OPTIMIZATION OF SCRAMJET COMBUSTOR WITH NORMAL AND TANGENTIAL FUEL INJECTION

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Abstract- Supersonic combustion ramjets, or scramjets, are expected to allow the economical launch of satellites into low Earth orbit, cut travel times between major cities to a matter of hours, and provide propulsion for high-speed missile applications. Scramjets offer significant performance benefits over other propulsion technologies for atmospheric flight at hypersonic speeds, as a result of their ability to extract the oxygen required for combustion from the atmosphere. However, the large amount of viscous drag present at hypersonic speeds remains one of the major obstacles to the successful development of operational scramjet engines. Depending on the vehicle configuration, the viscous drag can account for up to 40% of the overall drag of a scramjet-powered vehicle. A large component of the total viscous drag can be attributed to supersonic combustors, as a result of the increased density of the flow in this region.

One of the most promising methods of viscous drag reduction is the tangential slot injection of a fluid along a surface. A tangential slot injection system is simple to construct, adds thrust to the engine, energizes the boundary layer to prevent separation and reduces heating.

The analysis of various modes of injection is done through considering the temperature, velocity, density and pressure variations. Further the optimization of the injectors design is made. the cross section geometry is changed and are analyzed for the changes in temperature, pressure and velocity, and hence found that the combination of injection of tangential and normal injection technique offer higher flow rate with a reduced viscous drag along the chamber walls. The injector geometry optimization results that an injector with 12mm cross section could deliver high temperature delivery at the chamber outlet along with the high velocity flow and much less pressure drop.

INTRODUCTION

There has always been a need for air-breathing aerospace vehicles to travel higher and faster. Whether it is for more reasonable access to orbit, or for defence applications, the need for engines that are capable of propelling an aircraft to hypersonic speeds is clear. Traditional turbojets, in the extreme case, can operate from zero velocity up to around Mach 3. At this point the compressor starts to do more harm than good because of bending stress, rotational stress, structural vibration and fatigue. By removing the compressor, and thus the need for a turbine, a ramjet engine is created. Ramjets can operate in the range from Mach 3 or 4 to about M=5. At Mach 5, decelerating the flow to subsonic speeds for combustion becomes unreasonable due to the excessive temperatures and thus dissociation of fuel rather than combustion. This illustrates the need for a supersonic combustion ramjet, also known as a scramjet.

In the 1950s and 1960s a variety of experimental scramjet engines were built and ground tested in the US and the UK. . In 1964, Dr. Frederick S. Billig and Dr. Gordon L. Dugger submitted a patent application for a supersonic combustion ramjet based on Billig's Ph.D. thesis. This patent was issued in 1981 following the removal of an order of secrecy. In 1981 tests were made in Australia under the guidance of Professor Ray Stalker in the T3 ground test facility at ANU. First successful flight test of Scramjet was performed by Russia in 1991.

Rather than mixing and combusting fuel at subsonic speeds, the incoming air is allowed to remain supersonic. The task of mixing and combusting supersonically is a daunting one and the simulation of this process can be equally as difficult.

So performance of supersonic combustor depending on efficient fuel injection and complete burning. There are three type of fuel injection in the combustor,

- Parallel injection
- Angled injection
- Transverse injection

In this project, we use the combination of normal injection and tangential injection for increasing the thrust and also for reducing the viscous drag.

MOTIVATION OF WORK

Supersonic combustion ramjets, or scramjets, are expected to allow the economical launch of satellites into low Earth orbit, cut travel times between major cities to a matter of hours, and provide propulsion for high-speed missile applications. Scramjets offer significant performance benefits over other propulsion technologies for atmospheric flight at hypersonic speeds, as a result of their ability to extract the oxygen required for combustion from the atmosphere. However, the large amount of viscous drag present at hypersonic speeds remains one of the major obstacles to the successful development of operational scramjet engines. Depending on the vehicle configuration, the viscous drag can account for up to 40% of the overall drag of a scramjet-powered vehicle. A large component of the total viscous drag can be attributed to supersonic combustors, as a result of the increased density of the flow in this region.

One of the most promising methods of viscous drag reduction is the tangential slot injection of a fluid along a surface. A tangential slot injection system is simple to construct, adds thrust to the engine, energizes the boundary layer to prevent separation and reduces heating.

INTRODUCTION TO PROJECT

A study has been made to analyze combined injection method in the combustion chamber of the scramjet engine. There are other techniques that are used to increase the thrust , the principle used is to increase the mixture ratio. The flow of mixture in the chamber cause the generation of the viscous drag . the reduction of which reduce the thrust . Hence the combined injection method of tangential and normal injection is used to reduce the drag as well increase the thrust.

PROBLEM

Scramjets offer significant performance benefits over other propulsion technologies for atmospheric flight at hypersonic speeds, as a result of their ability to extract the oxygen required for combustion from the atmosphere. One of the major obstacles to the successful development of operational scramjet engines is the viscous drag present at hypersonic speeds. Depending on the vehicle configuration, the viscous drag can account for up to 40% of the overall drag of a scramjet-powered vehicle. A large component of the total viscous drag can be attributed to supersonic combustors, as a result of the increased density of the flow in this region.

One of the most promising methods of viscous drag reduction is the tangential slot injection of a fluid along a surface. A tangential slot injection system is simple to construct, adds thrust to the engine, energizes the boundary layer to prevent separation and reduces heating.

The aim of this project is to investigate the performance of a scramjet combustor fueled by tangential and normal injection, with the aim of reducing viscous drag while maintaining efficient combustion.

OBJECTIVE OF THE WORK

- To investigate the injection methods in scramjet combustor.
- To investigate the scramjet efficiency reducing parameter.
- To investigate a method to reduce the boundary layer formation.
- To investigate a method to increase the combustion efficiency in scramjet.
- To increase exit temperature and velocity by optimizing the injector cross section.
- To find the limitations and the further enhancements.

DEVELOPMENT OFSCRAMJET ENGINE

During the later half of the nineteenth century the first ideas concerning ram propulsion were developed by the Swedish engineer Gustaf De Laval. Naturally, it had nothing to do with flight at the time, since the first working plane did not fly before 1903. As soon as five year after the legendary Wright brothers flight the first concept of a ramjet engine was patented in France. Nevertheless it looks until 1949 before the technology could be implemented, even this time in France. At the time the research vehicle known as the Leduc Experimental Aircrafts, the world first aircraft with ramjet propulsion and named after inventors Rene Leduc was flown. In these days, shortly after the Second World War, large effort was put into exploring jet and rocket driven aircraft.

In the late 1950s, the first efforts to develop and demonstrate scramjet engines took place with Air Force, Navy and NASA laboratory experiments, which provided a foundation for the many development programs that followed.

The most influential program in modern scramjet development was National Aero-Space Plane (NASP) program, which was established in 1986 to develop and fly a synergistically integrated low speed accelerator, ramjet and scramjet propulsion system. Designed to operate on hydrogen fuel, the X-30, was developed intensively over the years of the NASP program.

A scramjet propulsion system is a hypersonic air-breathing engine in which heat addition, due to combustion of fuel and air, occurs in the flow that is supersonic relative to the engine. In a conventional ramjet, engine the incoming supersonic airflow is decelerated to subsonic speeds by means of a multi-shock intake system and diffusion process. Fuel is added to the subsonic airflow, the mixture combusts and then re-accelerates through a mechanical choke to supersonic speeds. By contrast, the airflow in a pure scramjet remains supersonic throughout the combustion process and does not require a choking mechanism.

The scramjet is composed of three basic components: a converging inlet, where incoming air is compressed and decelerated; a combustor, where gaseous fuel is burned with atmospheric oxygen to produce heat; and a diverging nozzle, where the heated air is accelerated to produce thrust. Unlike a typical jet engine, such as a turbojet or turbofan engine, a scramjet does not use rotating, fan-like components to compress the air; rather, the achievable speed of the aircraft moving through the atmosphere causes the air to compress within the inlet. As such, no moving parts are needed in a scramjet. In comparison, typical turbojet engines require inlet fans, multiple stages of rotating compressor fans, and multiple rotating turbine stages, all of which add weight, complexity, and a greater number of failure points to the engine.

BASIC PRINCIPLES OF SCRAMJETENGINE

Ramjets have a couple of important limits. One is that they don't work until the engine is moving at high speeds, so you need a way to get the plane moving at Mach speeds in the first place. The other problem is that as you approach speeds of Mach 6 or so, the air flowing into the inlet is moving so quickly that it creates a supersonic shock wave as it is compressed inside the engine. At best, the shock wave stops the ignition of the air-and-fuel mixture in the combustion, shutting the engine down. At worst, pressure and heat from the shock wave tear the engine to bits.

The solution is a supersonic combustion engine or scramjet. In scramjets, the engine inlet is designed so it doesn't create as much compression as in a ramjet, allowing the air to zip through the engine at supersonic speeds. This reduces shockwave problem, somewhat. Even so, when fuel is injected into the onrushing air, small shock waves are created, so the combustion chamber must be able to withstand the pressure. And at supersonic speeds, fuel injection and combustion have to be accomplished in mere milliseconds.

The scramjet engine occupies the entire lower surface of the vehicle body. Scramjet propulsion system consists of five major engine and two vehicle components: internal inlet, isolator, combustor, internal nozzle and the fuel supply subsystem. The vehicle forebody is an essential part of the air induction system while the vehicle aftbody is a critical part of the nozzle component.

The primary purpose of the high-speed air induction system, comprised of the vehicle forebody and internal inlet, is to capture and compress air for processing by the remaining components of the engine. In a conventional jet engine, the inlet works in combination with the mechanical compressor to provide the necessary high pressure for the entire engine. The forebody provides the initial external compression and contributes to the drag and moments of the vehicle. The internal inlet compression provides the final compression of the propulsion cycle. The forebody along with the internal inlet is designed to provide the required mass capture and aerodynamic contraction ratio at maximum inlet efficiency. The air in the captured stream tube undergoes a reduction in Mach number with an attendant increase in pressure and temperature as it passes through the system of shock waves in the forebody and internal inlet

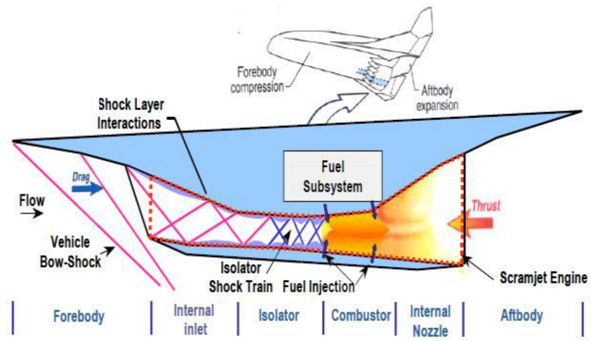


Fig.1: Scramjet Engine Operation

SCRAMJET FUEL INJECTORS

There are multiple ways of injecting fuel into a scramjet all of which have their advantages and disadvantages. Some injector types will be discussed in detail, along with their uses, advantages, disadvantages and integration problems that exist at present. Within each injector type chapter, the basic injection types will be covered before some more advanced and complicated approaches will be discussed. The broad injection categories that will be covered are wall injection, strut or in-stream injection, and finally hypermixers

WALL INJECTORS

Wall injectors in their simplest form are exactly as they sound, they are holes in the wall of the combustion chamber which jet fuel into the flow to create mixing. They are extremely effective at reducing the drag of the scramjet because there are no protruding objects in the path of the flow. While the wall jets break up the boundary layer in the flow slightly, compared to other injection methods, no major increase in total pressure is experienced. The flow surrounding these jets is however quite complex and includes break–up of the boundary layer, recirculation zones upstream of the jet caused by the separation of the boundary layer and the resulting shock that forms. The mixing of the jet into the flow to get good fuel/air mixing is quite complex and its boundary normally builds just under the shock formed. The significant disadvantage of wall injectors is the low amount of mixing penetration that occurs due to injection being from one side of the flow and the lack of vortices and turbulence to mix the fuel and air. This results in 'low exploitation of the air and a high thermal load of the combustor walls'. Wall jets also allow only a small Mach range due to the conditions required to maintain ignition within shock and recirculation structures. A scramjet with wall jets alone would therefore need to be carefully designed for one Mach number placing injectors in perfect locations for ignition based on predicted flow conditions in a particular location allowing ignition of the fuel.

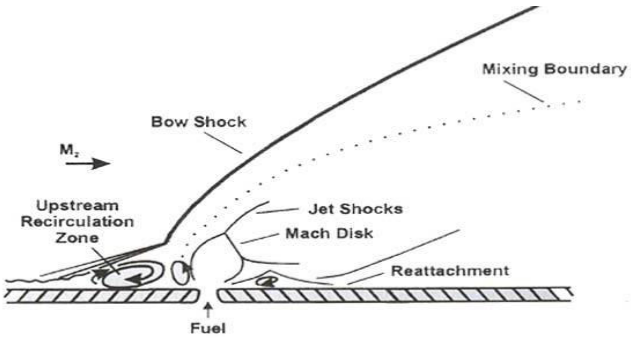


Fig.2: Wall Injector Flow Characteristics

TANGENTIAL INJECTORS

Tangential injection involves the angling of wall injectors completely to 90 degrees, making the fuel flow parallel to the air flow. This method comes originally from a method of de-icing airplane wings and induces the lowest possible drag. The mixing of this is however significantly lower than other types of injectors. An example of tangential injection methods is in Figure. Tangential Fuel Injection; take note that the height of the slot is very small compared with the height of the chamber.

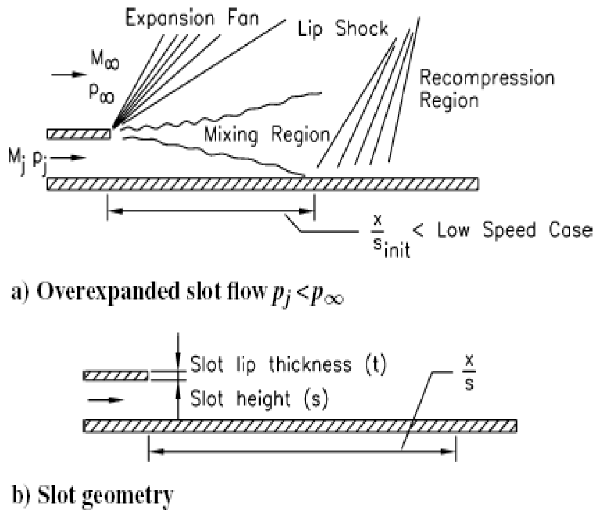


Fig.3: Tangential Fuel Injection

STRUT INJECTOR

Strut injection is extremely effective at mixing the fuel and air and creating effective burning due to the fuel being injected high in the flow and allowing full 3-Dimensional expansion mixing. The struts also produce large amounts of vortices in the flow enhancing the mixing. While struts have large advantages, they also have significantly large disadvantages in the great drag that the produce due to the physical obstructions to the flow. It is quite difficult to overcome this drag with the advantages of the mixing. The shock structures of the struts can also only be optimized for one Mach number so they have trouble operating across any range of Mach number. Due to the flow velocities, the recirculation and the burning that occurs near the struts, the temperatures reached in the struts is also very high causing difficulties in finding materials that withstand the conditions

COMBINED TANGENTIAL AND NORMAL INJECTOR

We put forward and tested the idea of a combined tangential and normal injection system and also used it to test the effectiveness of each of these independent methods by running a test scramjet with differing amounts of fuel injected from each of these inlets. The test section is shown in Figure: Design of Combined Tangential and Normal Injection Test. In these tests it was found that 100% normal injection produced the best performance results judge by increase of specific impulse. The normal injection disrupted the flow of the tangential injection causing an increase in drag as opposed to the decrease expected by the increased tangential injection. It is proposed that if there was a different arrangement of the normal and tangential injectors then it is quite possible that the extra tangential injection will provided a decrease in drag and hence an increase in performance. However, in this close arrangement, no benefit is found by using combined injection

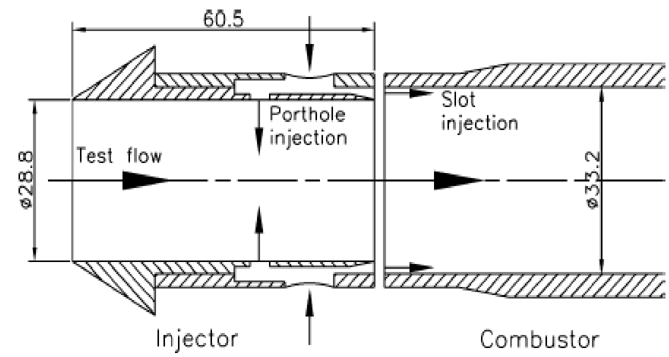


Fig.4:Combined Tangential and Normal Injection Test Section

HYPERMIXERS

Hypermixers were designed to be a trade off between wall injectors and strut injectors. Larger surface area on the ramp to the injector allows for easier cooling processes. The corners and top edge of the hypermixer ramp create large amounts of vortices and the encourage mixing. Examples of swept and unswept hypermixers are in Figure

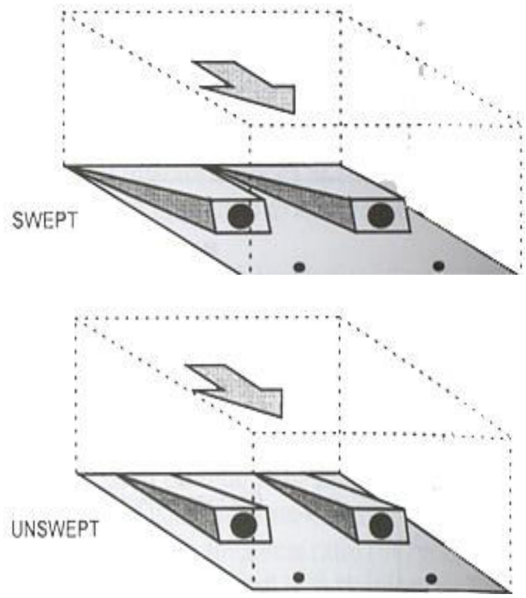


Fig.5: Two types of hypermixers

METHODOLOGY

Supersonic combustion inherently involves difficulties not present in other combustion systems. The high flow velocities in the combustor, which can reach several thousand meters per second, cause extremely low fuel residence times. Therefore, there is a requirement for a fuel injection/ignition system with enhanced performance characteristics. Fuel-air mixing, flame holding, pressure losses and thermal loading must all be considered for the successful design of a supersonic combustion ramjet (scramjet) engine. A practical system must induce rapid mixing while minimizing total pressure losses, without adverse effects to the flame holding capability or thermal/structural integrity of the device. Numerous techniques for injection into supersonic flows have been developed and tested over the years, such as swept, normal, tangential, struts, transverse injection.

Mathematical analysis of such system is complex and hence the generally applied method is to generalizing the system to a model and analyzing it under the system working environments. Here, a real system is simplified to a computational model that resembles the original problem but not in its full detail. Certain approximations and idealizations are also considered along with the fundamental laws of physics to yield a numerical result that sheds a light to the actual physics of the system. Computational Fluid Dynamics (CFD) provides an excellent tool for analyzing and understanding complex flow behavior, typically encountered in the supersonic flow regime. Studies on average focus either on the whole combustor, or on injection, from individual jets or multiple arrays, with grids that reflect where the attention is focused. These studies provide either too coarse a grid to correctly predict the plume's mixing profile or too fine a grid to predict the overall combustor behavior in reasonable computational times.

GOVERNING EQUATIONS

Spray combustion in liquid fuels in the combustors is governed by the principles of conservation of mass, momentum and energy. Dispersed liquid elements in the spray system interact collectively with the hot gas and ultimately combust to liberate heat. This process can be expressed in physical concepts and mathematical formulation of two-phase flow, leading to the establishment of the basis of modelling the key process. The fundamental equations that describe fluid flow behaviour are the Navier-Stokes 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 shockwave, as well as the physical characteristics of the shock layer, can be precisely determined. Neglecting the presence of body forces and volumetric heating,

Continuity equation, (1)

$$\frac{\partial \rho}{\partial t} + \left[\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z}\right] = 0$$

Momentum equation,

X-momentum, (2)

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

Y-momentum, (3)

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

Energy equation, (4)

$$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho u E}{\partial x} + \frac{\partial \rho v E}{\partial y} + \frac{\partial \rho w E}{\partial z} = \frac{\partial\left(u\sigma_{xx} + v\tau_{xy} + w\tau_{xz}\right)}{\partial x} + \frac{\partial\left(u\tau_{xy} + v\sigma_{yy} + w\tau_{zy}\right)}{\partial y} + \frac{\partial\left(u\tau_{xz} + v\tau_{yz} + w\sigma_{zz}\right)}{\partial z} + \frac{\partial\left(k\frac{\partial T}{\partial x}\right)}{\partial x} + \frac{\partial\left(k\frac{\partial T}{\partial y}\right)}{\partial y} + \frac{\partial\left(k\frac{\partial T}{\partial z}\right)}{\partial z}$$

u- velocity component in x direction
v- velocity component in y direction
w- velocity component in z direction
p- static pressure

For numerical modelling of multiphase flows existing in the flow field, the above equations are slightly modified to adjust the effect of the liquid-vapour mixture.

LIMITATIONS

A number of obstacles that hinder the understanding of the flow processes occurring within the scramjet. The most evident of these is the short residence time of the atmospheric air in the combustor. Since the air entry is at supersonic speed, the availability of air for sustained reactions is timely. The flow in the combustion chamber at high speed around the surface of the chamber cause the formation of the boundary layer and inturn generate the viscous drag. Another issue is the limited knowledge about the mixing region activities pertaining to atomization, chemical reaction, etc. There has been a significant amount of experimental and numerical research to study mixing layer and jet flows. Then there is the problem of excessive time and effort involved in the computation of the numerical system.

From the study conducted it was evident that, the future of scramjet engines will be brighter if the problem of turbulent mixing and enhancement of the combustor reactions were dealt with. Improving fuel injection methods is one way of doing so. Hence a study is done on the types of the injection systems and there associated drags and efficiencies. From the study a conclusion has been drawn, such that the use of the tangential and the normal injection system in the combustion chamber of the scramjet would produce as much thrust through the normal injection and the tangential injection through the wall port could hinder the formation of the boundary layer formation by modifying the velocity gradient at the wall and hence reduce the viscous drag.

Numerical analysis provides for the best means of understanding the actual flow conditions that occur in the scramjet combustor. The results presented in this thesis were largely obtained through the use of numerical experiments conducted with computational fluid dynamics. Hence to study this approach a computer generated model has been developed using the GAMBIT software. The experiments were conducted in the T4 free-piston shock tunnel, located at The University of Queensland. An axisymmetric contoured Mach 4 nozzle was used to produce a test flow with a core uniformity of ±5% and a diameter of approximately 100 mm, the dimensions of which are discussed at the later part of the project. The hence generated model was finitely meshed using the same GAMBIT software and is then imported into FLUENT software. The analysis is done separately for the normal injection and for the tangential injection systems and also for the combination pattern of the normal and tangential injection. This analysis is done for the second order and the first order iteration and hence accuracy is obtained.

DESIGN

There are multiple ways of injecting fuel into a scramjet all of which have their advantages and disadvantages. Some injector types will be discussed in detail, along with their uses, advantages, disadvantages and integration problems that exist at present. The broad injection categories that will be covered are wall injection, strut or in-stream injection, and finally hypermixers. The injector designs that are used in the combustion process of the scramjets are based on various principles that could slow down the flow and enhance proper mixing. Normal injectors were used in the first phases of design for the injectors in scramjet. The combustion efficiency of these types of injectors is very low due to the incomplete mixture which is made to the high speed air passing through. The main problem was on incompleteness of holding the air. Hence another proposed way of injection was the tangential injection design. Here the drive ports along the chamber surface are used to spray fuel along the tangential direction. This only helped in reducing the boundary layer formation inside the chamber. Another design was a strut injector. They have a wedge surface on the flow field which generate the shock formation and hence uses this turbulent after flow to mix the fuel. This however increases the thrust and inturn the drag. Hyper mixers are another proposed injectors which have a wedge surface that are either swept or unswept. The flow over these surfaces cause the generation of the vortices and fuel is mixed to it. Hence the design method that we adopt is the combination of the normal and the tangential fuel injection. This design has the normal injection for the thrust generation and the tangential injection help in reducing the boundary layer formation. This results in the increase of thrust by increase of the exit velocity.

2mm normal 4mm tangential injector		4mm normal 4mm tangential injector		6mm normal 4mm tangential injector		8mm normal 4m tangential injector	
x mm	y mm	x mm	y mm	x mm	y mm	x mm	y mm
0	0	0	0	0	0	0	0
33.5	0	32.5	0	31.5	0	30.5	0
35.5	0	36.5	0	37.5	0	38.5	0
60.5	0	60.5	0	60.5	0	60.5	0
60.5	4	60.5	4	60.5	4	60.5	4
110.5	4	110.5	4	110.5	4	110.5	4
110.5	-32.8	110.5	-32.8	110.5	-32.8	110.5	-32.8
60.5	-32.8	60.5	-32.8	60.5	-32.8	60.5	-32.8
60.5	-28.8	60.5	-28.8	60.5	-28.8	60.5	-28.8
35.5	-28.8	36.5	-28.8	37.5	-28.8	38.5	-28.8
33.5	-28.8	32.5	-28.8	31.5	-28.8	30.5	-28.8
0	-28.8	0	-28.8	0	-28.8	0	-28.8

DESIGN OF COMBUSTER

Scramjets offer significant performance benefits over other propulsion technologies for atmospheric flight at hypersonic speeds, as a result of their ability to extract the oxygen required for combustion from the atmosphere. However, the large amount of viscous drag present at hypersonic speeds remains one of the major obstacles to the successful development of operational scramjet engines. Hence the tangential injection of the fuel is made to reduce the formation of the boundary layer and hence viscous drag is reduced. The normal injection of the fuel is made to increase the thrust and hence a significant method of combining these methods of injection helps to increase the thrust as well as the reduction of the viscous drag. An optimized combustion chamber was developed form varying the slot injection diameter. The design of the combustion chamber is done in gambit. First creating the vortices then the edges and finally faces.

Table.1: Combustor Coordinates From 2 to 8 mm Normal and 4 mm Tangential Injectors

DIMENSIONS

Combustor Length - 110.5mm
Combustor Internal Diameter - 32.8mm
Combustor Wall Thickness - 0.75mm
Slot Hole diameter - 4mm
Injector Internal Diameter - 28.8mm

Table.2: Combustor Coordinates From 10 to 16 mm Normal and 4 mm Tangential Injectors

10mm normal 4mm tangential injector		12mm normal 4mm tangential injector		14mm normal 4mm tangential injector		16mm normal 4mm tangential injector	
x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
29.5	0	0	0	0	0	0	0
39.5	0	28.5	0	27.5	0	26.5	0
60.5	0	40.5	0	41.5	0	42.5	0
60.5	4	60.5	0	60.5	0	60.5	0
110.5	4	60.5	4	60.5	4	60.5	4
110.5	-32.8	110.5	4	110.5	4	110.5	4
60.5	-32.8	110.5	-32.8	110.5	-32.8	110.5	-32.8
60.5	-28.8	60.5	-32.8	60.5	-32.8	60.5	-32.8
39.5	-28.8	60.5	-28.8	60.5	-28.8	60.5	-28.8
29.5	-28.8	40.5	-28.8	41.5	-28.8	42.5	-28.8
0	-28.8	28.5	-28.8	27.5	-28.8	26.5	-28.8
0	0	0	-28.8	0	-28.8	0	-28.8

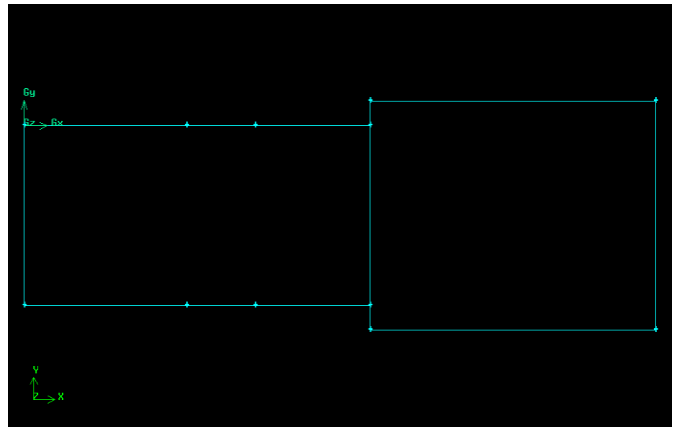


Fig.6: Design In Gambit – Scramjet Combuster

DESIGN CONSTRAINTS

Scramjets are designs to operate under the hypersonic range and hence they produce many constrains in design such as the combustion in the chamber should be self sustainable and the curvature design should be such that the boundary layer formation decreased . The engine is provided with injectors that face the airflow in normal and in tangential direction and hence the tube heating is high .Also the meshing of such surfaces for the analysis purpose is difficult. The positioning of the injectors as per the scaling is another difficult task.

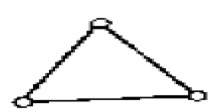
MESHING

Generating a good mesh is the most important part of CFD problem, to reduce overall mesh size confine small cells to area where they are needed that is where high gradients are expected. The smaller the meshes are the finer is the result obtained. Meshing is the program of discretion of the model into finer elements which later form up the complete model. The basic parts from which meshes are built:

- points, sometimes called nodes
- volumes, also known as cells in some documentation
- elements

TYPES OF MESH

The types of mesh are structured mesh and unstructured mesh. Consists of face mesh, volume mesh, and edge mesh, etc. Some of the commonly used sub-domain are;



3-node triangle

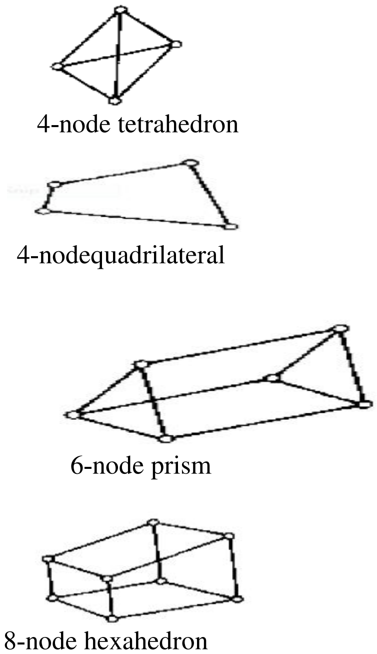
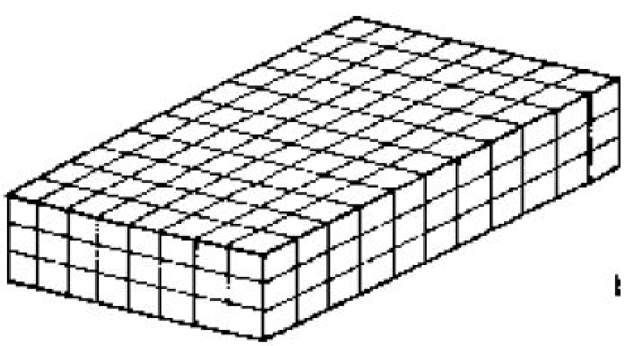


Fig 7: Sub-Domains of Mesh

A regular structure or topology, where the points of the mesh can be imagined as a grid of points placed in a regular way throughout a cuboid (also known as a shoebox).These points can then be stretched to fit a given geometry. The stretching is takes place as if the mesh were made of rubber, and the so-called topology, or form, of the mesh remains the same.



Fi.8: Regular Structure

An irregular structure or topology, where the points fill the space to be considered but are not connected with a regular topology. A mesh with an irregular structure is often referred to as an unstructured mesh or a free mesh. The fact that any particular node is attached to an element cannot be known from the form of the mesh.

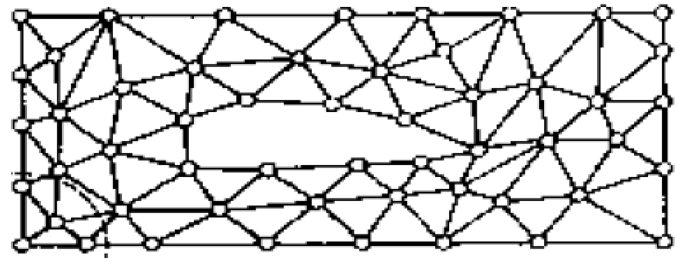


Fig.8: Irregular Structure

Relating the mesh structure to the numerical method; finite difference programs require a mesh to have a regular structure and finite element programs can use a mesh with an irregular structure. In theory finite volume programs could use a mesh with an irregular structure, but many implementations insist that the mesh has a regular structure.

The structured mesh needs the mesh volume in quadrilateral in 2d or hexahedral in 3d and each volume is linked only to its immediate volume. The advantages are reducing the storage and CPU requirement and disadvantage is dead zones waste storage. The unstructured mesh can be linked to any other volume in the domain. The advantages are it can be shape and the disadvantage is less computationally efficient than the structured grid. The mesh selected for all the design are structured mesh. Because of its give good results and need only less CPU requirements.

5.3 CHOOSEN MESH

The quad mesh are chosen for all the design, because when a mesh with a regular structure is used there is an advantage in that the solver program should run faster than if a mesh with an irregular structure is used. This is due to the implicit relationship that exists between the number of a cell or a point and the number of its neighbours in a regular mesh, which enables data to be found easily. No such relationship occurs for meshes that have an irregular structure and so when trying to find the values of flow variables in neighbouring volumes there must be a computational overhead. This often takes the form of a look-up table which relates the faces to the cells or the nodes to the elements.

The boundary layer thickness for all the design is calculated as;

Calculations:
At inlet, M=2
From Isentropic Flow Properties,

$$\frac{P}{P_0} = .12781186 \qquad (6)$$

P-static pressure

$P_0 - initial\ pressure$

P=350000 X .12781186

P= 44734.151 Pa (7)

$$\rho_0 = \frac{P_0}{RTo} \quad (8)$$

$$= \frac{3.5\ X\ 10^5}{287\ X\ 500}$$

$$= 2.4390\ \text{Kg/m}^3$$

$$a_t = \sqrt{\gamma R T_t} = 334.09\ \text{m/s} \quad (9)$$

$$\mu = 1.789 \times 10^{-5}\left[\frac{T}{288.2}\right] (10)$$

$$\mu = 1.789 \times 10^{-5}\left[\frac{277.8}{288.2}\right]$$

$$\mu = 1.724442050X10^{-5}\ Kg/ms$$

$$\nu = \frac{\mu}{\rho} m^2/s \quad (10)$$

$$\nu = \frac{1.7244X10^{-5}}{0.560975} m^2/s$$

$$\nu = 3.0739\ X\ 10^{-5} m^2/s$$

$$R_e = \frac{\rho V L}{\mu} \quad (11)$$

$$R_e = 6.260X10^5$$

$$C_{f_x} = \frac{0.074}{Re^{\frac{1}{5}}} = 5.1276 \times 10^{-3} \quad (12)$$

$$T_w = \frac{\rho V^2\ X\ C_{fx}}{2} \quad (13)$$

$$T_w = 642.117631$$

Boundary layer thickness (δ) for nozzle flows is given by formulae

$$\delta = .654mm$$

Turbulent length scale (l) is given by formulae

$$l = 0.4\delta_{99}$$

$$= .216\text{mm}$$

where, δ_{99} = boundary layer thickness where velocity reaches 99% of the free stream velocity.

Growth factor = 1.3; Number of rows = 21

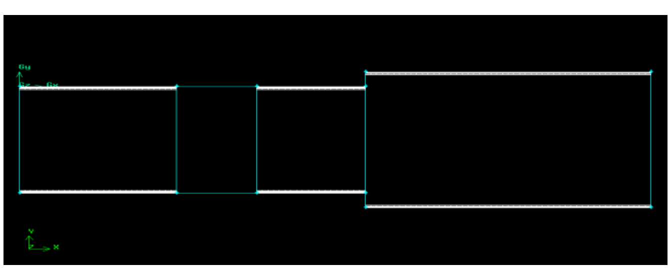


Fig:9: Boundary Layer Created For Scramjet Combustor

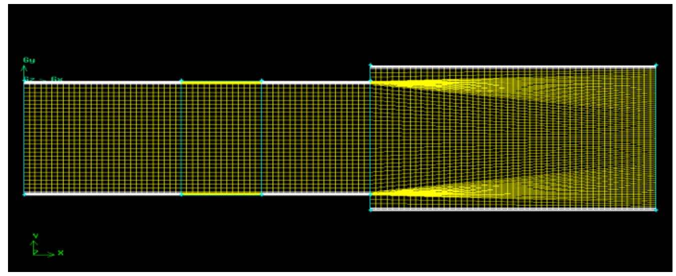


Fig 10: Mesh for Scramjet Combustor

Table 3. Number of Cells and Nodes

2mm normal 4mm tangential injector		4mm normal 4mm tangential injector		6mm normal 4mm tangential injector		8mm normal 4mm tangential injector	
Cells	Nodes	Cells	Nodes	Cells	Nodes	Cells	Nodes
10059	10288	8268	8478	10059	10288	10059	10288
10mm normal 4mm tangential injector		12mm normal 4mm tangential injector		14mm normal 4mm tangential injector		16mm normal 4mm tangential injector	
Cells	Nodes	Cells	Nodes	Cells	Nodes	Cells	Nodes
10059	10288	10725	10960	10059	10288	10059	10288

The CFD analysis requires the meshing of the surface. For this we want to estimate the boundary layer thickness. This is what required for the meshing to get accurate and easy. Hence we select the quad meshing formats this is done because in order to mesh a particular region, the quad requires only four nodes whereas the triangular elements requires more nodes and increase the complexity. And hence the quad mesh are used to do the meshing program

COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics (CFD) is concerned with numerical solution of differential equations governing transport of mass, momentum, and energy in moving fluids. CFD activity emerged and gained prominence with availability of computer in the early 1960s. Today, CFD finds extensive usage in basic and applied research, in design of engineering equipment, and in calculation of environmental and geophysical phenomena. Since the early 1970s, commercial software packages (or computer codes) became available, making CFD an important component of engineering practice in industrial, defense, and environmental organizations.

TURBULENCE MODELLING

A turbulent flow field is characterized by velocity fluctuations in all directions and has an infinite number of scales (degrees of freedom). Solving the NS equations for a turbulent flow is impossible because the equations are elliptic, non-linear, coupled and the flow is three dimensional, chaotic, diffusive, dissipative, and intermittent. The most important characteristic of a turbulent flow is the infinite number of scales so that a full numerical resolution of the flow requires the construction of a grid with a number of nodes that is proportional to $Re^{9/4}$. Turbulent flows occur at high Reynolds numbers, when the inertia of the fluid overwhelms the viscosity of the fluid, causing the laminar flow motions to become unstable. Under these conditions, the flow is characterized by rapid fluctuations in pressure and velocity which are inherently three dimensional and unsteady. Turbulent flow is composed of large eddies that migrate across the flow generating smaller eddies as they go. Reynolds decomposition provides the answer to solving the problem, in which, any property can be written as the sum of an average and a fluctuation. This decomposition will, however, yield a set of equations governing the average flow field. The new equations will be exact for an average flow field not for the exact turbulent flow field. The result of using the Reynolds decomposition in the NS equations is called the RANS or Reynolds Averaged Navier Stokes Equations, with the introduction of new unknowns like turbulent stresses and turbulent fluxes. An easy approach is to use the PDEs for the turbulent stresses and fluxes as a guide to modeling. The turbulent models are as follows:

- Algebraic (Zero Equation) Model
  In zero equation models, as the name designates, we have no PDE that describes the transport of the turbulent stresses and fluxes. A simple algebraic relation is used to close the problem.
- One Equation Model
  In one-equation models, a PDE is derived for the turbulent kinetic energy and the unknowns (turbulent viscosity and conduction coefficient) are expressed as a function of the turbulent kinetic energy
- Two Equation Model
  In the two-equation models, we develop two PDEs: one for the turbulent kinetic energy and one for the turbulent dissipation rate.

1) k-ε models

The standard, RNG and Realizable k-ε models are similar structured models, with transport equation for k and ε. The major differences in the three models are as follows:

- The method of calculating the turbulent viscosity
- The turbulent Prandtl numbers governing the turbulent diffusion of k and ε
- The generation and destruction terms in the ε equation.

This model is primarily valid for turbulent core flows (sufficiently away from the wall).

1) Standard k-ε: The standard k-ε model is a semi-empirical model based transport equation for the turbulent kinetic energy (k) and its dissipation rate (ε). The model transport equation is derived from exact equation, while the model transport equation is for ε was obtained using physical reasoning and bears little to its resemblance to its mathematically exact counterpart. In the derivation of the model, it is assumed that the flow is fully turbulent, and the effects of molecular viscosity are negligible. Therefore the standard k-ε model is valid only for fully turbulent flows.
2) Renormalization Group k-ε (RNGKE): The RNG based turbulence model is derived from the instantaneous Nervier-Stokes equation, using a mathematical technique called renormalization group methods. The analytical derivation results in a model with constants different from those in standard k-ε model, and additional terms and functions in the transport equations for k and ε.
3) Realizable k-ε (RKE): the term realizable means that the model satisfies certain mathematical constraints on the normal stresses, consistent with the physics of turbulent flows.

2) k-ω models

The standard and SST are the two models having similar structure in this category. Both have similar structure but differ in the following ways:

- Gradual change from the standard k-ω model in the inner regions of the boundary layer to a high Reynolds number version of the k-ε model in the outer part of the boundary layer.

- Modified turbulent viscosity formulation to account for the transport effects of the principal turbulent shear stress

1) Standard k-ω model: This is an empirical model based on model transport equations for the turbulence kinetic energy (k) and the specific dissipation rate (ω), which can also be thought of as ratio of ε and k.

2) Shear Stress Transport k-ω model: In this model the turbulent viscosity is modified to account for the transport of the principal turbulent shear stress. It is this feature that gives this model advantage in terms of performance over both the standard k-ε model and the standard k-ω model. In addition to this, a cross diffusion term in the equation.

3) Adaptive grids

An adaptive grid is a grid network which automatically clusters grid points in regions of high flow field gradients; it uses the solution of the flow field properties to locate the grid points in the physical plane. During the course of the solution, the grid points in the physical plane move in such fashion to adapt to the regions of large flow-field gradients as these gradients evolve with time. Hence, the actual grid points in the physical plane are constantly in motion during the solution of the flow. It becomes stationary only when the flow approaches a steady state. It is advantageous as there is an increased accuracy for a fixed number of grid points. Also, it has the ability to incorporate solution-adaptive refinement if the mesh.

Boundary conditions

<u>Inlet air conditions</u>

Total pressure, $P_0=3.5x10^5$ N/m^2

Total temperature $T_0=500K$

Ratio of specific heat, $\gamma=1$

Mach number, M=2

<u>Inlet fuel conditions</u>

Total pressure, $P_0=3.5x10^5$ N/m^2

Total temperature $T_0=500K$

In our computation, pressure based Shear Stress Transport k-ω model is selected, because this work is based on the viscous effect at the wall of the combustion chamber. The fuel used for this combustion analysis is hydrogen.

Among the different Turbulence Models, Shear Stress Transport k-ω model is selected, because this work is based on the viscous effect at the wall of the combustion chamber that causes the formation of boundary layer which hence reduce the exit velocity. The viscous prediction with 1st order upwind discretization could not capture the actual combustion structure. However, the 2nd order upwind discretized solutions predicted combustion in the scramjet engine.

PERFORMANCE ANALYSIS

In our analyze we carry out a set of calculation and analysis. The fuel used for the combustion analysis is hydrogen. This analysis is done for a primary target to reduce the viscous drag and to maintain a good combustion. At the first stage of the analysis a good injection technique is found by using three set of injection patterns and there data of temperature, velocity, and pressure is analyzed. Hence it is found that the usage of a combination of tangential and normal injection of fuel to the flow field could result a high reduction of the viscous drag as the boundary layer formation is reduced. Further the selected method of the injection i.e., combination injection method is further optimized to have high combustion efficiency. This is done by varying the port hole injector radius. A various set of injector radius are tried and the hence obtained results are plotted down graphically.

PERFORMANCE MEASURE

For the performance measures, types of injectors are analyzed and compare with the results. The values are given below. The combination injection method is analyzed for the variation of the velocity, pressure and the temperature. The contours also taken for the turbulence in the combustion chamber, mass fraction of fuel and the product obtained after the combustion. The fuel is hydrogen and the product obtained after combustion is H_2O. This is shown through the following representations.

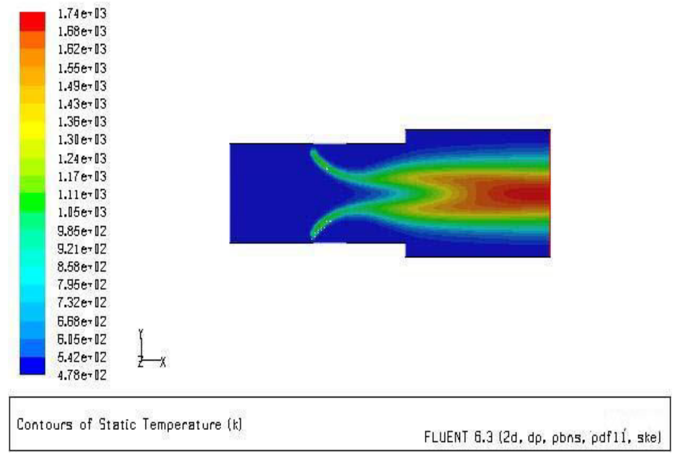


Fig.11: Temperature Contours For 12mm Normal and 4mm Tangential Injector

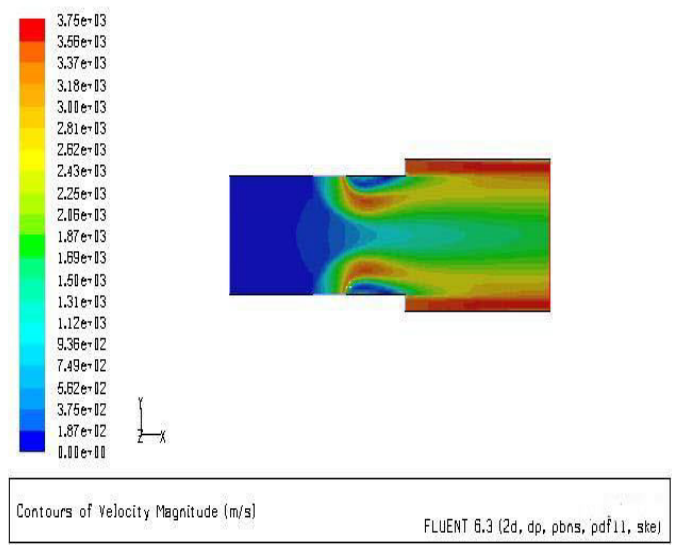


Fig.12: Pressure Contours For 12mm Normal and 4mm Tangential Injectors

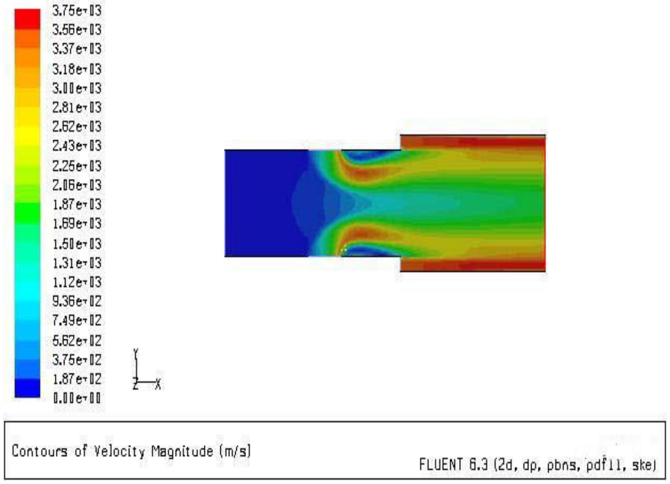


Fig.13: Velocity Contours For 12mm Normal and 4mm Tangential Injectors

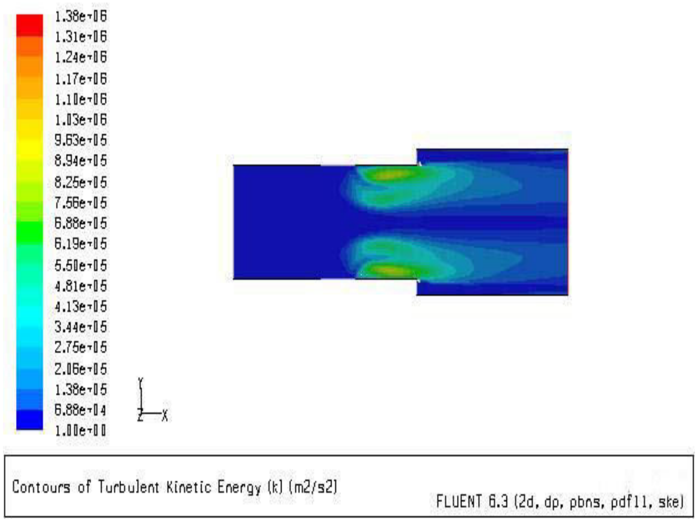


Fig.14: Turbulence Contours for 12mm Normal and 4mm Tangential Injectors

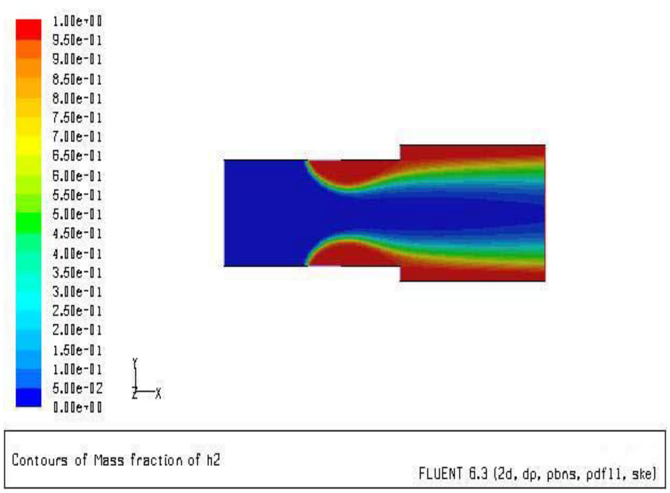


Fig.15: Mass fraction of h2 Contours for 12mm Normal and 4mm Tangential Injectors

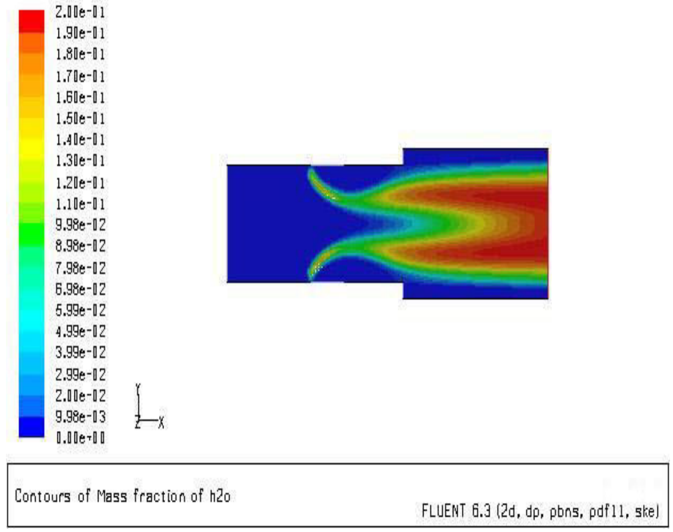


Fig.16: Mass fraction of h2 Contours for 12mm Normal and 4mm Tangential Injectors

PERFORMANCE ANALYSIS

Velocity variation for the flow through the scramjet is analyzed for various injector cross sections at a distance of 60.5mm from the combustion chamber inlet and at a distance 2mm from the wall of the combustion chamber. A such position is considered because the tangential injection to reduce the boundary layer formation is done at this position. The below shown is the representation of the velocity variation with respect to the position along the scramjet combustion chamber. The graph shows the velocity variation for eight different injector cross sections. From the graph the desirable velocity is obtained in 16mm and 12mm cross section.

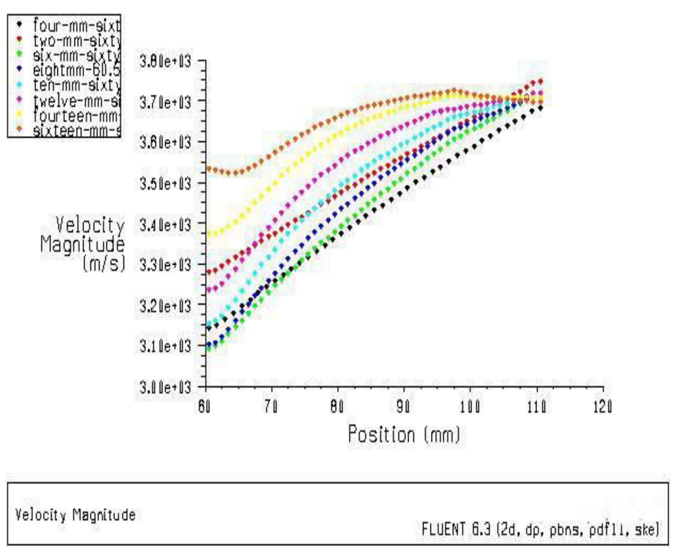


Fig.17: Velocity Plot of Normal and Tangential Fuel Injectors after 60.5mm

Velocity variation for the flow through the scramjet is analyzed for various injector cross sections. The below shown is the representation of the velocity variation with respect to the position along the scramjet combustion chamber. It is shown that most of the line show a sudden increase of the velocity after a certain point. These sudden increase are mostly found for those injectors having a comparatively high cross section dia. This is because these injectors leave much more fuel and hence they expand more to give high velocity change. The graph shows the velocity variation for eight different injector cross sections. From the graph the desirable velocity is obtained in 16mm, 14mm and 12mm cross section.

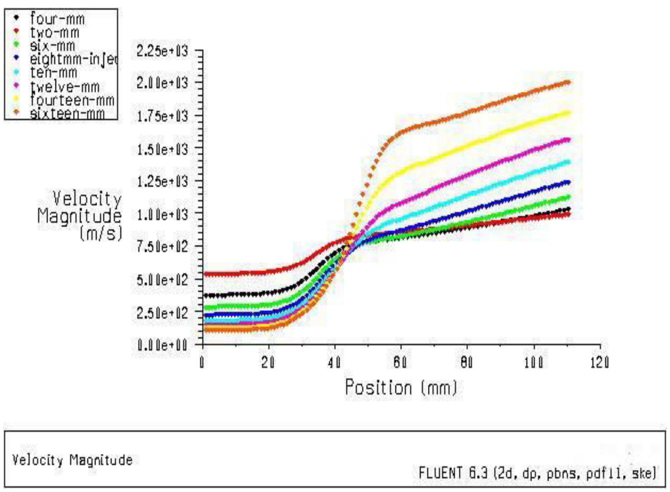


Fig18: Velocity Plot of Normal and Tangential Fuel Injectors

Pressure variation for the flow through the scramjet is analyzed for various injector cross sections. The below shown is the representation of the pressure variation with respect to the position along the scramjet combustion chamber. It is shown that most of the line shows a drop in pressure along the length of the chamber. The graph shows the pressure variation for eight different injector cross sections. From the graph the desirable velocity is obtained in 14mm, 12mm and 10mm cross section.

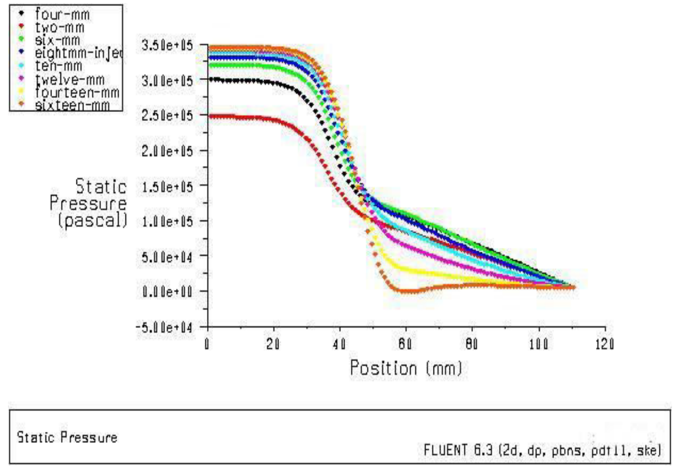


Fig.19: Pressure Plot of Normal and Tangential Injectors

Temperature variation for the flow through the scramjet is analyzed for various injector cross sections. The below shown is the representation of the temperature variation with respect to the position along the scramjet combustion chamber. It is shown that most of the lines show a sudden increase up to a point and then a reduction of temperature after a certain point is found. These sudden increases are mostly found for those injectors having a comparatively high cross section dia. This is because these injectors leave much more fuel and hence the combustion in them are vigorous and short time combustion. But there are also some combustion which withstand long time and give high temperature. The graph shows the temperature variation for eight different injector cross sections. From the graph the desirable temperature is obtained in 12mm cross section injectors which give a high temperature at the outlet of the chamber.

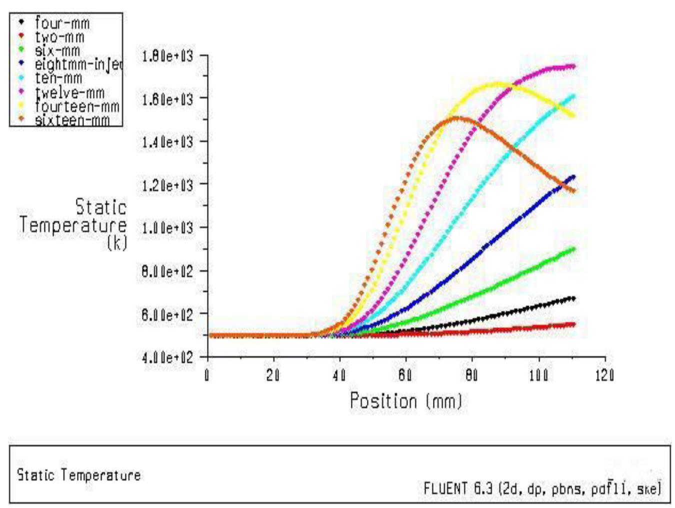


Fig.20: Temperature Plot of Normal and Tangential Injectors

From the performance analysis we can see that during normal injection combustion will happen and in tangential injection there is a reduction of viscous drag. We also analyze with the combination of normal and tangential injections there happen to be a reduction of the viscous drag and an increase of combustion. In this we can see the effect of both normal and tangential injection. Comparing with these we can see that use of combined injection technique is good for combustion and also for the reduction of viscous drag. Further the optimization is done with the motive of having a high temperature at the outlet of the chamber from a long period of combustion. Such flow should also have a very less pressure drop and a high velocity. By keeping to the above conditions we find that the injectors having a 12mm cross section delivers high performance.

FUTURE ANALYSIS AND CONCLUSION

Combustor development remains a semi empirical art. During the past decade numerous in-house and contractual studies, both experimental and analytical, have been performed. Many of these studies utilized cold mixing. Because combustion in the scramjet combustor flaw is primarily mixing dependent, initially cold mixing investigations were used to predict combustor performance. The efficiency of the scramjets depends mainly on the fuel air mixture ratio. The mass flow rate in the scramjet engine is high and hence the thrust is high. Since we are using the combination of the normal and tangential injectors it reduces the velocity gradient at the wall of the combustion chamber increase and thereby decreasing the viscous drag. The combination of the injection system causes the increase in the rate of combustion and hence increases the efficiency of the system.

The flame holding in the supersonic combustion process is hard to obtain. The tangential flow of the fuel does not help in the mixing of the fuel and hence the combustion is not helped much by the tangential fuel injected. The design features of the combinational injection system are a complex task. As a sum of the fuel do not help in combustion, there is pretty much lose in unburned fuel. Sort injectors do not help in the much efficient burning of the fuel. Hence the concluded injection technique is further optimized by varying the injector cross sections. The variation of the injector cross section will control the amount rate of the fuel that is dumped to the chamber. This could affect the chamber conditions. An optimum amount is required and this should not be more or very less. The addition of more amount of the fuel could reduce the efficiently by incomplete burning.

LIMITATIONS

The scramjet operates at a supersonic range of flight and hence the airflow holding for the proper mixing of the fuel is a major concern. The improper mixing of the fuel cause the trouble of the flame outing and a self-sustaining flow cannot be attained. The fuel injector optimization is a major concern. The positioning and the design configuration of the injector is very important as far as the combustion efficiency is concerned. An example of this is the sort injectors that are placed at an inclined position. The flow through these injectors does not actively participate in the combustion. And also the cross section of the fuel causing more or less mass rate.

The tangential injection of fuel has a certain velocity that might be same as the flow velocity. This has to be controlled if a better reduction of the viscous drag is needed. So far no techniques are made to do the same.

FUTURE RECOMMENDATIONS

Scramjet engines account for various types of injections. But each of these injection system systems has their own drawbacks. The system we consider has a combination of normal and tangential injection. As mentioned above a large amount of fuel could be left unburned due to tangential injection. Hence some of the future recommendations could be the usage of any alcoholic substance instead of the fuel for the tangential injection, so that they increase the mass flow rate as well as the thrust. The alcohols could produce high density compared to the other fuels. Another recommendation system includes the usage of after burners. Boundary layer suction can be used instead of tangential injection to reduce the boundary layer formation. This method is already used for the reduction of the boundary layer on the wing surfaces. Experiments can be done to analyze the effectiveness of this combination method. To increase the number of normal injectors could increase the thrust generated.

CONCLUSION AND DISCUSSION

The field of scramjet propulsion is worth rewarding section. And the future works on it will thrive. The reason for this is the high efficiency of the propulsion system and its meeting performance for the present day fast and furious operations. The system will be capable of propelling small rockets to large airplanes at high speeds. The above project deals with the chamber optimization with a suitable mode of injection techniques. The optimization is done with keeping knowledge of reducing the drag that are found in the chamber. The analysis of various modes of injection is done through considering the temperature, velocity, density and pressure variations. Further the optimization of the injectors design is made . the cross section geometry is changed and are analyzed for the changes in temperature, pressure and velocity, and hence found that the combination of injection of tangential and normal injection technique offer higher flow rate with a reduced viscous drag along the chamber walls. The injector geometry optimization results that an injector with 12mm cross section could deliver high temperature delivery at the chamber outlet along with the high velocity flow and much less pressure drop

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