Computational Analysis of Mixing in Strut Based Combustion at Air Inlet Mach number 2

K. M. Pandey, B. K. Azad, S. P. Sahu and M. Prajapati

***Abstract*—A computational analysis of mixing of hydrogen and air has been performed considering scramjet (supersonic combustion ramjet) combustor. Hydrogen is injected at M=1 through the rear of a simple strut located at a distance of 37.54 mm from inlet of combustor. The shape of the strut is chosen in a way to produce strong streamwise vorticity and thus to enhance the hydrogen/air mixing. Strength and size of the vortices are defined by the strut geometry and may be modified. The induced vortices cause an increase in entropy and larger losses in total pressure.**

***Index Terms*—shock waves, vorticity, skin friction drag, compressibility.**

I. Introduction

Due to the extremely short residence time of the air in supersonic combustors, an efficient (rapid and with small losses in total pressure) fuel/air mixing is hard to achieve. Nevertheless this is an important issue to keep the combustor length short and to reduce the skin friction drag. In supersonic flows a rapid fuel/air mixing additionally suffers from inherently low mixing rates due to compressibility effects at high convective Mach numbers. 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.

In some cases both types of injectors approach each other, e.g. if a ramp injector extends over most of the channel height. A good near field mixing can be achieved by wall injection. On the other hand transverse injection systems cause a significant blockage of the flow resulting in irreversibility's due to shock waves and thrust losses. Another concern is that the penetration of the fuel jet may be insufficient for real size combustors. Wall injectors have the advantage of being easy to manufacture, easy to cool, and, in case of staged injections, they cause no losses in total pressure if they are switched off. The last point is in contrast to ramp or strut injectors which may not be removed from the flow field if no hydrogen is injected. Moreover, the injected hydrogen usually acts as a coolant for the strut. This has to be kept in mind if the hydrogen mass flux is reduced. An alternative to physical ramp injectors are aeroramps which have a similar physical behaviour but lower pressure losses. Aeroramps are multi hole transverse injectors which induce pairs of counter-rotating vortices to improve mixing and fuel penetration.

If strut injectors are used, usually all or most of the fuel is injected in main flow direction. This is possible without the induction of strong shock waves. Moreover, additional momentum is added by parallel fuel injection increasing the engine thrust. This may become important at high flight Mach numbers (10–15). Due to the limited mixing capabilities of parallel high speed streams, techniques for mixing enhancement are required. This can be achieved either by the use of shock waves or by creation of streamwise vorticity. Streamwise vortices may be induced by favourable chosen strut geometry. In case of strut injectors hydrogen should be injected in such a way that a good mixing is achieved over a short length resulting in a homogeneous temperature distribution. Local temperature peaks have to be avoided as to keep dissociation losses and nitrogen oxides low. An important issue at low flight Mach numbers of a scramjet is autoignition. Due to relatively low air static temperatures this may become a problem for axial strut injectors which only induce weak shock waves and small recirculation zones downstream of the strut. Thus the advantage of avoiding normal shock waves (as in case of transverse injection) may cause problems for a stable ignition.

II. Literature Review

V. E. Terrapon et_al.[1] had given review on a flamelet-based model for supersonic combustion and they made the following observations:

i. A flamelet approach seems to be feasible to simulate high-speed flows, although many aspects are still to be evaluated.
ii. 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.

Rafiqul Hoque et_al.[2] worked on the effects of air

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stream mach on mixing in a supersonic combustor and they made the following observations:

i. The Mach number of air stream is varied as (3, 3.25, 3.5, 3.75 and 4) to investigate the mixing flow field. High penetration of hydrogen increases the mixing efficiency along the injector position. It is found that strong interaction is occurring between the main and injecting flows for high Mach number (M=4). High Mach number increases both the mixing efficiency and flame holding capability . So air stream in supersonic flow having Mach number 4 might act as a good flame holder and become efficient in mixing.

Anand Raj Hariharan et_al.[3]had done experiment on numerical analysis of supersonic combustion with clover nozzle and they made the following observations:

i. The Mach number variation along combustor axis have been studied. The result shows that overall trend of decreasing Mach number which is higher when Clover nozzle is used compared to conical nozzle . When combustor was run by conical nozzle the minimum Mach number was 1.09 and 1.12 respectively for hydrogen and kerosene fuel. The same values in the case of Clover nozzle was unity indicating that flow was thermally chocked.
ii. Static pressure tends to increase along combustor axis.

S.O'Byrne et_al.[4] had done experiment on Measurement and imaging of supersonic combustion in a model scramjet engine and they made the following observations:

i. It is possible to achieve supersonic combustion using a plane base strut injection technique at conditions simulating flight at two different Mach numbers**.**
ii. The calculation of the fraction of hydrogen consumed in the combustion at each of the conditions indicates that, for a given fuel-air equivalence ratio, a greater proportion of the fuel is consumed at the lower Mach number condition.
iii. Shadowgraph imaging and static pressure measurements, although simple techniques, have proved useful in examining the complex flowelds arising in the scramjet engine by highlighting the main features in the flow.

Yeong-Pei Tsai et_al.[5]had done experiment on Direct Numerical Simulation of Turbulent Hydrogen-Oxygen Reacting Flow and they made the following observations:

i. Build a 2D numerical code for solving the Navier-Stokes equations describing hypersonic flow which involves shock-induced finite-rate combustion of H2.
ii. According to section of 8.25D and 27.9D, the mass fraction date of different vary large of the same chemistry element could be different significantly.
iii. Form to H2O mass fraction date can shows H2O produce found in the present study were lower than the Evans et al.(1978) in the two reactions.
iv. Application of this technique to simulate physical problems such as scramjet, Ram accelerator, re-entry etc.

D. Davidenko1, et_al.[6] had fone experiment on Ignition and Combustion of Hydrogen and Methane in a Model Supersonic Combustion Chamber and they made the following observations:

i. New correlations have been proposed for the ignition of H2 and CH4-H2. A reduced kinetic mechanism for the CH4-H2 oxidation has been elaborated and integrated into a CFD code. This mechanism is accurate in comparison with its parent mechanism and provides a correct evaluation of the ignition delay in a large parameter domain. Simulations of supersonic combustion in a model combustion chamber have been conducted for the CH4-H2 fuel with the H2 mass fraction ranging from 1 to 0.2. Computational results are in a close agreement with available experimental data.

K. Sundararaj et_al.[7] had done experiment on Numerical Simulation of Staged Transverse Injection of H2 Fuel in a Ducted Supersonic Air Stream with SST k-w Turbulence Model and they made the following observations:

i. For the configuration of interest in this Study, grid sensitivity test was conducted on grids 99450 points, 276000 points and 589680 points. Since the differences in solutions on the two finer grids were small, the investigation was carried out with 276000 points. Numerical results were obtained for nominal operating conditions and the results are compared with the available experimental data. To assess the agreement between the predicted and experimental values the mean differences are calculated at different locations of the flow field.

Christopher J. Montgomery, et_al.[8] had done experiment supersonic combustion simulation using reduced chemical kinetic mechanism and isat and they made the following observations:

i. The reduced mechanisms have been implemented into the Vulcan CFD code and used for simulations of a supersonic jet flame. CFD simulations using reduced chemical kinetic mechanisms for hydrogen/air combustion show better agreement with detailed chemistry simulations and with experiments than existing models using the same number of species, indicating the importance of kinetic effects retained by the CARM-produced reduced mechanism

Zheng Chen et_al.[9] had done experiment on High temperature ignition and combustion enhancement by dimethyl ether addition to methane–air mixtures and they made the following observations:

i. In homogeneous ignition, small amounts of DME addition to methane lead to a significant decrease in ignition time. The effect is even more profound than that of hydrogen addition. This significant ignition enhancement is caused by the rapid build-up of CH3 and HO2 radicals when DME addition is present in the system. The resulting chain propagation reaction via CH3 and HO2 replaces the slow reactions via CH3 and O2 in the pure methane case and thus accelerates the ignition.
ii. In non-homogeneous ignition, it is found that the ignition enhancement is strongly affected by the stretch rate. There exist two ignition regimes: a kinetic limited regime and a transport limited regime. In the kinetic limited regime, small amounts of DME addition cause a dramatic decrease of ignition time. However, in the transport limited regime, ignition enhancement by DME addition is much less effective.

M.R. Gruber et_al.[10] had given review on fundamental studies of cavity-based flame holder concept for supersonic combustors and they made the following observation :

i. fuel injection, ignition, and flame holding present fundamental challenges to the design of a hydrocarbon-fueled supersonic combustion ramjet (scramjet) engine.
ii. To achieve efficient combustion within a manageable length, a successful fuel injection scheme must provide rapid mixing between the fuel and airstreams.
iii. At low flight Mach numbers, the benefits of high static pressure near the flameholder should be achievable.
iv. In the dual-mode scramjet, it is desirable to minimize the drag generated by the flameholding system because thrust margins are generally small.
v. For a fixed flameholder shape, increasing blockage, that is, drag, resulted in a decrease in residence time and an increase in exchange rate.
vi. Fuel-air mixing in an air breathing engine becomes increasingly inefficient at higher velocity, hence requiring a longer combustor length. Although this is caused by the reduced flow residence time inside the combustor and the compressibility effect that adversely affects the rate of mixing1¡3, a short combustor length is desirable because the thrust-to-drag ratio of an engine is roughly proportional to the ratio between the combustor diameter and length. To generate practically useful thrust to drag, length-to-diameter ratio of a combustor should be sufficiently small.
vii. Combustor wall cavities that are strategically placed can provide many potential benefits that include mixing improvement as well as stable flame holding.

J.P. Drummond et_al.[11] had given review on mixing enhancement in high speed reacting flows and they made the following observation:

i. The injector design also must produce rapid mixing and combustion of the fuel and air.
ii. Rapid mixing and combustion allow the combustor length and weight to be minimized, and they provide the heat release for conversion to thrust by the engine nozzle.
iii. At moderate flight Mach numbers, up to Mach 10, fuel injection may have a normal component into the flow from the inlet, but at higher Mach numbers, the injection must be nearly axial since the fuel momentum provides a significant portion of the engine thrust.
iv. A combination of transverse and streamwise injection, varied over the flight Mach number range, often has been utilized to control reaction and heat release in a scramjet combustor.
v. The injector cannot result in too severe a local flow disturbance, that could result in locally high wall static pressures and temperatures, leading to increased frictional losses and severe wall cooling requirements.
vi. Improved mixing has also been achieved using alternative wall injector designs. Wall injection using geometrical shapes that introduce axial vorticity into the flow field has been successful. Vorticity can be induced into the fuel stream using convoluted surfaces or small tabs at the exit of the fuel injector. Alternatively, vorticity can be introduced into the air - upstream of the injector using wedge shaped bodies placed on the combustor walls. Vorticity addition to the air stream provides more significant mixing enhancement of fuel and air.

N. Peters et_al.[12] had given review on laminar flamelet concepts in turbulent combustion and they made the following observation :

i. A characteristic property of compressible flows is the strong coupling between velocity, density, pressure, and temperature In contrast, the one-dimensional diffusion flamelets are calculated under the low Mach number assumption leading to a constant spatial pressure.

Michael Oevermann et_al. [13] had given review on numerical investigation of turbulent hydrogen combustion in a scramjet using flamelet modeling and they made the following observation:

i. There is critical aspect in using flamelet models for the computation of turbulent diffusion flames in compressible flows with discontinuities. If a shock wave crosses the flame front, the change in temperature over the shock wave and over the flame front can be of comp arable order of magnitude. That means, the basic condition of the flamelet model assuming the changes in temperature and mass-fractions profiles tangential to the flame front of lower order compared to changes normal to the flame front could be violated. In that case, one cannot expect universal one-dimensional flame structures anymore and the results from such a computation have to be interpreted with care.

ii. The particular interest of this study is the application of the presented finite volume scheme to the pre diction of the transport of hydrogen injected into a supersonic air stream.

iii. A further critical aspect in the simulation is the neglect of the non-slip condition on fixed walls leading to turbulent boundary layers. Whereas the influence of the boundary layers along the upper and lower channel walls on the flame in the center of the channel can be neglected, the introduction of a non-slip boundary condition and the surface of the wedge could have an important aspect on a more realistic simulation of the flow directly behind the wedge.

iv. Three-dimensional effects, which are not captured by the two-dimensional method, are certainly present and important in the investigated combustion chamber. These effects include corner-boundary layer interaction, the generation of three dimensional shock waves originates from the attachment of the wedge at the side-walls of the channel, and three dimensional mixing of the fuel with the air stream.

Kiran Hamilton Jeffrey Dellimore et_al.[14] given review on investigation of fuel-air mixing in a micro-flameholder for micro power and scramjet applications and they made the following observation :

i. Because of NOx emissions concerns and material limitations it is also desirable to operate scramjet and micro power devices at extremely lean equivalence ratios.

ii. In the case of supersonic combustion, the situation is further complicated by difficulties associated with holding a flame at supersonic speeds, which makes achieving stable and sustained combustion extremely difficult.

iii. Fuel-air mixing at the conventional-scale is an extremely complicated process which can be accomplished in many ways using a wide variety of technologies. One of the most common and extensively investigated means of achieving mixing is via the transverse injection of a fuel jet into a crossflow of air (usually air). In this approach, mixing is achieved by the shearing and subsequent breakup of the jet as it penetrates into the crossflow; however, the physics governing this process is extremely complex and is still being actively researched. In general, due to the relatively large characteristic dimensions associated with conventional-scale devices mixing at the conventional-scale invariably occurs at high Reynolds numbers (>10000) where the flow is inertially-dominated.

W. F. O'Brien et_al.[15] had given review on An Integrated Aerodynamic-Ramp-Injector/ Plasma-Torch-Igniter for Supersonic Combustion Applications with Hydrocarbon Fuels and they made the following observation :

i. Supersonic combustion with hydrocarbon fuels is a challenge, mainly because of the longer ignition delay and auto-ignition temperatures compared to hydrogen, which has been studied more extensively.

ii. To produce positive thrust, the mixing of fuel in the combustor of a scramjet, must take place in as short a distance as possible. With superior mixing enhancement, the length of the mixing chamber in a supersonic combustor can be minimized.

iii. If the combustion efficiency of the combustor is increased by enhancing the mixing characteristics of the injection system, then the total thrust produced by the scramjet will also increase.

Matthew J. Gaston et_al.[16] had given review on A Comparison Of Two Hypermixing Fuel Injectors In A Supersonic Combustor and they made the following observation :

i. The SCER (swept compression-expansion ramp) should produce a pair of large and very strong counter-rotating streamwise vortices energised by the pressure difference between the faces of the compression and expansion ramps.

ii. The pressure differences must therefore arise from differences in mixing efficiency between the two injector geometries.

iii. Combustion and attendant heat release and pressure rise occurred in flows in which hydrogen fuel was injected into an incoming air flow.

iv. For the same injector base geometry, greater mixing was obtained by increasing the number of fuel exhaust nozzles. This is one manifestation of the well known phenomenon that increasing the surface area of the fuel/air interface, increases the mixing rate.

v. It seems that any flow effect generated by an injector geometry needs to be either very strong or very close to the fuel-air interface to have an effect on the mixing due to the short residence times of these flow effects.

Zhaoyuan Han et_al.[17] had given review on An experimental investigation of the influence of streamwise vortex on flame propagation in a supersonic air-hydrocarbon fuel mixture and they made the following observation :

i. The influence of streamwise vortex on the flame propagation in the supersonic, combustible mixed gas of air-gasoline is remarkable. The reason would be that the supersonic air-gasoline mixture was disturbed by the streamwise vortex and the interaction between streamwise vor tex and waves in the supersonic flow. Such disturbances make the turbulence levels in the supersonic mixed gas flow enhance and then result in the propagation speed of turbulent flame further increase.

Xing Jianwen et_al.[18] had given review on Application Of Flamelet Model For The Numerical Simulation Of Turbulent Combustion In Scramjet and they made the following observation:

i. Interaction of turbulence and combustion increase the combustion zone nearby the jet, weak the intensity of combustion close-by the jet.
ii. The zone where the interaction of turbulence and combustion is acute mostly locate nearby the jet.

In-Seuck Jeung et_al.[19] had given review on Numerical Simulation of Supersonic Combustion for Hypersonic Propulsion and they made the following observation:

i. Strong unsteady flow characteristics were identified for a scramjet combustor. The work appears to be the first of its kind in the numerical study of combustion oscillations in a supersonic combustor.
ii. When the combustion takes place throughout the entire chamber, an unstable Mach reflection is formed above the injector and the pressure builds high enough for propulsion applications.

III. METHODOLOGY

Mathematical modeling is usually central to the analysis of engineering systems, which are often very complicated. For a typical fluids system, this complexity arises mainly due to the time dependent, multidimensional nature of the fluid flow and the complex supplementary conditions that govern these systems. In addition, the non-linearity of the flow equations makes the analysis all the more complicated. Consequently, a real system is often simplified to a computational model resembling the original in shape, geometry and other physical characteristics in the gross features, but not in every detail. Thus, by the application of fundamental physical laws, and by incorporating approximations and idealizations, a mathematical model is generally amenable to numerical simulations, which hopefully without involving exorbitant time and effort in computation gives an adequate picture of the physics of the system.

Physical model

This model is considered as one of the geometry of strut based combustor. Dimensions of combuster and strut is indicated in the below figure. Also inlet condition of air and hydrogen is depicted in the figure

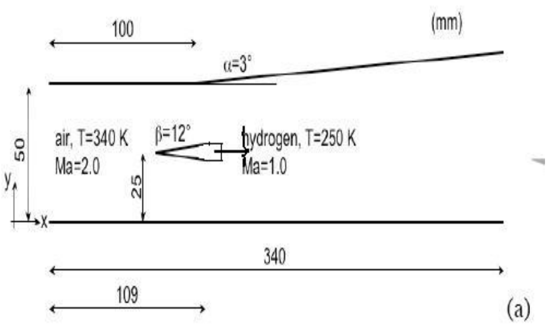

Fig.1 Physical model of Strut based combustor

Approximations and Idealizations

The physical model described in the preceding section is a simplified model, with respect to the surface geometry, when compared with typical components actually encountered in applications. The further approximations and idealizations made for the present investigations are as follows:

- The fluid is Oxygen and Hydrogen.
- The flow is assumed to be two-dimensional.
- The flow is belongs to k-epsilon model.

Mathematical Model

A mathematical model comprises equations relating the dependent and the independent variables and the relevant parameters that describe some physical phenomenon. Typically, a mathematical model consists of differential equations that govern the behavior of the physical system, and the associated boundary conditions.

Employing the approximations and the idealizations listed in section 3.3, the physical model described in section 3.2 is simulated by an equivalent mathematical model involving the conservation of mass, momentum, with appropriate boundary conditions. The mathematical model comprising the partial differential equations, along with their boundary conditions is presented in the following subsection.

Governing Equations

The unsteady, conservative and dimensionless forms of the Navier-Stokes equations in two dimensions for the incompressible flow of a constant viscosity fluid are as follows:

Continuity

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0$$

X- Momentum

$$\frac{\partial U}{\partial \tau}+\frac{\partial (UU)}{\partial X}+\frac{\partial (VU)}{\partial Y}=-\frac{\partial P_n}{\partial X}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)$$

Y-momentum

$$\frac{\partial V}{\partial \tau}+\frac{\partial (UV)}{\partial X}+\frac{\partial (VV)}{\partial Y}=-\frac{\partial P_n}{\partial Y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)$$

With

$$U=\frac{u}{u_\infty},V=\frac{v}{u_\infty},\tau=\frac{tu_\infty}{D},X=\frac{x}{D},Y=\frac{y}{D},P_n=\frac{p}{\rho u_\infty{}^2}$$

where u_∞ is the constant inlet velocity. Note that all velocities are non- dimensionalised by u_∞ and v_∞, respectively.

IV. RESULTS AND DISCUSSIONS

Inlet conditions are the followings.

For air, the inlet conditions are taken as the following :
Pressure- 1 atm
Temperature- 340 K
Mach number- 2

For hydrogen the inlet conditions are taken as the following:
Presuure-1 atm
Temperature-250 K
Mach number-1

Static Pressure **-**The static pressure at the inlets are $1 x 10^5$ Pascal. It remains constant till the initial vertex of the strut. After that due to shock waves the pressure increases and it becomes maximum at the wall at a position where shock waves are reflected.

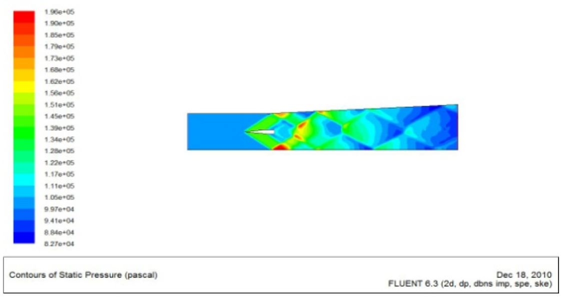

Fig.2 Static Pressure Contour

Total Pressure:-The total pressure is constant in maximum area and is equal to the inlet total pressure, but in the direction of flow of hydrogen it is equal to the total pressure of hydrogen at the inlet.

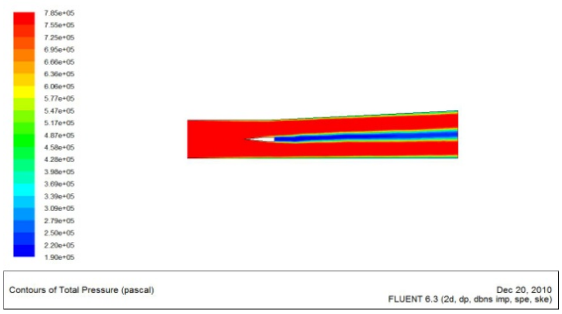

Fig.3 Total Pressure Contour

Static Temperature: - The static temperature over the walls remains as 300K and varies to 450K and the change is shown in the above figure. The static temperature of the fluid changes as it comes near the wall.

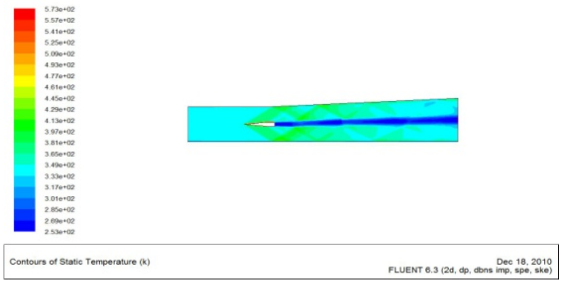

Fig.4 Static Temperature Contour

Turbulent kinetic energy:-In the inlet conditions turbulent kinetic energy is around 52 m^2/s^2. In the direction of flow of hydrogen, it changes from 52 to 2930m^2/s^2.

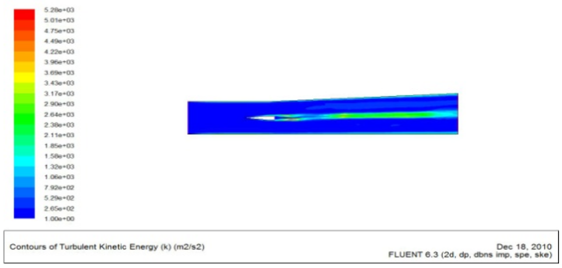

Fig.5 Turbulent kinetic energy Contour

Mach number: The Air enters at Mach number 2 and hydrogen is injected at Mach number 1. The direction of flow of hydrogen is subsonic region because of shocks and this act as a flame holder.

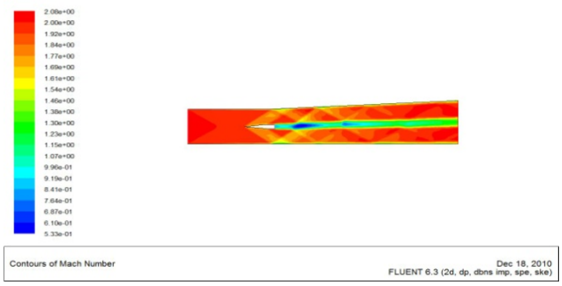

Fig.6 Mach number Contour

Density: Oblique shocks are produced due to the collision of the fluid particles to the strut and deflecting into itself. Across the shock wave, density increases. Density is maximum at the wall and is equal to approx 1.8 kg/m^3.

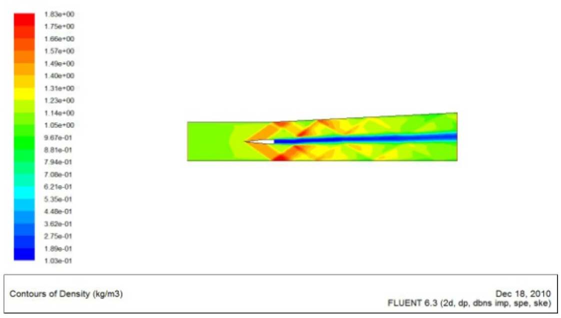

Fig.7 Density Contour

Molecular viscosity: Molecular viscosity is the viscosity due to the random motion and interaction of molecules. At outlet randomness is more, so molecular viscosity is maximum at outlet. Maximum molecular viscosity is 1.5X 10^5 kg/m-s

Fig.8 Molecular viscosity Contour

Specific heat (C_p): Specific heat is maximum at the fuel inlet point and decreases along the flow of fuel. Its maximum value is approx 1.37x10^4 j/kg-k.

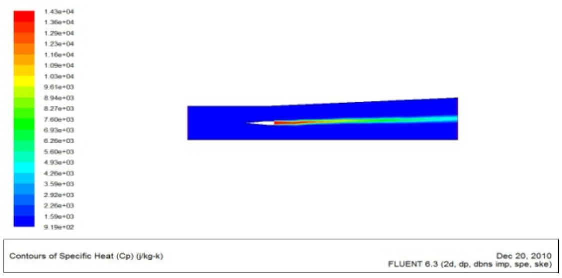

Fig.9 specific heat contour

Thermal conductivity: Thermal conductivity is maximum at the fuel inlet point and decreases along the flow of fuel. Its maximum value is approx 0.161w/m-k.

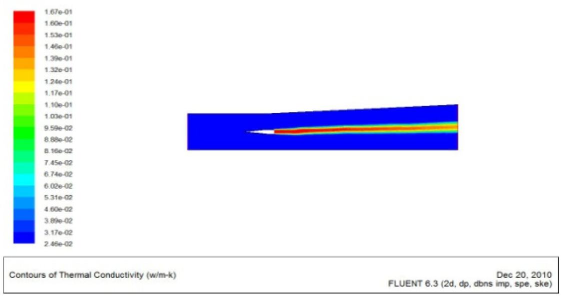

Fig.10 Thermal conductivity contour

V. Conclusion

In the present boundary conditions, oblique shocks are produced. These oblique shocks are produced due to the collision of the fluid particles to the strut and deflecting into itself. Across the shock wave, the Mach number decreases, and the static pressure, density, and static temperature increases. These shocks are weak since reflection is regular. Due to these shocks middle region is subsonic, so this is responsible for flame holding in case of combustion.

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