CFD Analysis of Scramjet Engine Combustion Chamber with Alternating Wedge-Shaped Strut Injector at Flight Mach 6.5

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Abstract. This paper presents the CFD analysis for hydrogen fueled scramjet engine using alternating wedge-shaped strut injectors at flight Mach 6.5. The fuel used by alternating wedge-shaped strut injectors is hydrogen and this present work is constructed on the species transport combustion and k-epsilon turbulence model which is governed by both mixing and chemical kinetics. This turbulence model is most common in CFD for simulation of mean flow characteristics for turbulent flow conditions. This CFD analysis of scramjet engine combustion chamber is basically focused on for optimizing various flow fields of flue gases and the combustion efficiency. There is increase in temperature and pressure at the boundary walls of the combustor. The shock waves have great influences on increasing the pressure and temperature which results in increasing at the combustion rate as well as it increases the combustion efficiency. From the analysis it’s investigated that alternating wedge-shaped strut injector provides the maximum temperature and pressure of 3825K and 1650784Pa respectively.

Keywords: CFD, efficiency, flight Mach, scramjet engine

1. Introduction

1.1. Scramjet engines

The scramjet is a generous of jet engine anticipated to operate in the high speed 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. This engine works by injecting the hydrogen into the supersonic air flow.

1.2. Fuel injectors for scramjet engine

Fuel injection techniques for scramjet engines are developing today. The fuel used in scramjets is either a gas or a liquid. For efficient combustion stoichiometric proportions of air and fuel are play 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, normal and transverse injection

The figure 1 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.
Normal fuel injector comprises an injection port on the combustor 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 2. These separation regions are responsible for the increased in pressure losses and it affects the engine efficiency [1].

2. Literature Review

Tomioka et al. [2,3] 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. Aleksandrov et al. [4] worked on hypersonic engine and it is observed that there is a capability for the boundary cooling of the scramjet combustor by air form improving the engine efficiency. Rabadan and Weigand [5] stated that with the increase of equivalence ratio combustion process will be more stronger, which results the movement of shock train produces with various pressure variations after numerical investigation. Baurle [6] addressed a comprehensive summary of several CFD techniques 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 advanced order Reynolds stress tensor model over linear models are used for predicting the mixing and combustion efficiency. Pan et al. [7] investigated that the air is injected at the temperature of 340K and a pressure of 0.1 Mpa whereas the hydrogen is injected at ambient temperature and pressure of 250K and 0.1 Mpa respectively. The accuracy of the CFD results for scramjet combustor is significantly depends on the fineness of a grid. The computational domain is said to enter into the regime of the grid independence and hence, this limit is called the ‘Grid Independent Limit (GIL)’. The combustion flame is more stabilized in case of cavities in tandem than cavities in parallel while combustion process is better in cavities in parallel at the inflow conditions of flight Mach .64 and 1.84MPa of pressure.
3. Material and methods

3.1. Physical model

The figure 3 presents the physical model of the DLR based scramjet engine which is investigated by Oevermann [8]. The total length of the combustor is 340 mm in stream wise direction and the backward spacing arrow shows the fuel injector for alternating wedge-shaped strut structure. The upper wall of the combustor is $3^\circ$ of inclination just after the 100 mm from the leading edge which are shown in figure 3 and figure 4.

![Physical model of alternating wedge-shaped strut injector](image)

**Figure 3.** Physical model of alternating wedge-shaped strut injector

![Isometric view of alternating wedge-shaped strut injector](image)

**(a)**

![Side view of the injector](image)

**(b)**

**Figure 4.** (a) Alternating wedge-shaped strut injector, (b) Isometric view of alternating wedge-shaped strut injector and (c) Side view of the injector
3.2. Grid Independence Study

The figure 5 show the specification and justifications of the grid and grid independence study for the present strut injector and from the table 1 and figure 5 it is observed that better agreement is found between 118795, 152879 and 198227 no of nodes. Therefore the present analysis is done with a grid size of 152879 nodes whereas the figure 6 shows the grid refinement for alternating wedge-shaped strut injector.

![Grid independence study](image1)

**Figure 5.** Grid independence study

The changes of cell face and node are 743033, 11174319 and 369115 respectively which are shown in below in details;

| Grid size (Original / Adapted / Change) |
|----------------------------------------|
| Cells (84631 / 858934 / 774303)         |
| Faces (271384 / 11445703 / 11174319)    |
| Nodes (152879 / 998234 / 369115)        |

3.3. Validation of the model

The present supersonic combustor model is validated by comparing contours of density image with the shadowgraph image from the experiment which is shown in figure 7. From the figure 7 it is evident that the contours of density image and the shadowgraph image from the experiment are agreed very well.
3.4. Governing equations

The different governing equations used for the present analysis is mentioned below [9]:

3.4.1. 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)

3.4.2. Momentum equation in X direction

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho uu)}{\partial x} + \frac{\partial (\rho vu)}{\partial y} + \frac{\partial (\rho wu)}{\partial z} = \frac{\partial \sigma_{ux}}{\partial x} + \frac{\partial \sigma_{uy}}{\partial y} + \frac{\partial \sigma_{uz}}{\partial z}
\]  

(2)

3.4.3. Momentum equation in Y direction

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho vv)}{\partial y} + \frac{\partial (\rho wv)}{\partial z} = \frac{\partial \sigma_{vx}}{\partial x} + \frac{\partial \sigma_{vy}}{\partial y} + \frac{\partial \sigma_{vz}}{\partial z}
\]  

(3)

3.4.4. Momentum equation in Z direction

\[
\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho ww)}{\partial z} = \frac{\partial \sigma_{wx}}{\partial x} + \frac{\partial \sigma_{wy}}{\partial y} + \frac{\partial \sigma_{wz}}{\partial z}
\]  

(4)

3.4.5. Energy equation

\[
\frac{\partial (\rho E)}{\partial t} + \frac{\partial (\rho u E)}{\partial x} + \frac{\partial (\rho v E)}{\partial y} + \frac{\partial (\rho w E)}{\partial z} = \frac{\partial \sigma_{ex}}{\partial x} + \frac{\partial \sigma_{ey}}{\partial y} + \frac{\partial \sigma_{ez}}{\partial z} + \frac{\partial (\rho (K_{ex})/\partial x)}{\partial x} + \frac{\partial (K_{ey})/\partial y}{\partial y} + \frac{\partial (K_{ez})/\partial z}{\partial z}
\]  

(5)

\[E = e + \frac{1}{2} (u^2 + v^2 + w^2)
\]  

(6)

The equations from 1 to 6 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

\[P = \rho RT
\]  

(7)

Second, assuming that air is calorically perfect.

\[e = C_v T
\]  

(8)

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

Third, if the Prandtl number is considered as constant:

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

(9)

Equations used with Sutherland’s law are mentioned below:
\[\mu = \mu_0 \left(\frac{T}{T_0}\right)^{1.5} \frac{T_0+120}{T+120}\]  

(10)

3.4.6. Generalized form of turbulence equation

\[
(k)\frac{\partial k}{\partial t} + \frac{\partial (uk)}{\partial x} + \frac{\partial (vk)}{\partial y} + \frac{\partial (wk)}{\partial z} = \frac{\partial (\frac{\nu_T}{\sigma_k} \frac{\partial k}{\partial x})}{\partial x} + \frac{\partial (\frac{\nu_T}{\sigma_k} \frac{\partial k}{\partial y})}{\partial y} + \frac{\partial (\frac{\nu_T}{\sigma_k} \frac{\partial k}{\partial z})}{\partial z} + (S_k = P - D) \tag{11}
\]

\[
(\epsilon)\frac{\partial \epsilon}{\partial t} + \frac{\partial (\epsilon u_k)}{\partial x} + \frac{\partial (\epsilon v_k)}{\partial y} + \frac{\partial (\epsilon w_k)}{\partial z} = \frac{\partial (\frac{\nu_T}{\sigma_k} \frac{\partial \epsilon}{\partial x})}{\partial x} + \frac{\partial (\frac{\nu_T}{\sigma_k} \frac{\partial \epsilon}{\partial y})}{\partial y} + \frac{\partial (\frac{\nu_T}{\sigma_k} \frac{\partial \epsilon}{\partial z})}{\partial z} + (S_\epsilon = \frac{\epsilon}{\kappa} (C_{\epsilon 1} P - C_{\epsilon 2} D)) \tag{12}
\]

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

4. Results and discussion

The CFD analysis of scramjet engine combustion chamber using alternating wedge-shaped strut injector are discussed below:

4.1. Static pressure

![Figure 8. Contours of static pressure in Pa](image)

![Figure 9. Static pressure vs. position](image)

The figure 8 represents the contours of static pressure for the alternating wedge-shaped strut injector and from this contour plot it is evident that the maximum pressure of 165.078 KPa is attained. The figure 9 represents the static pressure distribution at lower and upper walls of the entire combustor and it is visualized from this figure that maximum static pressure attained at the lower wall is followed by the upper wall.
4.2. Static temperature

![Contour of static temperature in K](image1)

**Figure 10.** Contours of static temperature in K

![Static temperature vs. position](image2)

**Figure 11.** Static temperature vs. position

Figure 10 represents the contours of static temperature of alternating wedge-shaped injector. The temperature increases drastically at the central zone of the chamber. The maximum temperature of 3825K is attained to be at recirculation areas of the supersonic combustion chamber which is evident from this figure 10 whereas the figure 11 represents the static temperature distribution at the lower and the upper wall.

4.3. Contours Mach number

![Contours of Mach number](image3)

**Figure 12.** Contours of Mach number
The contours of Mach number distribution for the present combustor chamber shown in figure 12. At the combustor chamber with alternating wedge-shaped injector the highest Mach number is found to be 6.53 which is observed from the figure 12. The time taken for the mixing of fuel with air get delayed with the increase in Mach number of air. The figure 13 represents the variation of Mach number with respect to lower wall and the upper wall for alternating wedge-shaped strut injector.

4.4. Density Contours

The contours of density for the present injector is represented in figure 14 and from this figure it is investigated that due to combustion the shock structures getting weaker at the downstream of the combustion chamber. The shockwaves are greatly reflected by lower and upper walls of the combustion chamber. The maximum density of around 1.014 kg/m$^3$ is attained in the alternating wedge-shaped strut injector.

4.5. Contours of H$_2$ mass fraction

Figure 13. Mach number vs. position

Figure 14. Density Contours

Figure 15. H$_2$ mass fraction
The figure 15 represent the H\(_2\) mass fraction for the present strut injector. The maximum mass fraction of H\(_2\) is attained at the gradient of the fuel inlet of the present strut injector and then mass fraction of H\(_2\) starts decreasing along the axis. As this kind of strut injector H\(_2\) burns properly, there is smaller amount of flue gas emissions.

4.6. Combustion efficiency

Combustion efficiency is the useful parameter for identifying the performance of the scramjet engine. Combustion efficiency (\(\eta_{\text{Comb}}\)) implies 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 [10] and it’s shown below:

\[
\eta_{\text{Comb}}(x) = 1 - \frac{\int A(x) \rho \text{gas} u Y_{\text{H}_2} \, dA}{m_{\text{H}_2,\text{inj}}} \tag{13}
\]

where \(\rho\) and \(Y_{\text{H}_2}\) are gas density and H\(_2\) mass fraction respectively. The term \(m_{\text{H}_2,\text{inj}}\) represents the mass flux injected H\(_2\) and \(u\) represents the velocity component which is normal to the cross section.

The figure 16 represents the combustion efficiency where the plot starts right after the trailing edge of the present strut injector (x = 340 mm). The maximum combustion efficiency is found to be 91.1% for the stoichiometric value (\(\phi\)) of 1.

5. Conclusion

The very little ignition delay time of fuel and air mixture favors the efficient and profligate combustion; therefore there is progress of combustion efficiency. Since the time taken for the mixing of fuel and air very less, about millisecond so better injection technique has to be develop which must improve the mixing quality of fuel and air. Higher incoming Mach number and equivalence ratio prevent the appropriate mixing of fuel and air. The durable vorticity formed by the present wedge-shaped injector and it is liable for the mixing of fuel and air. The local recirculation zones with high residence time are formed in the combustors due to these shock waves and accordingly the combustion process is improved.

Nomenclature

| Symbol | Description                  |
|--------|------------------------------|
| C      | Specific heat at constant volume |
| CFD    | Computational fluid dynamics |
| H\(_2\) | Hydrogen                     |
| GIL    | Grid independent limit       |
| k      | Turbulence kinetic energy    |
| LES    | Large eddy simulations       |
| \(\eta_{\text{Comb}}\) | Combustion efficiency  |
φ        Stoichiometric condition
ρ        Density
ε        Turbulence dissipation rate
ρ        Density
µ        Viscosity
µ₀ and T₀ Reference values at standard sea level conditions

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