Mixing and Combustion Analysis of a Hydrogen Fueled Scramjet Engine Using Strut with Alternating Wedge Injector

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Abstract—A major problem in supersonic combustion is the short residence time of the fluid inside the combustor due to high flow velocities. Thus techniques for mixing enhancement have to be used to achieve a fast and efficient fuel-air mixing. In this paper, strut with alternating wedge injector is investigated numerically. The combustor and strut dimensions are same as DLR Scramjet model. It consists of a divergent channel with a flame – holding, wedge shaped structure in the middle of the flow field from the base of which hydrogen is injected. Mixing and combustion calculations are performed at Mach 2 for air and Mach 1 for Fuel (hydrogen). The simulation has been carried out by using FLUENT. Standard k-ε model has been used for modelling turbulence and single step finite rate chemistry has been used for modelling the H2-Air kinetics. k-ε model is based on a finite volume discretization of the continuity, momentum, energy equations. Numerically predicted profiles of static pressure, axial velocity, turbulent kinetic energy and static temperature for both non-reacting as well as reacting flows are compared. Validation is done by comparing numerically predicted profiles with experimental profiles. The results shows that alternating wedge injector is affecting the flow field of combustor considerably, due to this length required for the combustion chamber is reduced and also mixing efficiency and combustion efficiency of the injector calculated.

Key words: Alternating wedge injector; Scramjet; Mixing efficiency; Combustion efficiency

I. INTRODUCTION

A. Scramjet Engines

The name scramjet is an acronym for Supersonic Combustion Ramjet. A scramjet engine, is a type of jet engine intended to operate in the high velocity regime usually associated with rockets. The Scramjet engine design is an extension of the Ramjet. The difference between the two lies in flow state inside the engine. Both are designed to be used for supersonic flight; however a Scramjet allows the flow through the engine to remain supersonic, whereas in a Ramjet the flow is slowed to subsonic levels before it enters the combustor. Figure 1 shows a basic generic Scramjet design. At the most fundamental level it works by injecting fuel (typically hydrogen) into a flow of supersonic air. The air is at sufficiently high temperature and pressure for the fuel to combust, and the resulting mixture is expelled from the engine at a higher pressure. The Scramjet is composed of four main sections: the inlet, isolator, combustor and exhaust nozzle.

The inlet heats and slows the flow through a series of oblique shockwaves. This “ram” portion of the cycle means the engine cannot be operated statically. The isolator serves to separate the combustor from the inlet of the engine, allowing further slowing of the flow. Combustion is achieved through the continuous injection of fuel (usually hydrogen) into the supersonic flow. The fuel mixes and combusts, increasing the pressure and temperature of the flow. Finally the flow is expanded via the nozzle. This serves two purposes: to allow the flow to accelerate to the external speed, and to provide a mechanism by which the increase in pressure can be converted into forward thrust.

B. Fuel Injectors for Scramjet Engines

Fuel injection techniques into scramjet engines are a field that is still developing today. The fuel that is used by scramjets is usually either a liquid or a gas. The fuel and air need to be mixed to approximately stoichiometric proportions for efficient combustion to take place. The main problem of scramjet fuel injection is that the airflow is quite fast, meaning that there is minimal time for the fuel to mix with the air and ignite to produce thrust (essentially milliseconds). Hydrogen is the main fuel used for combustion. Hydrocarbons present more of a challenge compared to hydrogen due to the longer ignition delay and the requirement for more advanced mixing techniques. Enhancing the mixing, and thus reducing the combustor length, is an important aspect in designing scramjet engines. The fuel injector distribution in the engine also should result in as uniform a combustor profile as possible entering the nozzle so as to produce an efficient nozzle expansion process. There are mainly two concepts for fuel injection in supersonic combustors:

Wall injectors, where hydrogen is injected through the wall (normal or oblique to the main flow) or by ramps mounted to the wall.

Strut injectors, which are located at the channel axis and directly, inject the fuel into the core of the air stream. The advantages of strut injectors are the absence of strong shock waves due to a blockage caused by the fuel jet. Figure 2 shows the geometry of the strut with circular injector.

Fig. 1: Generic Scramjet engine [9]

Fig. 2: Strut with circular injector [4]
Modifying the trailing edge of strut is one of the active field of research, alternating wedge injector is one of the modified version of strut with circular injector Figure 3 shows the geometry of the Alternating Wedge strut, this type of injector will create either co-rotating or counter-rotating vortices that are used to enhance the mixing. All of the strut designs use the parallel fuel injection at the trailing edge of the injector, so that the fuel is entrained into the vortices which cause the increased mixing in the combustion section.

![Image](https://via.placeholder.com/150)

Fig. 3: Alternating Wedge strut [4]

Mixing, Ignition and flame holding in a scramjet combustor

The flow field within the combustor of scramjet engine is very complex and poses a considerable challenge in design and development of a supersonic combustor with an optimized geometry. Such combustor shall promote sufficient mixing of the fuel and air so that the desired chemical reaction and thus heat release can occur within the residence time of the fuel-air mixture. In order to accomplish this task, it requires a clear understanding of fuel injection processes and thorough knowledge of the processes governing supersonic mixing and combustion as well as the factors, which affects the losses within the combustor. The designer shall keep in mind the following goals namely,

- Good and rapid fuel air mixing
- Minimization of total pressure loss
- High combustion efficiency.

II. LITERATURE REVIEW

The performance of the scramjet engine is mainly dependent upon the fuel injection system. The complex phenomenon of supersonic combustion involves turbulent mixing, shock interaction and heat release in supersonic flow. In order to analyze these things, it requires a clear understanding of fuel injection processes. There are number of experimental and numerical techniques used for fuel injection processes into scramjet engines.

T. Sunami et al. [1] investigated supersonic mixing and combustion control using streamwise vortices, found that the alternating wedge design created a more uniform mixing region, but the overall combustion performance is similar to that of a strut with a flat trailing edge and causes a larger total pressure loss. L. A. Povinelli [2] conducted research on struts and studied the effects of the geometric parameters of the strut on the drag in the combustion section. The drag that develops in the combustion section must be balanced by the thrust produced by the engine. Therefore, the drag should be low for more efficient scramjet designs. K. Y. Hsu et al. [3] examined three different strut shapes and their effect on the combustion in a Scramjet chamber. Their research showed an increase in maximum temperature and mixing, as well as moving the centre of combustion into the main section of the flow as compared to a cavity without a strut. K.M.Pandey and Sivasakthivel.T [4] examined the Recent Advances in Scramjet Fuel Injection - A Review; Jacobsen et al. [5] developed a fuel injection system called as Plasma Ignitor it consisting of an aerodynamic ramp injector and a DC plasma torch for scramjet operating between Mach 4 and Mach 8. The injector consists of four holes placed upstream and a plasma torch downstream operated with methane and nitrogen. The toe-in angle of the injector holes was varied, and it was found that increasing the toe-in angle increased the mixing efficiency and penetration of the fuel into the flow. This is due to the uneven rotation and hence vorticity created due to fuel injection from these elliptic shaped holes. The same configuration was developed with a ramp set up, and it was found that the ramp configuration provided better mixing than a flat injector with injection holes. Vinogradov et al. [6] conducted experiment with gaseous fuel injection far upstream behind a swept, thin pylon with a various cross sectional pylon shapes. The results showed much improved mixing and penetration, improved flame holding, and a lack of pressure losses and pronounced edge shocks.

Gardner et al. [7] tested a fuel injection method called as upstream injection this basically involves injecting the hydrogen fuel from the intake into the flow from portholes upstream prior to combustion. This method is for a two dimensional scramjet engine. The main advantage this method has is that it allows for a shorter combustion chamber, thus a reduction in skin friction drag. It has been determined that drag in the combustion chamber is one of the main contributors to inefficiency in a scramjet. Epstein.M and Kitshenreuter.P [8] tested a fuel injection method called as Pulsed Injector in this fuel is injected as a continuous stream from injection ports into the combustion chamber where it ignites. This type of injection injects the fuel in a series of pulses, which allows for greater mixing between the fuel and air. Combustion occurs more rapidly as well as more efficiently, thus producing a greater thrust output. The time between pulses is dependent on the free stream conditions, and is coordinated to achieve near stoichiometric combustion. An advantage of this method is that combustion always remains in a transient state, and never reaches a steady state condition. Transient combustion further enhances fuel-air mixing, as well as allowing for a greater dispersal of the heat load on the combustor. K.M.Pandey and Sivasakthivel.T [9] worked on the topic of CFD Analysis of Mixing and Combustion of a Scramjet Combustor with a Planer Strut Injector, and they found that The static pressure distribution along the top and bottom walls for the case under the condition of engine ignition is much higher than that for the case under the condition of cold flow. There are three clear pressure rises on the top and bottom walls of the scramjet combustor. The eddy generated in the strut acts as a flame holder in the combustor, and it can prolong the residence time of the mixture in the supersonic flow.

Cornell et al. [10] investigated the flow behind a vee-gutter cascade in a gas turbine combustor. They compared their experimental results with the predictions of a theoretical model was able to successfully predict the wake shape, the total pressure loss, and the drag force of high blockage cascades of vee-gutter profiles. Mitani et
al. [11] showed experimentally that the micro-flame holder could successfully promote ignition in a Mach 2.5 air cross flow. The ignition performance of the micro-flame holder was found to be comparable to that of an oxygen plasma ignition torch; however, a much larger energy input was required for the operation of the microigniter. K.M. Pandey and T. Sivasakthivel [12] worked on the topic of CFD Analysis of a Hydrogen Fueled Mixture in Scramjet Combustor with a Strut Injector by Using Fluent Software and they investigated supersonic cold flow with hydrogen injection. Parent and Sislian [13] did numerical studies of mixing efficiencies of cantilevered ramp and waizamp ramp injector. In the analysis they used Favre averaged Navier–Stokes equations for multiple species with $\kappa$–$\omega$ turbulence model. The study shows the mixing efficiency variation with convective Mach number. Cantilevered design has the advantage that shock is formed under the injectors providing contiguous shock surface span–wise direction of the injector array, which will increase the baroclinic effect and hence larger mixing efficiency.

M Deepu [14] worked on recent advances in experimental and numerical simulation of scramjet combustor flow fields, and his findings are – Increase in jet to free stream momentum flux ratio will result in the increase of jet penetration to free stream for all kinds of jets. Injector orientation plays an important role in the strength of the bow shock, with the shocks created by oblique injector being substantially weak compared to transverse injector. Chadwick, C et al. [15] did experiments to examine the stability of hydrocarbon-fueled flames in cavity flame holders in supersonic airflows. Ethylene flames were stable over a wider range of fuel flow rates than methane flames, as expected because of the shorter ignition delay time and greater flame speed of ethylene. Methane flames would not ignite in Mach 3 airflow due to the low static temperature and pressure. S. Javoy et al. [16] studied Elementary reactions of interest in $\text{H}_2$ supersonic combustion chemistry using a shock tube technique connected to an atomic resonance absorption spectrophotometer. He concluded that Resonance absorption measurements of $\text{O}$ atoms, behind reflected shock waves, have been used to precisely the rate coefficients of elementary reactions Which play major role in $\text{H}_2$ supersonic combustion chemistry. V. E. Terrapon et al. [17] had given review on a flamelet-based model for supersonic combustion and they made the following observations: A flamelet approach seems to be feasible to simulate high-speed flows, although many aspects are still to be evaluated. The flamelet model has been derived and extensively used for low Mach number flows. However, the low Mach number assumptions do not hold anymore at supersonic speed where compressibility effects and viscous heating play a major role.

III. METHODOLOGY AND SOLUTION PROCEDURE

A. The DLR Scramjet Experimental Rig

A schematic of the DLR (German Aerospace centre) scramjet experimental facility is presented in Figure 4. Preheated air is expanded through a Laval nozzle and enters the combustor section at $\text{Ma} = 2.0$. The combustor has a width of 40 mm and a height of 50 mm at the entrance and a divergence angle of the upper channel wall of three degrees to compensate for the expansion of the boundary layer. A wedge shaped strut is placed in the combustion chamber downstream of the nozzle. Just downstream of the nozzle the height of the 32 mm long strut is 6 mm. along the first 100 mm downstream of the nozzle, the side walls and the upper wall are made from quartz glass to allow optical access and to minimize the reflection of scattered light on the wall opposite the observation window. Hydrogen ($\text{H}_2$) is injected at $\text{Ma} = 1.0$ through a row of 15 holes, 1.0 mm in diameter and 2.4 mm apart, in the strut base. Typical mass flows in the experiments were varied between 1.0 and 1.5 kg/s for the air and between 1.5 and 4.0 g/s for $\text{H}_2$, which correspond to equivalence ratios between 0.034 and 0.136, respectively. The hydrogen is injected at ambient temperature and pressure, i.e. at $\text{T} = 250 \text{ K}$ and $\text{p} = 10^5 \text{Pa}$, whereas the air was injected at $\text{T} = 340 \text{ K}$ and $\text{p} = 10^5 \text{Pa}$. Combustion was initiated by pre-burning of a small amount of $\text{O}_2$ in a $\text{H}_2$ tube by a spark.

![Fig. 4: Schematic of the supersonic combustion chamber](image)

B. Computational configurations

The computational configuration is simplified in the sense of all the gambit modellings are done in 3D and fluent analyses are done in 2D. The reason for this simplification is that to reduce the computational time as much as possible, but still retaining all relevant physics of the scramjet combustor.

Computational Configuration of Strut with Alternating Wedge Injector

A strut with alternating wedge injector is placed in the combustion chamber downstream of the nozzle. The length of the strut is 32 mm and diameter of the injector is 0.295 mm.

![Fig. 5: Scramjet combustion chamber and strut with alternating wedge injector](image)
C. Mesh Generation

Numerical calculations of the flow with fuel injection but without chemical reaction were first carried out on a base grid with 205,460 tetrahedral cells. This grid was then refined by adaption based on gradients of static pressure to capture the shocks, followed by refinement near all the no-slip surfaces to resolve the boundary layers well. The grid was further refined in the shear layer between the hydrogen jet and the incoming air so as to resolve the mixing and diffusion effects of hydrogen effectively. This refinement resulted in grids with 281,431 cells. For reacting flow calculations the grid was adapted further based on the gradients of reacting species so as to resolve the combustion phenomenon in the flow field accurately. After refinement, a grid with 340,840 cells has been taken as the final grid for all subsequent calculations.

D. Boundary conditions

In the present study three different types of boundaries are applied: inflow, outflow and fixed walls. The flow fields under consideration here are supersonic. According to the theory of characteristics all variables are prescribed at inflow boundaries, i.e. Dirichlet boundary conditions, and Neumann boundary conditions are used for all variables at outflow boundaries. At fixed walls the no slip condition are applied.

<table>
<thead>
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<th>Hydrogen</th>
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<td>Ma</td>
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<td>1.0</td>
</tr>
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<td>2</td>
<td>U [ m/s]</td>
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<td>T [k]</td>
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<td>k [m^2/s^3]</td>
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<td>Mass flow Rate[kg/s]</td>
<td>1.5</td>
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</tr>
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</table>

Table 1: Inflow conditions of the air stream [12].

E. Grid Independence Test

The grid independence test is carried out for analyzing the effect of grid number on the bottom wall static pressure with combustion chamber length. As illustrated in Figure 8, a good agreement is observed between 4, 00,000 cells and 3, 40,840 cells. Hence, the present analysis is carried out using a minimum grid size of 3, 40,840 cells.

F. Numerical Solution

The inlet conditions of the H_2 injection ports are adjusted so as to achieve sonic injection with the desired fuel mass flow rate. The equivalence ratio is 0.0125. The flow through the combustor is compressible and three-dimensional. In addition, turbulence and finite rate chemistry are also considered. K-ε model is used for modelling turbulence with default values for the constants (C_{1ε} = 1.44, C_{2ε} = 1.9). The turbulent Prandtl and Schmidt numbers have been assumed to be 1-2, 0-7 respectively. Single step, finite rate kinetics has been used to model chemistry. Viscosity and Cp of the mixture have been evaluated using mass-weighted mixing law. Adiabatic boundary conditions with standard wall functions have been used on all the wall surfaces. Stagnation temperature and pressure for the vitiated air are 612K and 7-825 bar respectively. In addition, k and ε have been specified [22].

IV. RESULTS AND DISCUSSIONS

In this section we describe the results from the numerical simulations for strut with alternating wedge injector under two categories namely (i) non reacting case (hydrogen injection but without combustion), and (ii) reacting case (hydrogen injection with combustion). All the times simulations are started with incoming air.

A. Non-reacting (mixing) flow

The cold flow (mixing) without combustion is investigated using k-ε model. Inert H_2 injection adds significant complexity to the flow in the scramjet combustor since H_2 has a considerably lower molar mass than air, which makes mixing an important process in establishing the conditions for scramjet combustion. Figure 9 shows a view of the flow together with a qualitative comparison of experimental shadowgraph images and numerical images from the cases of H_2 injection (without combustion) for strut with alternating wedge injector. With inert H_2 injection, oblique shocks are formed at the tip of the wedge that are later reflected by the upper and lower walls before interacting...
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Further with the unsteady, partly H₂ filled wake. At the upper and lower walls, the boundary layer is affected by the reflected oblique shocks. The boundary layer on the wedge surface separates at the base and a shear layer is formed. Because of the one-sided divergent channel the upper reflecting shock hits the H₂ filled wake further downstream than the lower shock. In some places the reflected shock waves are deflected by the hydrogen jets. After some distance the flow in the wake of the wedge is accelerated back to supersonic speed. Moreover, a small triangular recirculation region is formed just behind the wedge caused by low velocity.

Fig. 9: Shadow graph image (top), contour plots of pressure (bottom).

Figure 10 shows the experimental and numerical pressure distributions along the lower wall channel. The leading–edge shock wave is reflected from the top and bottom walls but the reflected shockwave from the bottom wall is stronger compared to that from the top wall due to the 3° divergence in the latter. There is also a subsonic recirculation zone at the base of the wedge. The fuel is injected into this subsonic recirculation zone, which helps in flame stabilization. The lower side of the hydrogen jet there is only a compression wave but not a shock wave. In the supersonic flow region at x = 175 mm the shock waves are not reflected at the jet, rather they are deflected by crossing the jet. The over- all agreement between the experiment and the numerical simulation is good, the high pressure is generated at the x = 130 mm at the lower channel wall. Figure 11 shows the pressure contours for the non reacting simulation. The shock generated from the blunt nose of strut and its multiple reflections from the wall boundaries can be seen clearly. As compare to other two models the effect of oblique shock wave in this model is less but the effect of expansion wave is more in this method of injection.

Fig. 10: Experimental and numerical pressure distributions

Fig. 11: Contours of static pressure

Figure 12 show the pressure variation at the bottom and top of the combustion chamber, it is clear that bottom wall pressure is high as compare to top wall temperature. There are three pressure raise in top and bottom wall of the combustor because of shock and expansion waves.

Fig. 12: Pressure variation at the bottom and top walls

From the Mach contour shown in Figure 13 the boundary layer can be seen clearly. Also there is Mach number increases in the divergent portion of the combustor due to expansion. Also small subsonic zone can be seen in the figure which acts as a flame holding device for reacting case. As compare with the entire models, the sub sonic region in this model very small.
B. Reacting flow

Mixing of fuel and air forms a combustible mixture, which is ignited, leading in turn to the combustion of the fuel. The resulting from the chemical reactions will likely alter the flow field due to density and temperature changes. Due to combustion the recirculation region behind the wedge becomes larger as compared to mixing case and it acts as a flame holder for the hydrogen diffusion flame. It is also clear from the above image that the combustion affects the flow field significantly. The leading edge shock reflected off the upper and lower combustor walls makes the setting of combustion when it hits the wake in a region where large portions of the injected fuel have been mixed up with the air. The recompression shocks at the upper and lower wedge corners become much weaker than mixing Case. The shear layers at the base of the wedge becomes more pronounced with combustion due to the fact that continuous ignition occurs within these shear layers. Figure 16 shows a qualitative comparison between CFD and experimental shadowgraph images, where especially the shear layers are clearly visible.
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Fig. 19: Reacting flow pressure contours

Figure 20 show the pressure variation at y= 10mm, y=25mm and y=40mm among this three the effect of oblique shock wave is higher at y=10mm. at the centre of the combustor variation of static pressure is not much high.

Fig. 20: Pressure variation at y= 10mm, y=25mm and y=40mm

Figure 21 shows the contours of static temperature from figure it is clear that combustion and heat release are taking place in the recirculation region. Since the heat addition is taking place in the divergent portion of the combustor, the flow is not thermally choked for this equivalence ratio and a small high temperature zone near the strut can be seen clearly.

Fig. 21: Reacting flow static temperature

C. Performance measures

For assessing the overall performance of the combustor, namely, mixing efficiency and combustion efficiency are essential that are discussed below.

Mixing Efficiency

The fuel-air mixture available for reaction can be determined using a mixing efficiency. At a given x = constant section, mixing efficiency is defined as:

\[ \eta_f = \eta_m \frac{\dot{m}_f}{\dot{m}_o} \]

Where; \( \dot{m}_f \) is the mass flow rate of fuel available for reaction, \( \eta_m \) is the mixing efficiency and \( \dot{m}_o \) is the mass flow rate of fuel through the injectors. The mixing efficiency changes in value from zero at the injector exit until it reaches unity at a defined mixing length \( L_{mix} \) where all the available fuel is mixed with the combustor air and is ready for combustion.

Fuel is injected from the base of the wedge at \( x \approx 0-111m \) and the mixing is completed at \( x \approx 0-130m \). Contours of mass fraction of H\(_2\) shown in Figure 23 It indicate that mixing taking place rapidly. The rapid mixing and the high values for mixing efficiency are typical of H\(_2\) fuel. Hydrocarbon fuels show lesser values for mixing efficiency. The other reason for the mixing efficiency being so high is the low global equivalence ratio.
Fig. 23: (a) mass fraction of H$_2$ at Y=25mm, (b) Contours of H$_2$ for circular injector (c) mixing efficiency

D. Combustion efficiency

Combustion efficiency at a given x = constant section is a measure of how much of the fuel injected upstream has been consumed at that station. This is defined as:

$$1 - \frac{\dot{m}_{H2} (x)}{\dot{m}_{H2, injected}}$$

The plots of combustion efficiency in Figure 26 show that it reaches 100% asymptotically. It appears from this figure that combustion is complete at x ≈ 0-175m. Contours of the mass fraction of H$_2$O are given in Figure 24. It can be seen that the maximum value for the mass fraction of H$_2$O is reached at a distance of 0-175m, which is just downstream of the wedge. However, the distribution of the mass fraction of H$_2$O continues to change till 0-30m, beyond which it remains the same.

Fig. 24: Mass Fraction of H$_2$O

Fig. 25: Contours of mass fraction of H$_2$O
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