CFD Analysis of Scramjet Engine Combustion Chamber with Diamond-Shaped Strut Injector at Flight Mach 4.5

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Abstract. The present work address the CFD analysis for scramjet combustor with diamond-shaped strut injectors at supersonic Mach 4.5 and it’s based on species transport combustor which is standard k-epsilon turbulence model. It is implied for supersonic combustion that the ramjet engine is focused for operating high speed engines. The combustion chamber assists as an envelope to clutch the propellant for a satisfactory period to certify complete mixing as well as combustion. The diamond-shaped strut injector gives the maximum temperature and pressure of 3517 K and 1.487 MPa respectively whereas the combustion efficiency is found to be 87.2%. The shear layers losses are extremely minimize the performance of the engine, thus interpreting trade-off programmes in a very difficult way to achieve maximum combustion efficiency. Further firmness by machines is essential for achieving higher combustion efficiency.

Keywords: CFD, combustion chamber, combustion efficiency, flight Mach

1. Introduction

1.1. Scramjet engines

The scramjet is a generous of jet engine anticipated to operate in the high rate regime typically associated by rockets. The scramjet engine has designed is a postponement of ramjet engine. The difference between the scramjet and ramjet lies in flow of state inside the engine. The figure below presents the basic design of scramjet engine. This engine works by injecting the hydrogen into the supersonic flow of air. The scramjet engine structure is presented in figure 1 [1].

![Scramjet engine](image)

Source: Engineering Department, ANU

Figure 1. Scramjet engine

1.2. Fuel injectors for scramjet engine

Fuel injection technique in scramjet engines is a field which is developing today. The fuel used in scramjets is either a gas or a liquid. For efficient combustion stoichiometric proportions of air and fuel are plays an important role. Here the issue is the airflow is very fast and there is negligible time for the
fuel to mix with air and ignite for producing thrust. H₂ is the main fuel for combustion. Hydrocarbons are additional of a task compared to H₂ due to the more ignition delay and the requirement for more unconventional mixing techniques. By improving the mixing, minimising the combustor distance is an significant feature in scheming scramjet engines.

1.2.1. Parallel and normal injection

The figure 2 shows the parallel fuel injector structure which in which air and fuel inject in a parallel way but divided by divider plate. At the exit portion of the splitter plate the shear layer is produced because of dissimilarities of velocities of air/fuel.

![Parallel fuel injector](source)

*Figure 2. Parallel fuel injector*

Normal fuel injector contains an injection port on scramjet wall which injects fuel in a common procedure in the flow of air. This kind of system produces barrel shock and mixing shock which results the separation zone at downstream and upstream of injector system which is presented in below figure. These separation regions are responsible for the increased in pressure losses and it affects the engine efficiency.

![Normal fuel injector](source)

*Figure 3. Normal fuel injector*

2. Objectives

- To identify the important parameters to optimize the injection system for supersonic flow field.
- To characterize the combustion behaviour in terms of identifying important parameter like temperature, pressure, Mach number, density etc.
- To determine the mass fraction of H₂O, H₂ and combustion efficiency
3. Historical background

The numerical investigation of reacting and non-reacting flow field of H\textsubscript{2} fueled scramjet combustor are done in their [2] study. Hydrogen and air mixture is injected in parallel way from the strut injector at Mach 2 with vitiated air streams to the scramjet combustion chamber which is discovered numerically. Baurle [3] provided a comprehensive summary of several CFD methods for the demonstration of supersonic flows. The necessity for steady state RANS in solving the compressible reacting flow for high speed commercial and military application. The superiority of higher order Reynolds stress tensor model over linear models are used for predicting the mixing and combustion efficiency. Povinelli [4] carried out the research on the struts and its properties of the geometrical factors for the combustion chamber. Tomioka et al. [5,6] found that at higher flow rates the intensive combustion within the constant area combustor is acquired. The pressure rise enhances with the auxiliary fuel injection from the strut injector which increase the fuel/air mixing quality. The incoming flow is divided into 2 parts. The pressure on diamond surface of the strut is assessed with a statement that the static pressure rise on the side wall is since the incident and reflected shocks with the same strength.

Rabadan and Weigand [7] stated that with the increase of equivalence ratio combustion process will be much stronger, which results the movement of shock train produces with various pressure variations after numerical investigation. Aleksandrov et al [8] focused on technology development for hypersonic engines and it is evident from the work that the small diffusion at the supersonic flow of air and it results combustion. There is a capability for the boundary cooling of the scramjet combustor by air.

4. Methodology

4.1. Physical model

The figure 4 represents the physical model of scramjet engine with diamond shaped strut injector which is address by Deepu et al. [9]. The total length and depth of the combustor are 290 mm and 36 mm respectively, length and depth of the fuel injector are 7 mm and 6 mm respectively and the fuel inlet gap is of 0.3 mm.

![Figure 4. Physical model of diamond-shaped strut injector [9]](image-url)
4.2 Grid independence test

![Figure 5. Grid independence test](image)

From the figure 5 it is observed that better agreement is found between 101876, 125746 and 181974 numbers of nodes. Therefore present analysis is carried out with the grid size of 125746 nodes.

4.3 Validation of the model

![Figure 6. Experimental shadowgraph image (upper) and contours plot of density of present work (lower)](image)

The present computational model is validated computational shadowgraph image and it’s almost agreed with experimental shadowgraph image; the computational result (lower) and experimental shadowgraph result (upper) for the cases of contours plot of density is shown in the figure 6 [9].

4.4 Governing equations

The governing equations used for the present analysis is mentioned below [10]:

4.4.1. Continuity equation

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  

(1)

4.4.2. Momentum equation in X direction

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho uu)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}
\]  

(2)

4.4.3. Momentum equation in Y direction

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho vu)}{\partial x} + \frac{\partial (\rho vv)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}
\]  

(3)

4.4.4. Momentum equation in Z direction

\[
\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho ww)}{\partial z} = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}
\]  

(4)
4.4.5. Energy equation

\[
\frac{\partial (\rho E)}{\partial t} + \frac{\partial (\rho u E)}{\partial x} + \frac{\partial (\rho v E)}{\partial y} + \frac{\partial (\rho w E)}{\partial z} + \frac{\partial (u \tau_{zx} + v \tau_{zy} + w \tau_{zz})}{\partial z} = \frac{\partial (K \frac{\partial T}{\partial x})}{\partial x} + \frac{\partial (K \frac{\partial T}{\partial y})}{\partial y} + \frac{\partial (K \frac{\partial T}{\partial z})}{\partial z}
\]  

(5)

The equations from 1 to 5 are stands for compressible flows whereas the below 3 equations are using as a supplementary equations for the above mentioned equations.

First, for the perfect gas

\[ P = \rho RT \]

Second, assuming that air is calorically perfect.

\[ e = C_v T \]

where \( C_v \) is the specific heat at constant volume.

Third, if the Prandtl number is considered as constant:

\[ k = \frac{\mu C_p}{Pr} \]

Equations used with Sutherland’s law are mentioned below:

\[ \mu = \mu_0 \left( \frac{T}{T_0} \right)^{1.5} \frac{T_0 + 120}{T + 120} \]  

(6)

4.4.6. Generalized form of turbulence equation

\[
\left( \frac{\partial k}{\partial t} \right) + \frac{\partial (uk)}{\partial x} + \frac{\partial (vk)}{\partial y} + \frac{\partial (wk)}{\partial z} = \left[ \frac{\partial \nu_T}{\partial x} \right] \frac{\partial k}{\partial x} + \left[ \frac{\partial \nu_T}{\partial y} \right] \frac{\partial k}{\partial y} + \left[ \frac{\partial \nu_T}{\partial z} \right] \frac{\partial k}{\partial z} + \left( S_k - P - D \right) \]  

(7)

\[
\left( \frac{\partial \epsilon}{\partial t} \right) + \frac{\partial (ue)}{\partial x} + \frac{\partial (ve)}{\partial y} + \frac{\partial (we)}{\partial z} = \left[ \frac{\partial \nu_T}{\partial x} \right] \frac{\partial \epsilon}{\partial x} + \left[ \frac{\partial \nu_T}{\partial y} \right] \frac{\partial \epsilon}{\partial y} + \left[ \frac{\partial \nu_T}{\partial z} \right] \frac{\partial \epsilon}{\partial z} + \left( S_\epsilon - \frac{\epsilon}{k} \left( C_{\epsilon 1} P - C_{\epsilon 2} D \right) \right) \]  

(8)

where \( P = 2\nu_T \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \) \( + \nu_T \left[ \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 \right] \) and \( D = \epsilon \)

5. Results and discussion

The CFD analysis for optimizing the supersonic combustion behaviour for supersonic combustor scramjet is discussed below:

5.1. Static temperature

\[ \text{Figure 7. Contours of static temperature (K) of diamond-shaped strut injector} \]

The figure 7. shows the resulting flow of diamond-shaped strut injector. At the boundary wall of the
combustor chamber shockwaves are reflected-off at the lower and upper portion of the combustor walls which strikes the wake where large quantity of fuel jet is mixed with supersonic air. The maximum temperature reached in case of diamond-shaped injector is 3516.23K which is appreciably a very high temperature for the combustion.

5.2. Static pressure

![Contours of static pressure (Pa) of diamond-shaped strut injector](image1)

**Figure 8.** Contours of static pressure (Pa) of diamond-shaped strut injector

![Static pressure vs. position of diamond-shaped strut injector](image2)

**Figure 9.** Static pressure vs. position of diamond-shaped strut injector

The contours of static pressure of diamond-shaped injector is presented in figure 8. It is evident from the fig.8 that just after the injection of hydrogen static pressure increases rapidly. During the combustion process the pressure in not increasing at very high rate as there is low equivalence ratio. At the boundary wall of the combustor the static pressure generation is very high compared to other regions because the air/fuel mixture is reflected back from the chamber walls. The amximum pressure of 1.487 Mpa is produced at the combustion chamber which is shown in figure 8. Figure 9 represents static pressure distribution at the the inner, lower and upper side wall of the combusto chamber.

5.3. Mach number
The contour of Mach number distribution is shown in figure 10. It is observed that there is increase of Mach number followed by diamond shaped injector. The Mach number of 4.54 is witnessed in this strut injector. The subsonic region has found at position of compression shock which influences the upper edge of the combustor wall. As H₂ is injected to the chamber there is a decrease of the Mach number and it is increases where the wakes are formed. The figure 11 presents the profile between the Mach number distribution at the inner wall, lower and upper side of the combustor walls.

5.4. Density Contours

Figure 10. Contours of Mach number of diamond-shaped strut injector

Figure 11. Mach number vs. position of diamond-shaped strut injector

Figure 12. Density contours (kg/m³) of diamond-shaped strut injector
The contours of density for the diamond-shaped injector at the supersonic Mach number is presented in figure 12. The contours of density circulation at the combustor address the as H₂ is injected density increases suddenly and decreases gradually when it starts mixing with supersonic air. The maximum density of 2.3 kg/m³ is attained at the combustion chamber and the figure 13 shows that the density distribution at the inner, lower and upper of the combustor walls.

5.5. Mass fraction of H₂O

The contours of H₂O mass fraction for diamond-shaped strut injector is shown in figure 14, and it is observed that water concentration is more at the shear layer of the combustion chamber. The mass fraction of H₂O for at pressure outlet is shown in figure 15. The maximum mass fraction of H₂O is of almost 0.051 which is observed at the middle of the combustion chamber throughout the Y-Y direction.
and at the other regions this mass fraction is found to be very low.

5.6. Mass fraction of $H_2$

![Figure 16. Mass fraction of $H_2$ for diamond-shaped strut injector](image)

The contour of mass fraction of $H_2$ for the present strut injector is presented in figure 16. The lip height of the fuel injector plays a vital role for the improvement of mixing quality and the maximum $H_2$ of 0.92 is detected from the contours of mass fraction of $H_2$.

5.7. Combustion efficiency

![Figure 17. Combustion efficiency of diamond-shaped strut injector](image)

Combustion efficiency is the useful parameter for identifying the performance of the scramjet combustor. Combustion efficiency ($\eta_{\text{Comb}}$) signifies the quantity of $H_2$ burned at a specified cross section, $A_x$ with respect to the total amount of injected $H_2$ which is given by Gerlinger [11] and it’s shown below:

$$\eta_{\text{Comb}} = 1 - \frac{\int A(x) \rho_{\text{gas}} u Y_{H_2} \, dA}{m_{H_2,\text{inj}}}$$

where $\rho$ and $Y_{H_2}$ are gas density and $H_2$ mass fraction respectively. $m_{H_2,\text{inj}}$ represents the injected mass flux of $H_2$ and $u$ represents the velocity component which is normal to the cross section. The figure 17 represents the combustion efficiency where the plot starts right after the trailing edge of the strut injector ($x = 290\,\text{mm}$). The maximum combustion efficiency is found to be 87.24% for the stoichiometric value ($\varphi$) of 1.

6. Conclusion
The less ignition interval time of air/fuel mixtures favours efficient and rapid combustion, leading to growth in the combustion efficiency. The combustion phenomenon and shock structure are not only affected by the geometry but also affected by flight Mach and combustor trajectory. As the mixing time of fuel/air is about millisecond, better injection systems have to be developed which progresses the mixing quality of fuel/air. The localized recirculation zones with high residence time are formed in combustors owed to the shock wave and therefore the combustion phenomenon is improved. The major attention is to be dedicated to the limited intensity of heat issue which together with the duct geometry, governs techniques for the flame commencement and equilibrium, fuel injection procedures, air supplied quantity and fuel/air mixing and gas dynamic stream regime. The required combustion residence time is a function of many parameters. The theoretical required combustion chamber volume is a function of the mass flow rate of the propellants, the average density of the combustion products and the residence time required for efficient combustion. The shock waves have great influences on increasing the pressure and temperature, which results in increasing the combustion rate of the fuel/air mixture and thus increases combustion efficiency, but problems happen due to reactants involvement, flame constancy and accomplishment of proper combustion throughout the entire combustor.

Nomenclature

- $H_2$: Hydrogen
- $k$: Turbulence kinetic energy
- LES: Large eddy simulations
- $M$: Mach number
- $\eta_{\text{Comb}}$: Combustion efficiency
- $\rho$: Density
- $\varepsilon$: Turbulence dissipation rate
- $\rho$: Density
- $\mu$: Viscosity
- $\mu_0$ and $T_0$: Reference values at standard sea level conditions

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