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Computational Analysis of Supersonic Flow Regime Using Ramp Injector with Standard K-ω Turbulence Model

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ABSTRACT
This work presents the supersonic combustion of hydrogen using ramp injector along with two-dimensional turbulent non-premixed combustion model. The work is based on the standard k-ω which has been used for modeling the turbulence and single step finite rate chemistry. As the combustion of hydrogen fuel is injected from the strut injector, it is successfully used to model the turbulent reacting flow field. It is observed from the present work that, the maximum temperature occurred in the recirculation areas which is produced due to shock wave-expansion and the fuel jet losses concentration and after passing successively through such areas, temperature decreased slightly along the axis. From the maximum mass fraction of OH, it is observed that there is very little amount of OH around 0.019 were found out after combustion. By providing strut injector, expansion wave is created which cause the proper mixing between the fuels and air which results in complete combustion.

Key words : CFD, combustion, hydrogen fuel, non-premixed combustion, scramjet, standard k-ω turbulence model, supersonic combustion, cavity injector.

1. INTRODUCTION

Supersonic combustion ramjet (scramjet) is the key enabling technology for endure hypersonic flights. In the present scramjet engines the combustor length is generally of the order of 600 mm and the residence time of the mixture is of the order of milliseconds. Problems occur in the mixing of the reactants, flame stability and completion of the combustion within the limited combustor length which occurs due to high speed of the supersonic flow in the combustion chamber. The flow field in the scramjet combustor is highly complex which shows that, when the flight speed is low, the kinetic energy of the air is not enough to be used for the optimal compression. In a supersonic combustion ramjet or scramjet, the flow is compressed and decelerated using a series of oblique shock waves. A scramjet engine is well known as hypersonic air-breathing engine in which heat release due to combustion process occurs in the supersonic flow relative to the engine. Therefore, the flow velocity around the scramjet remains supersonic and thereby it does not require mechanical chocking system [1]. Scramjet is an signifier for Supersonic Combustion Ramjet which is a type of jet engine aimed to operate in the high velocity regime usually it is related with rockets. 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 which is the main difference between Scramjet and the Ramjet. Figure1 shows a basic generic Scramjet design. It works by injecting fuel into a flow of supersonic air. The air is at sufficiently high temperature and pressure for the fuel to combust and the ensuing mixture is discharged from the engine at a higher pressure. The Scramjet engine is composed of four main sections i.e., the inlet, isolator, combustor and exhaust [2].

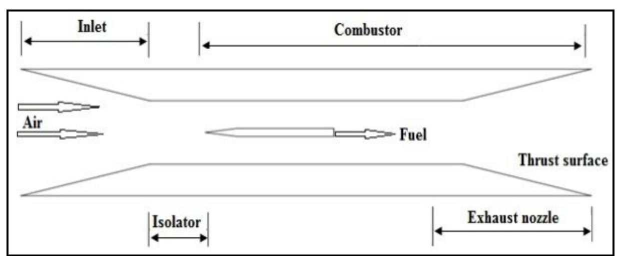

Figure 1: Generic Scramjet engine

K.M.Pandey, T.Sivasakthivel and S.K.Reddy K.K [3, 4] describe that there are many types of Fuel Injectors for Scramjet Engines. The fuel that is used by scramjets is usually either a liquid or a gas. The fuel and air need to be mixed about stoichiometric proportions for efficient combustion. The main problem of scramjet fuel injection is that the air flow is quite fast which shows that, there is minimal time for the fuel to mix with the air and ignite to produce thrust which require about milliseconds. Hydrogen is the main fuel used for combustion. The main important aspect in designing scramjet engines is to enhance the mixing and thus reducing the combustor length. A number of options are available for injecting fuel and enhancing the mixing of the fuel and air in high speed flows typical of those found in a scramjet combustor which are as follows.

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1.1 Parallel Injection

The parallel fuel injection consists of fuel flowing parallel to the air in the engine but separated by a splitter plate which is shown in figure 2. When the splitter plate ends, a shear layer is produced due to the different velocities of the fuel and air.

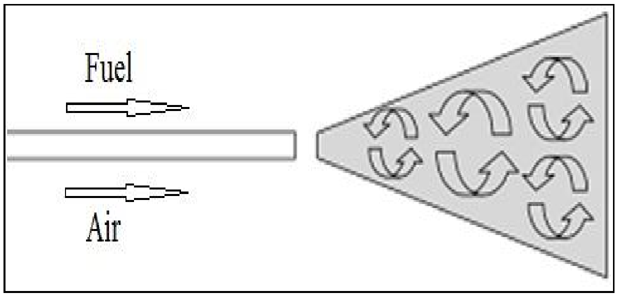

Figure 2: Parallel Fuel Injection

1.2 Normal Injection

The normal fuel injection consists of an injection port on the wall of a scramjet. Normal fuel injection creates a detached normal shock upstream of the injector which causes separation zones upstream and downstream of the injector as shown in figure 3. The port injects the fuel normal to the flow of air in the scramjet.

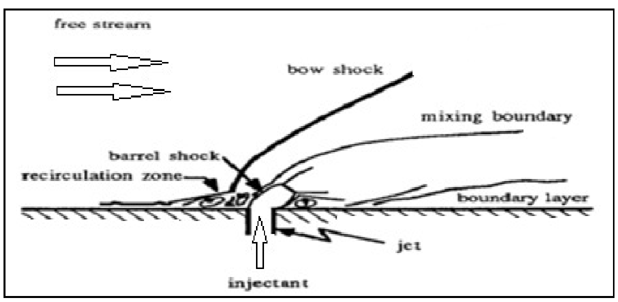

Figure 3: Normal Fuel Injection

1.3 Ramp Injectors

The flow over the ramps creates the counter-rotating vortices that increased the mixing of the ramps also create shocks and expansion fans which cause pressure gradients that also increase mixing. There are two types of Ramp injectors namely Compression Ramp Injector and Expansion Ramp Injector. Compression Ramps are elevated above the floor while Expansion Ramps create troughs in the floor which is shown in figure 4.

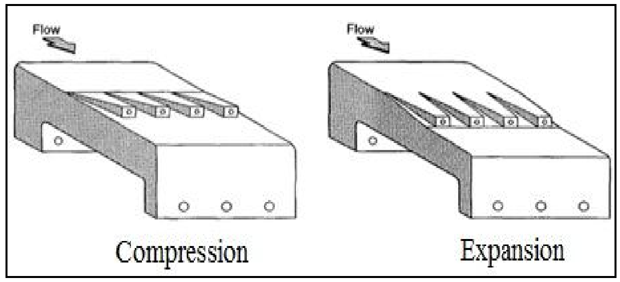

Figure 4: Ramp Injectors

1.4 Strut Injectors

An alternate Strut Injector is shown in figure 5. Strut Injectors are located at the channel axis and it can inject the fuel directly into the core of the air stream. This is possible without the induction of strong shock waves. Moreover, additional momentum is added by parallel fuel injection increasing the engine thrust.

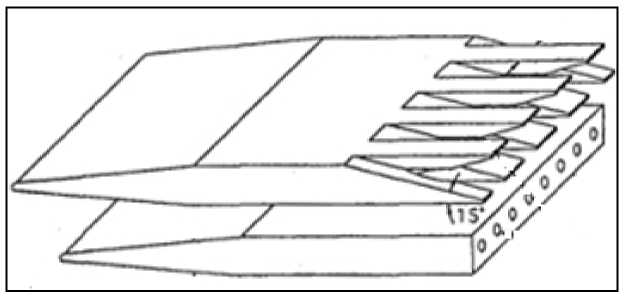

Figure 5: Wedge-Shaped Strut Injector (Alternating)

1.5 Cavity Flame Holder

An injection with a cavity set up is shown in figure 6. It uses a step to induce recirculation with fuel injected upstream of this cavity. It also provides a continuous ignition point or flame holder with little pressure drop. Hence, potential applications sustained combustion.

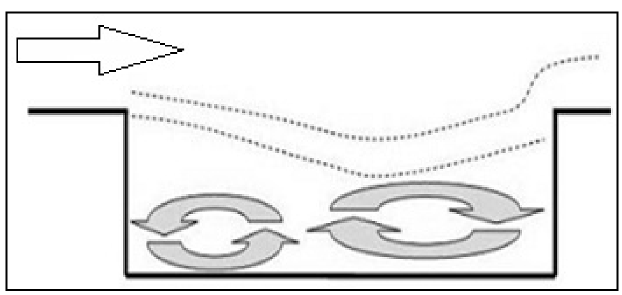

Figure 6: Rectangular Cavity Flame Holder

Scramjet combustor advances from the better performance of an air-breathing propulsion system. Scramjet necessitates a combustor having an efficient fuel-air mixing and combustion of fuel with air at supersonic speeds without much pressure loss[5,6]. Many experimental and

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numerical analyses have been reported during the last few decades with respect to the characteristics of the complex flow field, resulting due to fuel-air mixing and combustion. Riggins [7,8], et al. observed that, the shock waves, incomplete mixing and viscous effects are the main factors leading to the thrust loss in supersonic combustors though these effects aid mixing. Strut injectors offer a possibility for parallel injection without causing much blockage to the incoming stream of air and also fuel can be injected at the core of the stream. Tomioka [9,10] et al. observed the effects of staged injection from struts. M. Deepu [11] worked on recent advances in numerical and experimental analysis of scramjet combustor flow fields and he has observed that, 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 predilection plays an important role in the strength of the bow shock.

The air flow entering a combustor remains supersonic after the optimum compression when the flight speed is higher than a certain value and that time the efficiency of the engine will decrease with a further compression. Therefore the combustion has to take place under the supersonic flow condition. The efficiency of heat supply to the combustion chamber based on the analysis of literature data on combustion processes in a confined high-velocity and high-temperature flow for known initial parameters is considered which was given by Mr.P.K.Tretyakov [12]. The process efficiency is characterized by the combustion completeness and total pressure losses. The main attention is paid to the local intensity of heat release, which ascertains together with the duct geometry, flame initiation techniques and stabilization, injection techniques, quality of mixing the fuel with oxidizer and the gas-dynamic flow regime. The study of supersonic combustion of hydrogen has been conducted by Shigeru Aso and Arifnur Hakim et al. [13].

L. A. Povinelli [14] had work on struts and observed 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, for more efficient scramjet designs the drag should be low. Gardner et al. [15] canvassed that, a fuel injection method called as upstream injection which is basically involves in injecting the hydrogen fuel from the intake into the flow from portholes upstream anterior to combustion which method applicable for two dimensional scramjet engine. The main advantage of this method is that, it allows for a smaller combustion chamber and thus a reduction in skin friction drag.

T. Cain and C. Walton [16] observed that, supersonic combustion data obtained at the low static temperatures annexation for an efficient scramjet engine. The main attention is focused at the methods by which the fuel was ignited and combustion maintained which is particularly common for supersonic combustion experiments

R.Srikrishnan et al. [17] worked on experimental investigation of thermal mixing and combustion in supersonic flows and they have observed that, petal nozzle can achieve nearly uniform temperature and momentum fields by using mixing duct. The petal nozzle also results in better combustion, when it is used to inject the fuel-rich gases into a supersonic combustor. V. E. Terrapon et al. [18] describe that, 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 don’t hold anymore at supersonic speed where compressibility effects and viscous heating play a major role.

Xing Jianrven et al. [19] worked on application of flamelet model for the numerical simulation of turbulent combustion in scramjet and they have observed that, tnteraction of turbulence and combustion increase the combustion zone nearby the jet, weak the intensity of combustion close-by the jet and the zone where the interaction of turbulence and combustion is acute mostly locates nearby the jet. Yuan Shengxue [20] worked on supersonic combustion and they have observed that, the calculation of deflagration in supersonic flow shows that the entropy increment and the total pressure loss of the combustion products may decrease with the increase of combustion velocity. Gruenig et al. [21] observed that, kerosene was burnt in a steady and vitiated Mach number 2.15 - air flow of a model scramjet combustor. The fuel is injected into the supersonic air stream by means of pylons and by the addition of small amounts of hydrogen to the kerosene the liquid fuel jet is circularized and a fine spray is being produced. If the fuel is injected normally into the cross flow this additional fuel jet dispersion is not necessary for the supersonic combustion.

2. MATERIAL AND METHODS

2.1 Numerical Methodology

In this part my intension towards the formulation of the problem and realization of constraints and pre and post defining the problem. The main objectives in this stage were: First of all, to initiate combustion across the air-fuel (H_2) mixture with air inlet at Mach no. 2 and H_2 from the ramp injector at Mach no.1.Secondly, finding out the temperature distribution, for other critical parameters and quantities across the air-fuel mixture with standard k-ω turbulence

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model. The 2D modelling scheme was adopted in GAMBIT and it was analyzed using FLUENT

For purpose of defining the physical model has been used the following values:

Air inlet edge = 60 *mm.*
Fuel inlet edge = 20 *mm.*
Outlet edge = 100 *mm.*
Length of the ramp = 320 *mm.*
Length of the combustion chamber = 600 *mm.*
Angle of expansion (α_e) = 6^o.
Angle of compression (α_c) = 6^o.

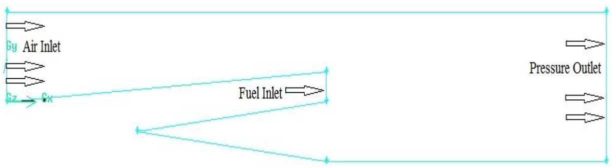

Figure 7: Two dimensional model of ramp injector

2.2 Governing Equations

The advantage of employing the complete Navier-Stokes equations extends not only the investigations that can be carried out on a wide range of flight conditions and geometries, but also in the process the location of shock wave, as well as the physical characteristics of the shock layer, can be exactly determined and by describing the three-dimensional forms of the Navier-Stokes equations below. Note that the two-dimensional forms are just simplification of the governing equations in the three dimensions by the omission of the component variables in one of the co-ordinate directions. Neglecting the presence ofbody forces and volumetric heating, the three-dimensional Navier-Stokes equations are derived as [22]:

Continuity: $\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$
(1)

X-momentum: $\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} + \frac{\partial(\rho wu)}{\partial z} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}$
(2)

Y-momentum: $\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} + \frac{\partial(\rho wv)}{\partial z} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}$ (3)

Z-momentum: $\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho ww)}{\partial z} = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}$
(4)

Energy: $\frac{\partial(\rho E)}{\partial t} + \frac{\partial(\rho uE)}{\partial x} + \frac{\partial(\rho vE)}{\partial y} + \frac{\partial(\rho wE)}{\partial z} = \frac{\partial(u\sigma_{xx}+v\tau_{xy}+w\tau_{xz})}{\partial x} + \frac{\partial(u\tau_{yx}+v\sigma_{yy}+w\tau_{yz})}{\partial y} + \frac{\partial(u\tau_{zx}+v\tau_{zy}+w\sigma_{zz})}{\partial z} + \frac{\partial(k\frac{\partial T}{\partial x})}{\partial x} + \frac{\partial(k\frac{\partial T}{\partial y})}{\partial y} + \frac{\partial(k\frac{\partial T}{\partial z})}{\partial z}$ (5)

Assuming a Newtonian fluid, the normal stress σxx, σyy, and σzz can be taken as combination of the pressure p and the normal viscous stress components τxx, τyy, and τzz while the remaining components are the tangential viscous stress components whereby $\tau_{xy} = \tau_{yx}$, $\tau_{xz} = \tau_{zx}$, and $\tau_{yz} = \tau_{zy}$. For the energy conservation for supersonic flows, the specific energy E is solved instead of the usual thermal energy H applied in sub-sonic flow problems. In three dimensions, the specific energy E is repeated below for convenience.

$E = e + \frac{1}{2}(u^2 + v^2 + w^2)$
(6)

It is evident from above that the kinetic energy term contributes greatly to the conservation of energy because of the high velocities that can be attained for flows, where Ma>1. Equations (1)-(6) represent the form of governing equations that are adopted for compressible flows. The solution to the above governing equations nonetheless requires additional equations to close the system. First, the equation of state on the assumption of a perfect gas in employed, that is,

$P=\rho RT$,

Where, R is the gas constant.

Second, assuming that the air is calorically perfect, the following relation holds for the internal energy.

$e= C_vT$,
Where, C_v is the specific heat of constant volume. Third, if the Prandtl number is assumed constant (approximately 0.71 for calorically perfect air), the thermal conductivity can be evaluated by the following.

$k=\frac{\mu C_p}{Pr}$

The Sutherland's law is typically used to evaluate viscosity μ, which is provided by

$\mu=\mu_0\left(\frac{T}{T_0}\right)^{1.5}\frac{T_0+120}{T+120}$
(7)

Where, μ_0 and T_0 are reference values at standard sea level conditions.

Generalized form of Turbulence Equations is as follows:

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

$$(\epsilon)\ \frac{\partial \epsilon}{\partial t}+\frac{\partial (u\epsilon)}{\partial x}+\frac{\partial (v\epsilon)}{\partial y}+\frac{\partial (w\epsilon)}{\partial z}=\frac{\partial\left[\frac{\nu_T}{\sigma_k}\frac{\partial \epsilon}{\partial x}\right]}{\partial x}+\frac{\partial\left[\frac{\nu_T}{\sigma_k}\frac{\partial \epsilon}{\partial y}\right]}{\partial y}+\frac{\partial\left[\frac{\nu_T}{\sigma_k}\frac{\partial \epsilon}{\partial z}\right]}{\partial z}$$
$$+\ \left(S_\epsilon = \frac{\epsilon}{k}(C_{\epsilon 1}P - C_{\epsilon 2}D)\right)$$
(8)

Where,

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

2.3 Reaction Model

The instantaneous reaction model assumes that a single chemical reaction occurs and proceeds instantaneously to completion. The reaction used for the Scramjet was the hydrogen-water reaction.

$2\ H_2 + O_2 \rightarrow 2H_2O$
(9)
.

3. COMPUTATIONAL MODEL PARAMETER

3.1 Geometry and Mesh Generation

Mesh generation was performed in a Fluent pre-processing program called Gambit. The current model is ramp injector with non-premixed combustion as shown in figure 8. The boundary conditions are such that the air inlet and fuel inlet surfaces are defined as velocity inlets and the exhaust is defined as pressure outlet. These conditions may be more appropriate for compressible flow. In this particular model the walls of the combustor duct do not have thicknesses. The domain is completely contained by the combustor itself; therefore there is actually no heat transfer through the walls of the combustor.

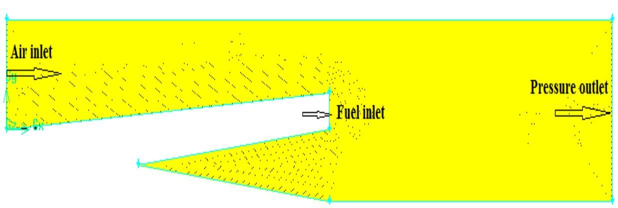

Figure 8: Two Dimensional Model of Ramp Injector

3.1 Geometry And Grid Arrangement

The geometry 2D axi-symmetric computational domain was considered for the simulation of supersonic combustion, the initial design parameters for ramp injector has taken at Mach 2 which is shown in figure 7. This was obtained by method of characteristics of nozzle program.

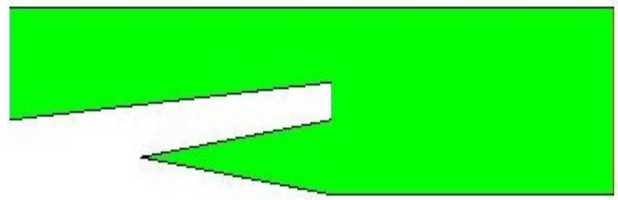

Figure 9: Grid refinement of Supersonic Combustor

4. RESULTS AND DISCUSSION

The results from the numerical simulation for supersonic combustion using ramp injector with non-premixed combustion model are discussed below:

4.1 Contours of Total Temperature

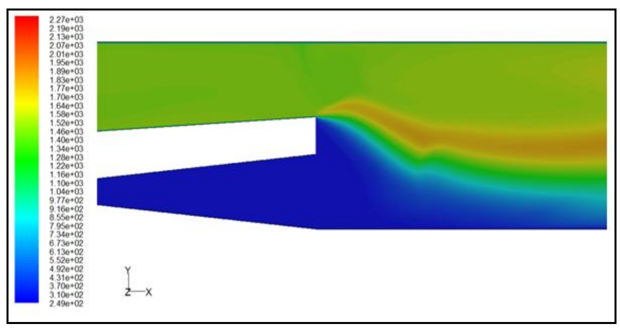

Figure 10: Contours of Total Temperature (k)

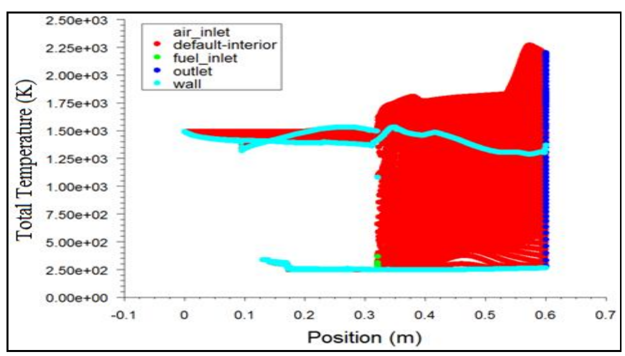

Figure 11: X-Y Plot of Total Temperature

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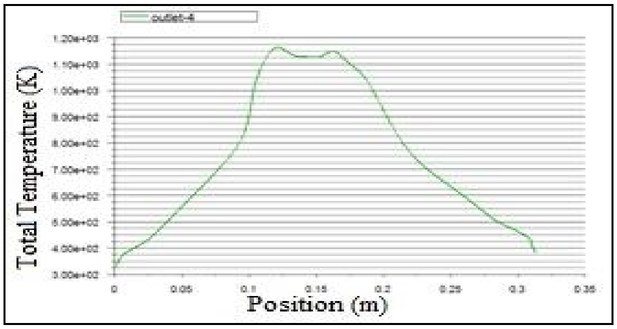

Figure 12: Total Temperature Distribution at Pressure Outlet

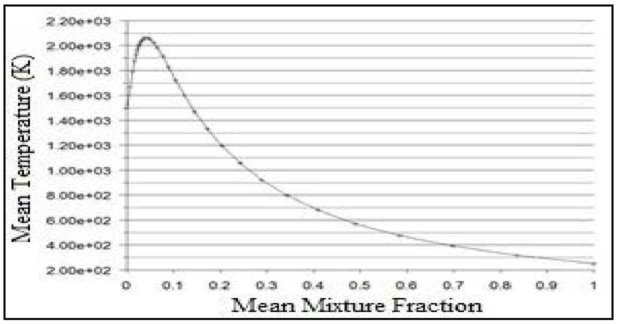

Figure 13: Contours of Mean Temperature

Contour of total temperature of the resulting flow is shown in figure 10. It is observed from the figure 10 and figure 11 that, the maximum temperature of 2270.41 k occurred in the recirculation areas which are produced due to shock wave interaction and fuel jet losses concentration and the temperature is decrease slightly a value of 248 k along the axis. The blue streamlines in the image representing the pressure gradients and hydrogen injection for the shocks. 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 corners become much weaker than mixing case. The figure 11 shows that the profile between the total temperature and the position of the combustion on all conditions such as air inlet, fuel inlet, pressure outlet, default interior and all walls whereas the figure 12 shows that the profile between the total temperature and the position of the combustion at pressure outlet. Figure 13 shows the total temperature distribution at pressure outlet and the position of the combustion at pressure outlet whereas the figure 6 shows the Contours of Mean Temperature.

4.2 Contours of Static Temperature

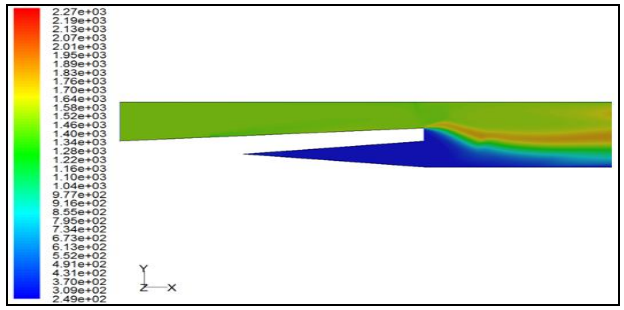

Figure 14: Contours of Static Temperature (k)

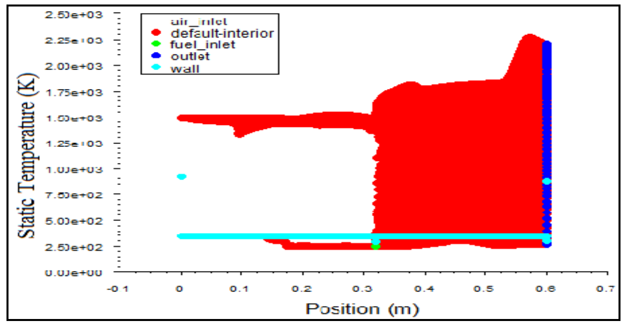

Figure 15: X-Y Plot of Static Temperature

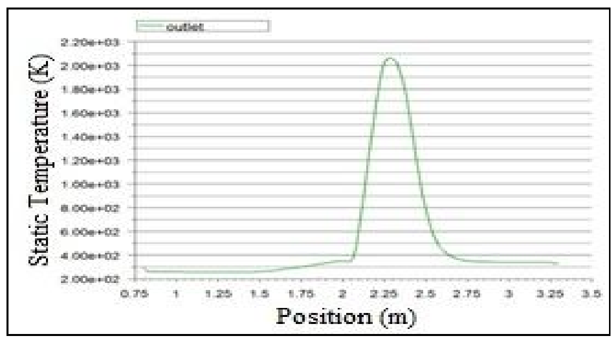

Figure 16: Static Temperature Distribution at Pressure Outlet

Contour of static temperature of the resulting flow is shown in figure 14. It is observed from the figure 14 and figure 15 that, the maximum temperature of 1495 k occurred in the recirculation areas which are produced due to shock wave interaction and fuel jet losses concentration and the temperature is decrease slightly a value of 249 k along the axis. The blue streamlines in the image representing the pressure gradients and hydrogen injection for the shocks. The figure 15 shows that the profile between the static temperature and the position of the combustion on all conditions such as air inlet, fuel inlet, pressure outlet, default interior and all walls whereas the figure 16 shows that the profile between the total temperature and the position of the combustion at pressure outlet.

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4.3 Contours of Mass Fraction of H_2

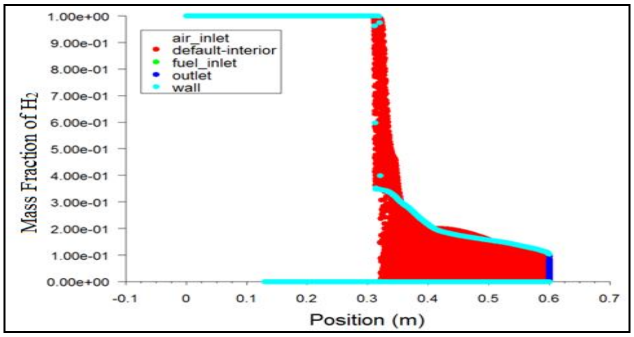

Figure 17: X-Y Plot of H_2

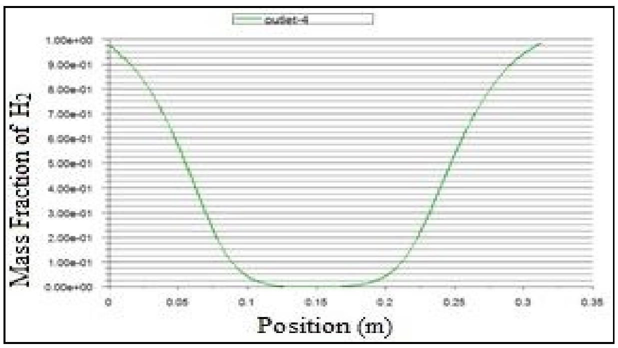

Figure 18: Contours of Mass Fraction of H_2

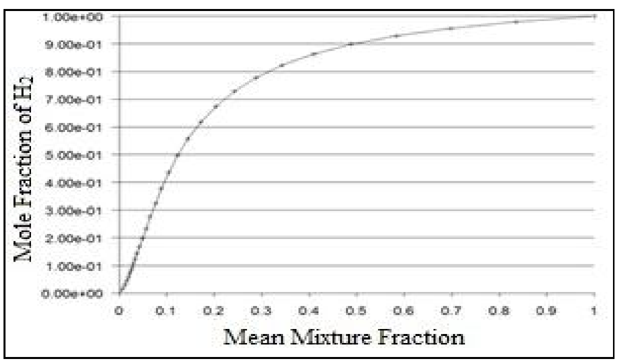

Figure 19: Contours of Mole Fraction of H_2

The contour of H_2 Mass fraction plot for the flow field downstream of the injector is shown in the figure 17. Low-velocity regions could be identified along the path of progress of the hydrogen jet. Alternate compression and expansion took place for the jet and was not enough to disorder the flow field much in the region near to the jet outlets. But the shock wave or expansion wave reflections interfered with the upcoming jet and localized low velocity regions were produced. Though, these regions are responsible for pressure loss of the jet, certainly enhanced the mixing and reaction. Figure 18 shows the profile between mass fraction of H_2 and the position of the combustion at pressure outlet whereas the figure 19 shows the graph between mole fraction of H_2 and mean mixture fraction.

4.4 Contours of Mass Fraction of N_2

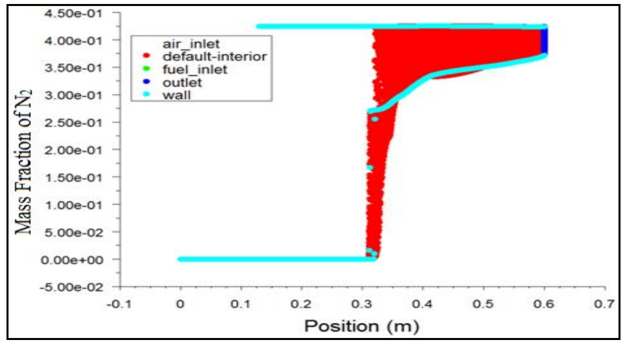

Figure 20: X-Y Plot of N_2

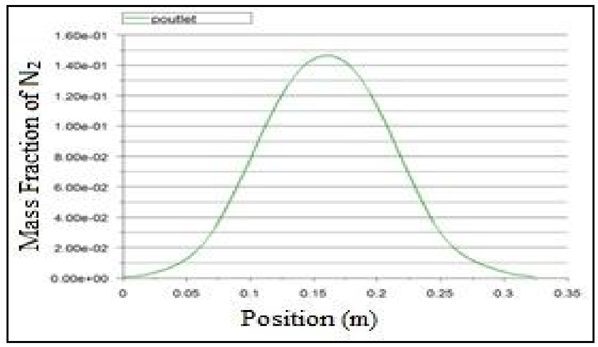

Figure 21: Contours of Mass Fraction of N_2 for Pressure Outlet

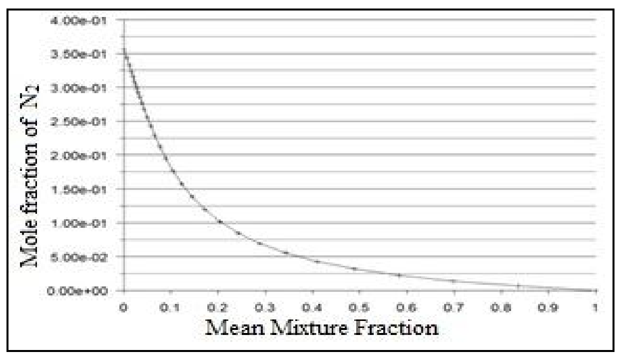

Figure 22: Contours of Mole Fraction of N_2

The contour of N_2 Mass fraction for the flow field downstream of the injector is shown in the figure 20. The major ratio of the N_2 to the O_2 is 3.76. When air supplies the O_2 in a combustion reaction, therefore every mole of O_2 is accompanied by 3.76 moles of N_2. From the figure 20 it is observed that, the maximum mass fraction of N_2 is 0.426 which is found out after combustion. The figure 21 shows that the profile between mass fraction and the position of the combustion of N_2 at pressure outlet only whereas the figure 22 shows the mole fraction of N_2.

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4.5 Contours of Mass Fraction of H_2O

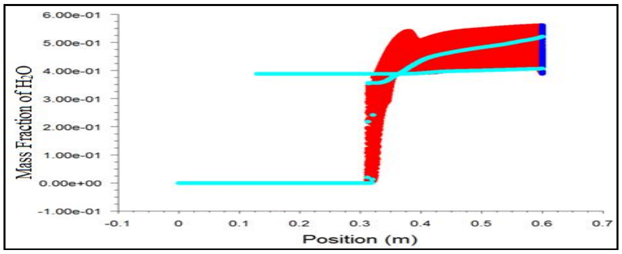

Figure 23: X-Y Mass Fraction of H_2O

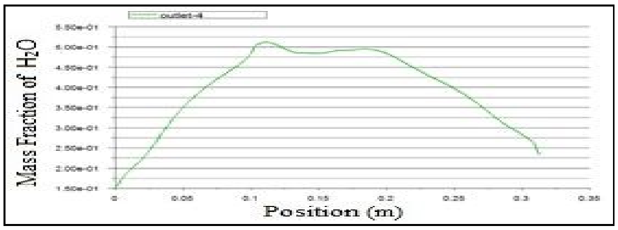

Figure 24: X-Y Mass Fraction of H_2O

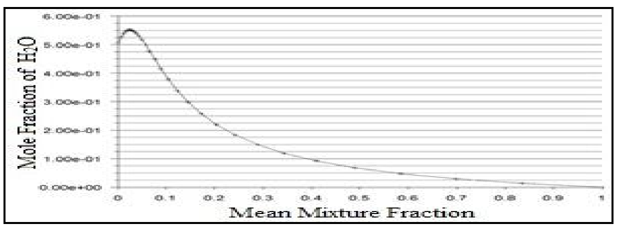

Figure 25: Contours of Mole Fraction of H_2O

Typically, when dealing the chemical reaction, it's important to remember that mass is conserved, so the mass of product is same as the mass of reactance. Even though the element exists in different the total mass of each chemical element must be same on the both side of equation. Figure 23 shows that the profile between the Mass fraction of H_2O and the position of the combustion on all conditions such as air inlet, fuel inlet, pressure outlet, default interior and all walls and the figure 24 shows that the profile between mass fraction and the position of the combustion of H_2O at pressure outlet only whereas the figure 25 shows the mole fraction of H_2O.

4.6 Contours of Mass Fraction of OH

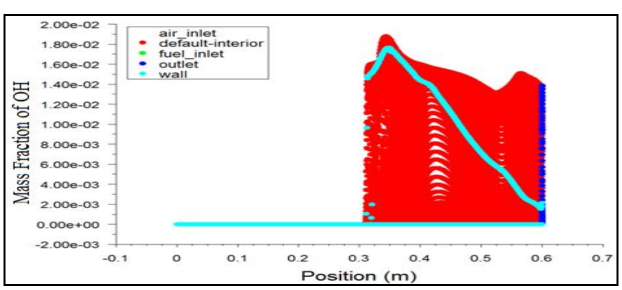

Figure 26: X-Y Mass fraction of OH

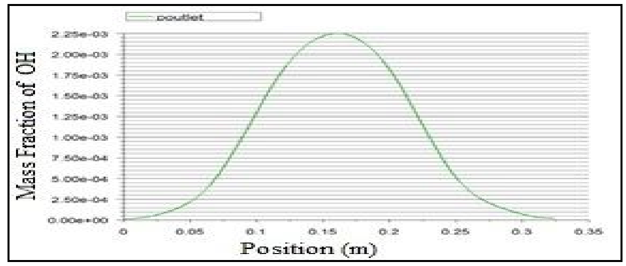

Figure 27: X-Y Mass fraction of OH

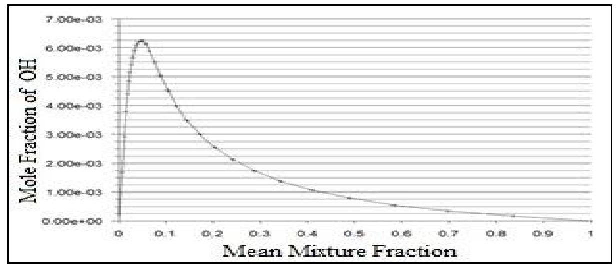

Figure 28: Contours of Mole fraction of OH

Figure 26 shows the profile between the position of the combustion on all conditions such as air inlet, fuel inlet, pressure outlet, default interior and all walls. From the figure 26 it is observed that, the maximum mass fraction of OH is 0.019 which is found out after combustion, where the minimum value is 20 and the figure 27 shows that the profile between mass fraction and the position of the combustion of OH at pressure outlet only whereas the figure 28 shows the mole fraction of OH.

4. GRID INDEPENDENCE STUDY

The grid independence test is accomplished on a basis of grid. The grid was then refined by adaption based on gradients of total pressure to capture the shocks which is shown in figure 29. The changes in cell, faces and nodes are 217014, 596034 and 200364 respectively as shown in the residual plot. All the refinement has been done in fluent itself rather than in the associated mesh generation software gambit.

Grid size (Original /	Adapted /	Change)
Cells (168684 /	564354 /	217014)
Faces (254128 /	850162 /	596034)
Nodes (85445 /	285809 /	200364)

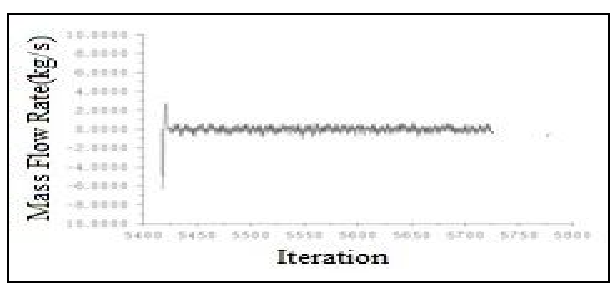

Figure 29: Convergence History of Mass Flow Rate

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5. CONCLUSION

The computational analysis of 2D Ramp injector was carried out with k-ω turbulence model for exposing the flow structure of progress of hydrogen jet through the areas disturbed by the reflections of oblique shock. For that single step reaction kinetics has been used to model the chemistry. The k-ω turbulence model also predicted the fluctuations in those regions where the turbulence is reasonably isotropic. From the maximum mass fraction of OH a very small amount of OH of 0.019 was observed after combustion. From the simulation it was concluded that the maximum temperature occurred in the recirculation areas which is produced due to shock wave-expansion, wave-jet interaction and the fuel jet losses concentration and after passing successively through such areas, temperature decreased slightly along the axis.

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