CFD Analysis of a Hydrogen Fueled Mixture in Scramjet Combustor with a Strut Injector by Using Fluent Software

K.M.Pandey and T.Sivasakthivel

Abstract—**In this study, k-ε model has been used to examine supersonic flow in a model scramjet combustor. The configuration used is similar to the DLR (German Aerospace Center) scramjet model and it is consists of a one-sided divergent channel with a wedge-shaped flameholder at the base of which hydrogen is injected. Here, we investigate supersonic cold flow with hydrogen injection. For the purpose of validation, the k-ε results are compared with experimental data for temperature at the bottom wall. In addition, qualitative comparisons are also made between predicted and measured shadowgraph images. The k-ε computations are capable of predicting cold flow simulations well and good.**

Index Terms—**Flameholder, k-ε model, Scramjet and Supersonic combustion.**

I. Introduction

The Supersonic Combustion Ramjet (SCRAMJET) engine has been recognized as the most promising air breathing propulsion system for the hypersonic flight (Mach number above 5). In recent years, the research and development of scramjet engine has promoted the study of combustion in supersonic flows. Extensive research is being carried out over the world for realizing the scramjet technology with hydrogen fuel with significant attention focused on new generations of space launchers and global fast-reaction reconnaissance missions. However, application for the scramjet concept using high heat sink and hydrogen fuels offers significantly enhanced mission potential for future military tactical missiles. Scramjet being an air-breathing engine, the performance of the missile system based on the scramjet propulsion is envisaged to enhance the payload weight and missile range. Supersonic combustion ramjet engine for an air-breathing propulsion system has been realized and demonstrated by USA on ground and in flight. X-43 vehicle used hydrogen fuel. Hydrocarbon fuel scramjet engine is still under study and research. Mixing, ignition and flame holding in combustor, ground test facilities and numerical simulation of Scramjet engine are the critical challenges in the development of scramjet engine.

A. Mixing, Ignition and flame holding in a scramjet combustor

Among the critical components of the scramjet engine, the combustor presents the most formidable problems. The complex phenomenon of supersonic combustion involves turbulent mixing, shock interaction and heat release in supersonic flow. 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

Shigeru Aso et.al [1] worked on the topic of "Fundamental study of supersonic combustion in pure air flow with use of shock tunnel", and their findings are – The increase of injection pressure generated strong bow shock, resulting in the pressure loses. The shock generator is an effective method to accelerate the combustion. The increase of the injection total pressure raises the penetration of fuel; thus, the reaction zone expands to the center of flow field. Kyung Moo Kim et.al [2] worked on the topic of "Numerical study on supersonic combustion with cavity-based fuel injection", and their findings are – When the wall angle of cavity increases, the combustion efficiency is improved, but total pressure loss increased. When the offset ratio of upper to downstream depth of the cavity increases, the combustion efficiency as well as the total pressure loss decreases. Yuan shengxue [3] worked on the topic of "supersonic combustion", and his findings are – 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. The oblique detonation wave angle may not be controlled by the wedge angle under weak under driven solution conditions and be determined only by combustion velocity. Gruenig and F. Mayinger [4] worked on the topic of "Supersonic combustion of kerosene/h_2-mixtures in a model Scramjet combustor", and their findings are – The necessary temperature level is partly achieved by the oblique shock waves in the supersonic flow with increasing combustor area ratio. K. Kumaran and V. Babu [5] worked on the topic of "Investigation of the effect

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K.M.Pandey, Senior Member, IACSIT and Professor, is with the Department of Mechanical Engineering, N.I.T Silchar, Assam, India. (Email: kmpandey2001@yahoo.com).

T.Sivasakthivel, M.Tech - Thermal Engineering, is with the Department of Mechanical Engineering, N.I.T Silchar, Assam, India (Email: sivasakthivel.t@gmail.com).

of chemistry models on the numerical predictions of the supersonic combustion of hydrogen", and their findings are – Multi step chemistry predicts higher and wider spread heat release than what is predicted by single step chemistry. The single step chemistry model is capable of predicting the overall performance parameters with considerably less computational cost. A better tradeoff between thrust augmentation and combustion efficiency can be achieved through staged combustion.

T. Cain and C. Walton [6] worked on the topic of "review of experiments on ignition and Flame holding in supersonic flow", and their findings are – Low combustor entry temperature is desirable /essential due to intake and nozzle limitations. Hydrogen and hydrocarbon the optimum temperature /pressures are in regions in which ignition delay is very sensitive to temperature, varying from 0.1ms to >>10ms. At low Mach number and static temperatures but at these conditions combustion results in free subsonic regions with very high turbulence. Chemical initiators such as silane, fluorine and OTTO can be used but there are penalties in specific impulse, system complexity and handling hazards. G. Yu, J.G. Li, J.R. Zhao, et al. [7] worked on the topic of "An experimental study of kerosene combustion in a supersonic model combustor using effervescent atomization", and their findings are – The smaller kerosene droplet having higher combustion efficiency. A local high temperature radical pool in the cavity is crucial in promoting the initiation and the subsequent flame holding of the kerosene combustion in a supersonic combustor. A. R. Srikrishnan and j. Kurian et.al. [8] worked on the topic of "An Experimental Investigation of Thermal Mixing and Combustion in Supersonic Flows", and their findings are – A 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. Temperature and pressure rises were measured and the supersonic combustion efficiency was found to be of the order of 60%. The performance of a conventional conical nozzle was found to be much inferior to that of the petal nozzle under identical conditions. M Deepu [9] worked on the topic of "Recent Advances in Experimental and Numerical Analysis 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. S. Zakrzewski and Milton [10] worked on the topic of "Supersonic liquid fuel jets injected into quiescent air", and their findings are – Supersonic liquid jets M = 1.8 develops from a flat front to a rounded bow within some 10 mm M = 5.2, the bow shape is more pointed and shows signs of an oscillation from more to less pointed. K.M.Pandey and Amit Kumar [15] worked on the topic of "Studies on Base Pressure in Suddenly Expanded Circular Ducts: a Fuzzy Logic Approach" ", and their findings are – The methodology can be easily extended to a situation involving diverse conflicting objectives. This study can be extended to different nozzles having different geometries with variations in Mach numbers, primary pressure ratio and area ratio. It is observed that L/D ratio is 6 for base pressure for Mach numbers of 1.58, 1.74, 2.06 and 2.23 , which is in very close agreement with the experimental results cited in the literature. This has been discussed with fuzzy logic as a tool for three area ratios 2.89, 6.00 and 10.00. The primary pressure ratio has been varied from 2.10 to 3.48 and L/D ratio has been varied from 1 to 6. From this analysis it is observed that L/D ratio 6 is the optimum needed keeping in view all the parameters like wall static pressure and pressure loss including base pressure.

III. Governing Equations

The advantage of employing the complete Navier-Stokes equations extends not only to 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 precisely determined. We begin 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 of body forces and volumetric heating, the three-dimensional Navier-Stokes equations are derived as

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

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

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

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

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

IV. Experimental Setup and Computational Details

A schematic of the DLR (German Aerospace centre) scramjet experimental facility, [11–14], is presented in Fig. 1. Preheated air is expanded through a Laval nozzle and enters the combustor section at 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 10 cm 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 (H_2) is injected at Ma = 1.0 through a row of 15holes, 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 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. atT = 250 K and p =10^5Pa, whereas the air was injected at T = 340 K and p =10^5Pa. Combustion was initiated by pre-burning of a small amount of O_2 in a H_2 tube by a spark.

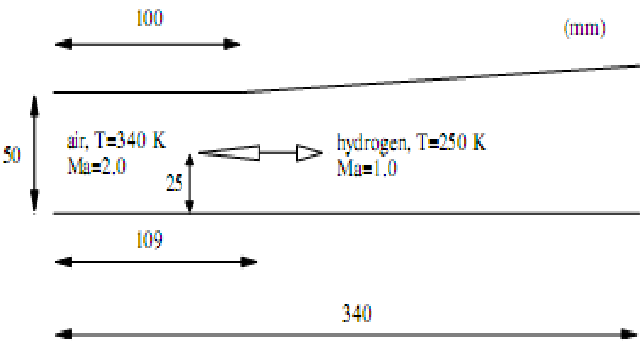


Figure 1 Schematic of the supersonic combustion chamber.

A. Gambit modelling of 3D Combustion Chamber and Strut Injector

In The computational configuration we are taking same DLR scramjet model so that we can validate our Result with Experimental Results but here we are using only 3 holes and gap between hole is 10mm this simplification is made to Reduce the Computational work and we are maintaining the same Experimental mass flow Rate of H_2.

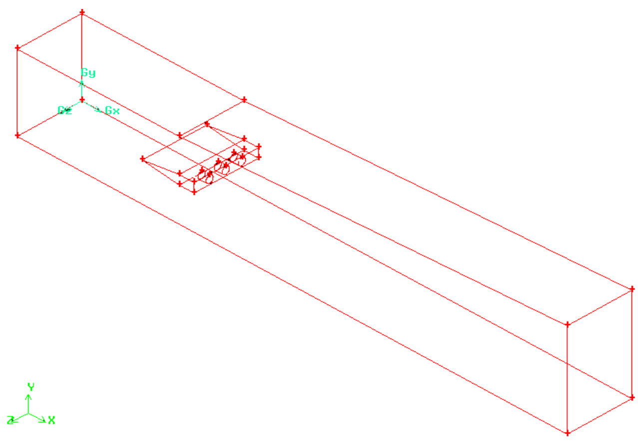


Figure- 2, 3D gambit modelling of DLR Scramjet Combustion Chamber and strut injector

B. 3D strut injector

A wedge-shaped strut is placed in the combustion chamber downstream of the nozzle. The height of the 32 mm long strut is 6 mm, it having 3 holes of 2.23mm diameter and gap between the holes is 10mm and mass flow rate of strut is 1.5 to 4.0g/s.

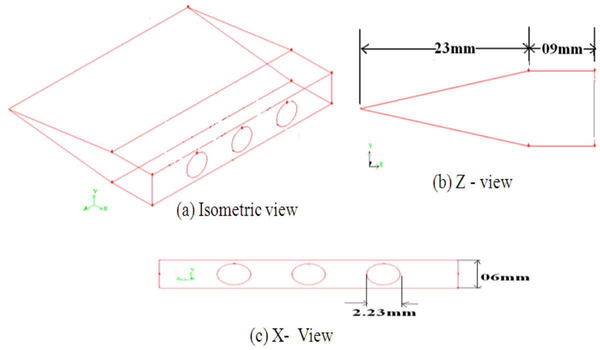


Figure- 3, 3D wedge shaped strut injector

V. 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.Accordingto 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. All computations are initialized with the state of the incoming air.

TABLE I. INflOW CONDITIONS OF THE AIR STREAM AND THE HYDROGEN JET.

Variables	Air	H_2
Ma	2.0	1.0
u (m/s)	730	1200
T (K)	340	250
P (Pa)	101325	101325
ρ (kg/m^3)	1.002	0.097
Y_{O_2}	0.232	0
Y_{N_2}	0.736	0
Y_{H_2O}	0.032	0
Y_{H_2}	0	1
Mass flow rate(kg/s)	1.5	0.0015 to 0.004

A. Approximations and Idealizations

- The flow is considered to be in steady state
- The gas is compressible, obeying the ideal gas laws.

VI. Results and Discussions

The results are validated qualitatively by using shadow graph pictures and numerically by comparing the temperature of the bottom wall with experimental data that are given below.

A. Cold flow analysis of DLR Scramjet model (without combustion)

In this section the cold flow 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 4 shows the grid after several adaptions and the computed density distribution.

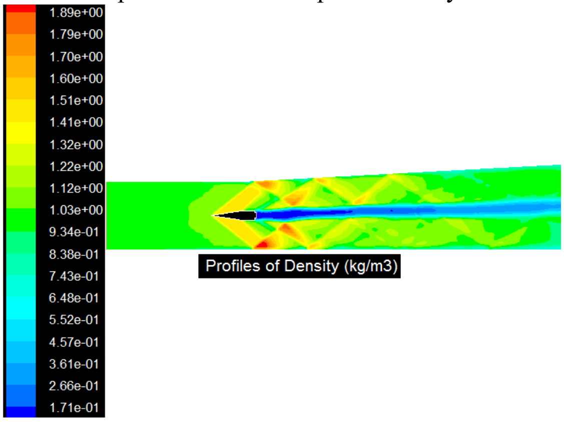
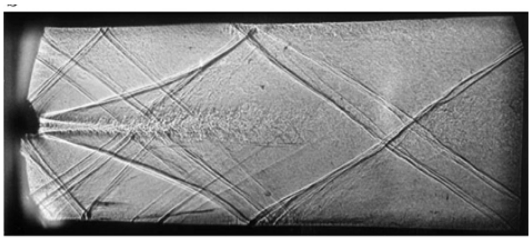
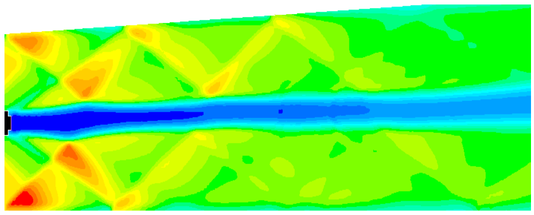


Figure 4 density distributions with cold flow.

Figure 5 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). 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 further with the unsteady, partly H_2 filled, wake. Together with the slightly bent expansion fan coming off the base of the wedge this causes a characteristic shock-wave pattern in the downstream region. At the upper and lower walls, the boundary layer is affected, at least locally, by the reflected oblique shocks. These local modifications involve thickening of the boundary layer, increased rms pressure fluctuations, and elevated wall temperatures. With the exception of the reflected shocks interacting with and further reflecting off the partly H_2 filled wake, these structures are similar to the ones found without H_2 injection, cf. [10, 11]. The boundary layer on the wedge surface separates at the base and a shear layer is formed. This shear layer is naturally unstable and is therefore prone to break-up and develops into Kelvin–Helmholtz (KH) structures. Because of the one-sided divergent channel the upper reflecting shock hits the H_2 filled wake further downstream than the lower shock, causing an asymmetric flow field through which the KH modes are amplified. It is important also to notice that compressibility leads to reduced shear layer growth, affecting the formation and subsequent break-up of large coherent structures. In addition, 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 and the subsequent shocks (reflecting off the walls) pass through the accelerating wake.



(a)



(b)

Figure 5 Cold flow simulation: (a) experimental shadowgraph; and (b) numerical shadowgraph

B. Pressure

1) Static pressure

Static pressure is the pressure that is exerted by a fluid. Specifically, it is the pressure measured when the fluid is still, or at rest. The below figure 6 reveals the fact that the gas gets compressed at the tip of the wedge wall. The value of static pressure at the wedge wall is 1.65e+05 Pa. but the entrance given static pressure is 1atm, the pressure is increased due to shock wave creation further, the pressure is increased at the bottom wall to 2.61e+ 05 it is due to reflection of shock waves and figure 7 is giving the details about static pressure variation in top and bottom walls, figure 8 gives overview of static pressure variation in the wedge wall and interior of the combustion chamber and figure 9 is giving the comparison of the results of CFD work with experimental work.

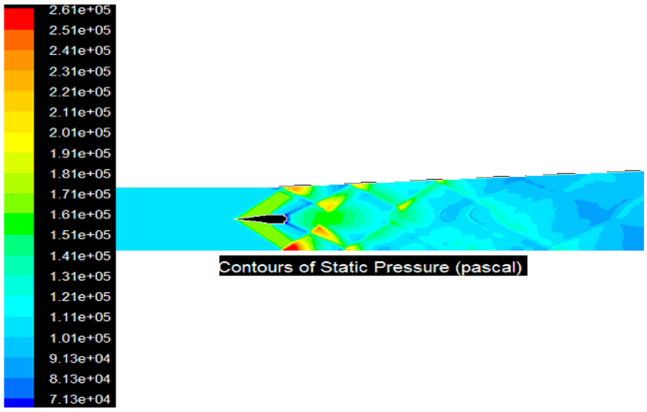


Figure 6 static Pressure variations

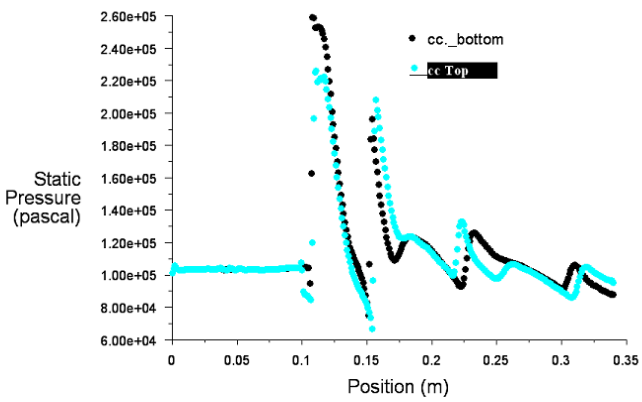


Figure 7 static pressure variations in top & bottom wall

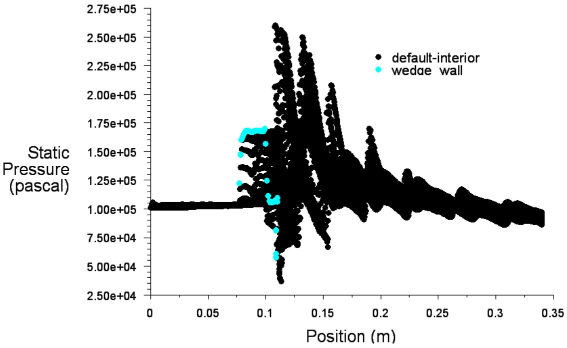


Figure 8 static pressure variations in interior and wedge wall

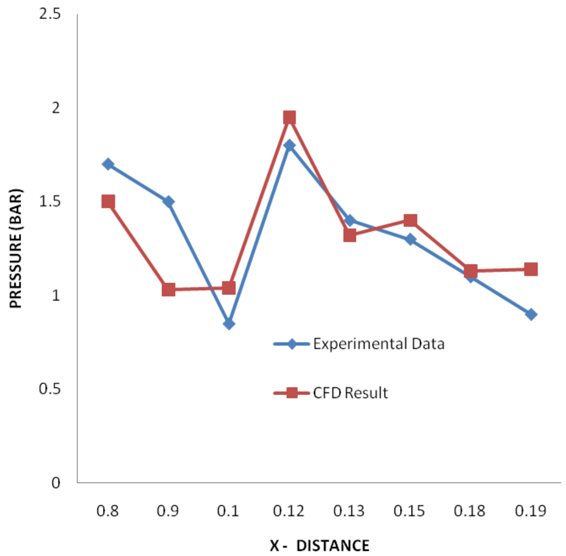


Figure 9 static pressure variations in bottom wall comparison with experimental data

2) *Total pressure*

Figure 10 is giving the details about total pressure variation, it is clear that total pressure is getting decreased gradually up to sudden level after that the variation is high due to shock wave creation.Figure11 shows the variation of total pressure in the top ad bottom side of the wall in the top wall total pressure loss is more compare to bottom wall it is because of the change in area at top side and figure 12 shows the pressure variation over wedge wall and interior.

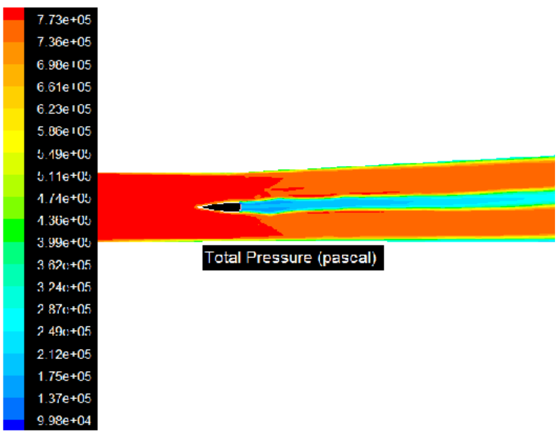


Figure 10 Total pressure variations

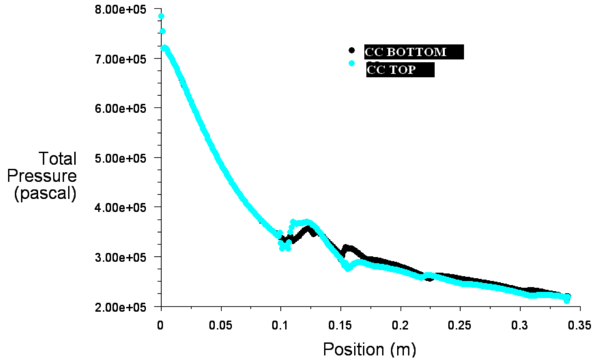


Figure 11 Total pressure variations in top & bottom wall

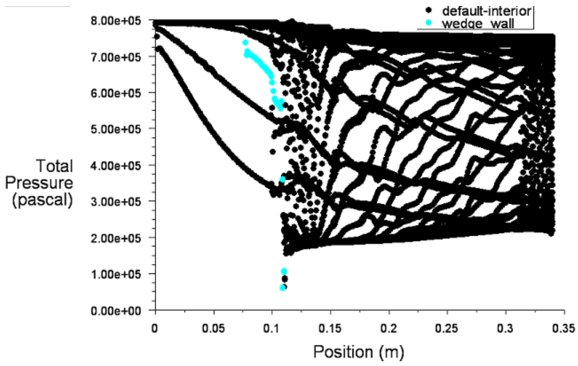


Figure 12 Total pressure variations in interior and wedge wall

C. *Temperature*

1) *Static Temperature*

The given inlet air temperature is 340k.Figure 13 shows that static temperature is varying little bit up to wedge after that variation is more due to creation of shock waves at the tip of the wedge, the temperature is around 400k. This variation is taking place up to sudden level after that the temperature is coming to normal inlet temperature. In the middle of the chamber hydrogen is injected at the temperature of 250k.Figure 14 shows the variation of static temperature at the top and bottom wall, it is clear from the graph the temperature at the bottom wall is more compare to top wall it is because of the changing of area at the top side, figure 15 giving the overview of the temperature variations over the wedge wall and interior of the chamber.

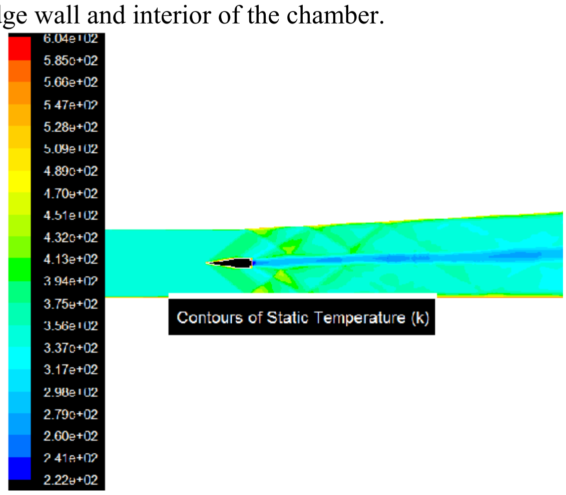


Figure 13 Static Temperature variations

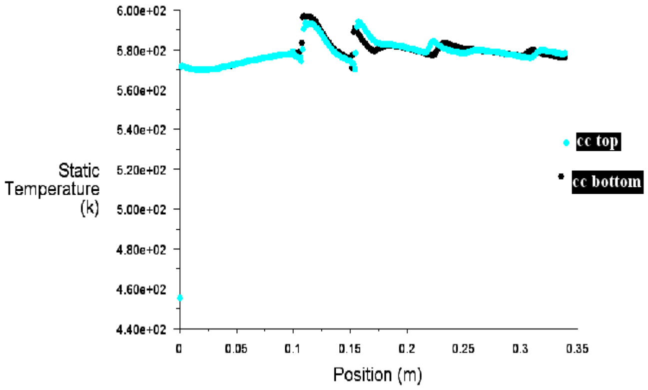


Figure 14 Static Temperature variations in top & bottom wall

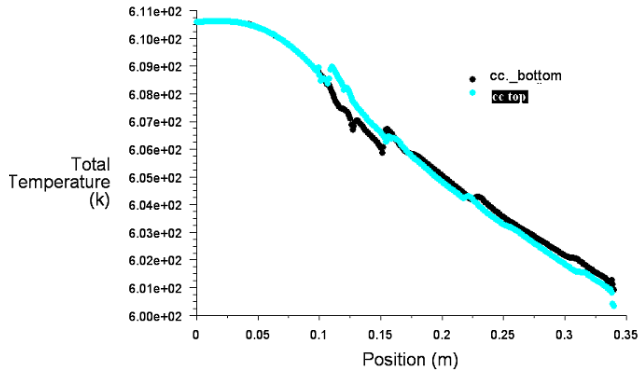


Figure 17 Total Temperature variations in top & bottom wall

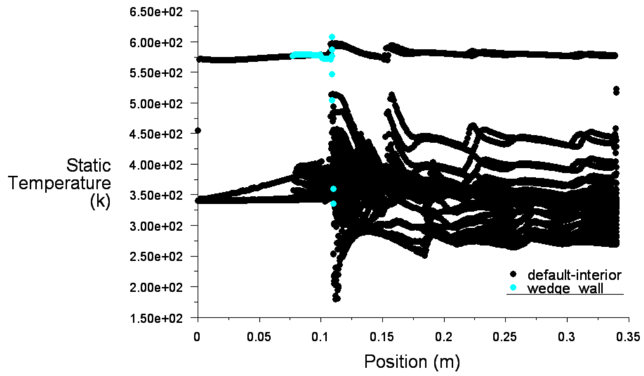


Figure 15 Static Temperature variations in interior and wedge wall

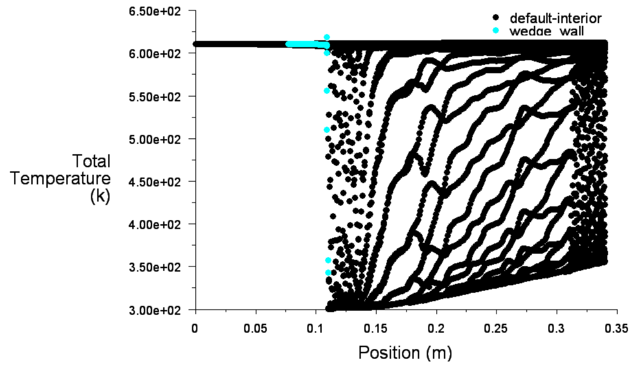


Figure 18 Total Temperature variations in interior and wedge wall

2) Total Temperature

Figure 16 shows about total temperature variation in inside the chamber, at the entrance the temperature is 609k but it is decreasing gradually up to 570k.In the middle of the chamber the hydrogen total temperature is varying from 301k to 412k, this variation is due to mixing, figure 17 shows variation of the total temperature at the top and bottom wall, the temperature is more at the top wall due to change in area of the chamber and figure 18 shows the variation of temperature at the interior and wedge wall.

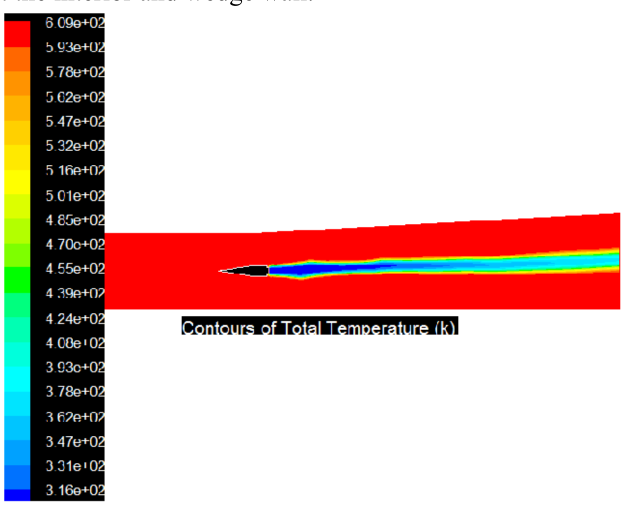


Figure 16 Total Temperature variations

D. Velocity

1) Mach number

Figure 19 shows variation of the Mach number at the different level, at the entrance the air Mach no is 2, at the base of the strut the hydrogen is injected at Mach no 1. In the middle of the chamber the Mach number values is reduced to below 1, it is due to interaction of different waves, this subsonic region act as a flame holder for combustion. The exit t Mach no is 2.17.

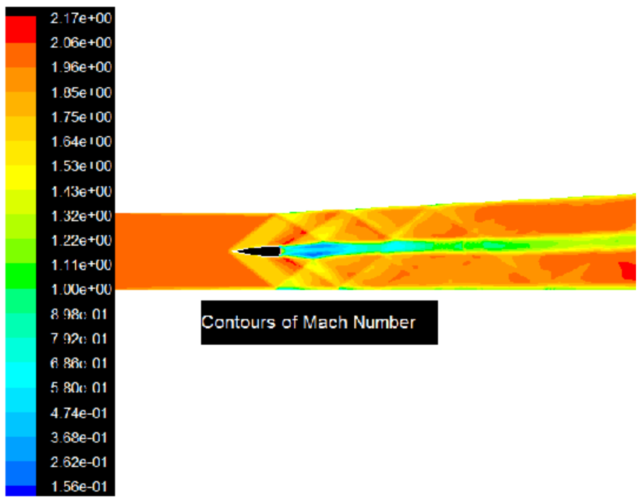


Figure 19 Mach number variations

VII. CONCLUSION

In the present work k-ε has been used to investigate mixing in a scramjet model under realistic operating conditions. The configuration used is similar to the laboratory scramjet engine developed and experimentally investigated at DLR in Germany. The scramjet engine consists of a rectangular, one-sided divergent channel with a wedge-shaped flame holder at the base of which hydrogen can be injected through an array of holes. In the computational model periodicity is imposed in the z direction (with a span encompassing three holes) to reduce the overall computational work. In the scramjet engine model a mixing-controlled turbulent diffusion flame is anchored in the wake of the wedge-like strut, thus acting as a flame holder, whereas combustion is initiated in the shear layers leaving the edges of the wedge. Qualitative and quantitative comparisons were made with experimental data for both shock wave generation and bottom wall temperature.

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Dr. K.M.Pandey did his PhD in Mechanical Engineering in 1994 from IIT Kanpur. He has published and presented 170 papers in International & National Conferences and Journals. Currently he is working as Professor of the Mechanical .Engineering Department, National Institute of Technology, Silchar, Assam, India..He also served the department in the capacity of head from July 07 to 13 July 2010. He has also worked as faculty consultant in Colombo Plan Staff College, Manila, Philippines as seconded faculty from Government of India. His research interest areas are the following; Combustion, High Speed Flows, Technical Education, Fuzzy Logic and Neural Networks , Heat Transfer, Internal Combustion Engines, Human Resource Management, Gas Dynamics and Numerical Simulations in CFD area from Commercial Software's. Email:kmpandey2001@yahoo.com.

T.Sivasakthivel doing his M.Tech – Thermal Engineering in NIT Silchar from 2009. He has also worked as a Graduate Apprentice in BHEL Trichy from 2008 to 2009. His research interests are CFD, Combustion and Gasification.
Email: sivasakthivel.t@gmailcom