{-E/RT}, \quad A = 9.87 \times 10^8 \text{ s}^{-1}, \quad E = 3.1 \times 10^7 \text{ J / kg - mole} \]

where A and E are the frequency factor and the activation energy, respectively. The other one was the H₂/O₂ chemical kinetic mechanism found in Ref. [11], consisting of 9 species and 19 reaction steps for the gaseous reaction. To demonstrate the effect of turbulence model on the flow behavior, the SA, the RKE, and the SST-κω turbulence models were chosen for comparison. No higher order turbulence-chemistry interaction was considered. Two cases were studied: one was related to the flight test, and the other the ground test. The inlet conditions are given in Tables 1 and 2. The corresponding fluid parameters are specified in Table 3.
III. RESULTS

Figure 3 shows the comparison of the pressure distribution between the ground test data and the computing results. For the convenience of comparison, the location of fuel injection is shifted to $x = 0$ in this plot. On account of the effects of supersonic combustion, both experimental and computing results show that the pressure at the bottom wall increases in the downstream direction in the combustor. For $x > 242$ mm, the pressure gradually decreases as the flow passes through the expanding nozzle. The computed pressure distributions using the three turbulence models show good agreement with measured data, while the laminar model under-predicts the pressure rise from $x = 0 – 242$ mm. The capture of the expansion process through combustion in the combustor section (the measured lower pressure in Fig. 3) is not successful. This is also observed in Ref. [5]. It is believed that inappropriate grid arrangement is responsible for this aspect. For the pressure distribution on the top wall, good agreement between the results of the SST model and the experiment is shown in Figure 4. The computed pressure on the inclined nozzle plane is not included owing to the difficulty of post-data sampling. In Figure 5, the average temperature distributions using the three turbulent models are shown. The temperature as a result of the combustion captured by the $k-\varepsilon$ model is higher than those by the SA and SST-$k\omega$ models. The laminar model is apparently incapable in supporting the simulation of this combustion process, as only minor temperature rise is predicted to take place for $x = 0 – 242$ mm. Figures 6 – 10 show the isopleths of three species mass fractions ($OH$, $H_2O$, $H_2$), temperature and Mach number at five $x$-locations in the combustor, i.e., 95 mm, 145 mm, 195 mm, 245 mm and 295 mm. They present the flow development and the flame propagation in the flow path. The vortices induced by the fuel injection and the chemical reactions in the boundary layer near the wall are not easily observable due to the insufficient grid density. However, the results show that the major features of supersonic reacting flow in the HyShot II combustor can be captured with good accuracy.

Figures 11 and 12 compare the pressure and averaged temperature distributions predicted using both the single-step and the 19-reaction step mechanisms, respectively; such comparison was performed using only the SST-$k\omega$ model. This single-step reaction mechanism predicts higher pressure and also higher averaged temperature distributions than the multi-step mechanism. The differences between the results using the two reaction mechanisms (shown in Figures 11 and 12) increase in the flow direction. The largest pressure difference is approximately $1/3$ of the combustor entrance pressure, while the maximum temperature difference is approximately $100^\circ C$.

IV. CONCLUSIONS

Flows with supersonic hydrogen combustion under realistic scramjet flight and ground test conditions were simulated and the following conclusions are summarized.

1. Turbulence model is important to the simulation of the scramjet flow fields. The calculations using the SST-$k\omega$ model well capture the pressure distributions of the supersonic hydrogen combustion fueled by transverse jets in the present cases. The simulations conclude that the credit for the SST-$k\omega$ model goes to its robust capability in processing the flow and chemistry interaction.

2. The difference due to the different turbulence models appears to be amplified by increasing the equivalence ratio. Furthermore, it shows more complete heat release and less fuel survival in the simulation obtained using the RKE model.

3. With low density of grids, the chemical reactions within the boundary layer and the vortices induced by the fuel injection cannot be properly simulated even though the wall-function is implemented.

4. Significant difference in temperature ($100$ degree in Fig. 12) and in pressure ($1/3$ of inlet pressure in Fig. 11) is observed between the results modeled by the single-step reaction and the multi-step reaction mechanisms in this study. Increasing the equivalence ratio does not generate significant difference as well.

References


**Tables**

### Table 1. Flow conditions of the combustor for case A [5].

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach Number</td>
<td>2.4</td>
</tr>
<tr>
<td>Pressure</td>
<td>130 kPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>1300 K</td>
</tr>
<tr>
<td>Velocity</td>
<td>1720 m/s</td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>0.29</td>
</tr>
</tbody>
</table>

### Table 2. Flow conditions of the combustor for case B [1].

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach Number</td>
<td>2.6535</td>
</tr>
<tr>
<td>Pressure</td>
<td>119.11 kPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>1311.6 K</td>
</tr>
<tr>
<td>Velocity</td>
<td>1910.5 m/s</td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>0.377</td>
</tr>
</tbody>
</table>

### Table 3. Fluid parameters of conditions for case A and B.

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th>Case B (1/8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density – Air</td>
<td>0.348 kg/m³</td>
<td>0.316 kg/m³</td>
</tr>
<tr>
<td>Density – H₂</td>
<td>0.369 kg/m³</td>
<td>0.486 kg/m³</td>
</tr>
<tr>
<td>Total Pressure – Air</td>
<td>1,923,327 Pa</td>
<td>130,000 Pa</td>
</tr>
<tr>
<td>Static Pressure – Air</td>
<td>119,110 Pa</td>
<td>601,325 Pa</td>
</tr>
<tr>
<td>Mass Flow Rate – Air</td>
<td>0.0541375 kg/s</td>
<td></td>
</tr>
<tr>
<td>Total Pressure – H₂</td>
<td>460,000 Pa</td>
<td></td>
</tr>
<tr>
<td>Static Pressure – H₂</td>
<td>456,780 Pa</td>
<td></td>
</tr>
<tr>
<td>Mass Flow Rate – H₂</td>
<td>0.00059468 kg/s</td>
<td></td>
</tr>
<tr>
<td>Viscosity – Air</td>
<td>4.845×10⁻⁵ kg/m-s</td>
<td>4.870×10⁻⁵ kg/m-s</td>
</tr>
<tr>
<td>Viscosity – H₂</td>
<td>1.846×10⁻⁵ kg/m-s</td>
<td>1.846×10⁻⁵ kg/m-s</td>
</tr>
</tbody>
</table>
Figures

Figure 1. Geometry and dimensions of the computational domain.

Figure 2. The grid distribution of the computational domain.

Figure 3. Pressure distribution on the bottom wall of the symmetry plane between the fuel injectors.

Figure 4. Pressure distribution on the top wall of the symmetry plane between the fuel injectors.

Figure 5. Average temperature distribution of the combustor and nozzle.

Figure 6. Isopleth of OH mass fraction.

Figure 7. Isopleth of H_{2}O mass fraction.
Figure 8. Isopleth of H$_2$ mass fraction.

Figure 9. Isopleth of temperature.

Figure 10. Isopleth of Mach number.

Figure 12. Average temperature distribution of the combustor and nozzle.

Figure 11. Pressure distribution on the bottom wall of the symmetry plane between the fuel injectors.