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Design and Analysis on Scramjet Engine Inlet

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Abstract- Generally a Scramjet Engine starts at a hypersonic freestream Mach no. 5.00. In order to propel to those speeds, we use turbojet engines which propel to around 3.00-4.00 Mach and from there the ramjet picks upon and starts to propel to start the scramjet engine. If we reduce the scramjet engine starting Mach number to say 3.50 or 4.00, we can eliminate one propulsion engine, i.e., ramjet engine and thus reducing weight and complexity. The design for such a scramjet engine is carried out in this project considering only the inlet designs and the flow analysis is carried out in CFD. A two dimensional analysis is carried out in this project. GAMBIT is used to create a model. FLUENT is used to cover the flow analysis.

Index Terms- CFD Analysis , Design of Scramjet, Mach Number 4.00, Inlet Ramps, k-ε Turbulence Model, Manipulation of Pure Scramjet, Scramjet Engine, Shock Capturing.

I. INTRODUCTION

In order to provide the definition of a scramjet engine, the definition of a ramjet engine is first necessary, as a scramjet engine is a direct descendant of a ramjet engine. Ramjet engines have no moving parts, instead operating on compression to slow freestream supersonic air to subsonic speeds, thereby increasing temperature and pressure, and then combusting the compressed air with fuel. Lastly, a nozzle accelerates the exhaust to supersonic speeds, resulting in thrust. Due to the deceleration of the freestream air, the pressure, temperature and density of the flow entering the burner are "considerably higher than in the freestream". At flight Mach numbers of around Mach 6, these increases make it inefficient to continue to slow the flow to subsonic speeds. Thus, if the flow is no longer slowed to subsonic speeds, but rather only slowed to acceptable supersonic speeds, the ramjet is then termed a 'supersonic combustion ramjet,' resulting in the acronym *scramjet*. Figure 1 below shows a two-dimensional schematic of a scramjet engine.

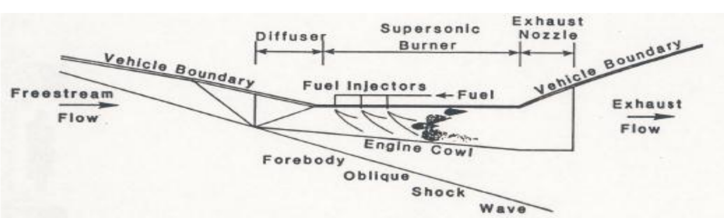

Fig 1: Two-dimensional Schematic of a Scramjet Engine

As in ramjets, a scramjet relies on high vehicle speed to forcefully compress and decelerate the incoming air before combustion (hence *ram*jet), but whereas a ramjet decelerates the air to subsonic velocities before combustion, airflow in a scramjet is supersonic throughout the entire engine. This allows the scramjet to efficiently operate at extremely high speeds.

II. LITERATURE SURVEY

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. The parts described above can be seen in figure below.

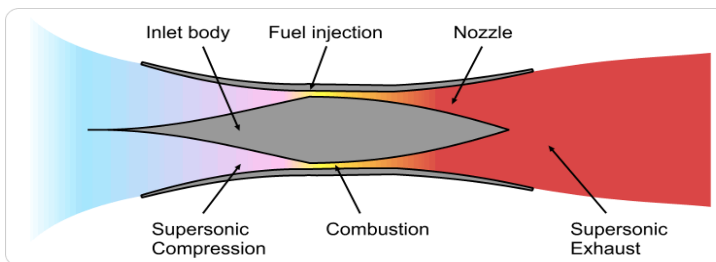

Fig 2: A two dimensional image of a Scramjet Engine

Due to the nature of their design, scramjet operation is limited to near-hypersonic velocities. As they lack mechanical compressors, scramjets require the high kinetic energy of a hypersonic flow to compress the incoming air to operational conditions. Thus, a scramjet powered vehicle must be accelerated to the required velocity by some other means of propulsion, such as turbojet, railgun, or rocket engines. While scramjets are conceptually simple, actual implementation is limited by extreme technical challenges. Hypersonic flight within the atmosphere generates immense drag, and temperatures found on the aircraft and within the engine can be much greater than that of the surrounding air. Maintaining combustion in the supersonic flow presents additional challenges, as the fuel must be injected, mixed, ignited, and burned within milliseconds. While scramjet technology has been under development since the 1950s, only very recently have scramjets successfully achieved powered flight.

III. DESIGN PRINCIPLES

Scramjet engines are a type of jet engine, and rely on the combustion of fuel and an oxidizer to produce thrust. Similar to conventional jet engines, scramjet-powered aircraft carry the fuel on board, and obtain the oxidizer by the ingestion of atmospheric oxygen (as compared to rockets, which carry both fuel and an oxidizing agent). This requirement limits scramjets to suborbital atmospheric flight, where the oxygen content of the air is sufficient to maintain combustion. Scramjets are designed to operate in the hypersonic flight regime, beyond the reach of turbojet engines, and, along with ramjets, fill the gap between the high efficiency of turbojets and the high speed of rocket engines. Turbomachinery-based engines, while highly efficient at subsonic speeds, become increasingly inefficient at transonic speeds, as the compressor fans found in turbojet engines require subsonic speeds to operate. While the flow from transonic to low supersonic speeds can be decelerated to these conditions, doing so at supersonic speeds results in a tremendous increase in temperature and a loss in the total pressure of the flow. Around Mach 3–4, turbomachinery is no longer useful, and ram-style compression becomes the preferred method. Ramjets utilize high-speed characteristics of air to literally 'ram' air through an inlet nozzle into the combustor. At transonic and supersonic flight speeds, the air upstream of the nozzle is not able to move out of the way quickly enough, and is compressed within the nozzle before being diffused into the combustor. The lack of intricate turbomachinery allows ramjets to deal with the temperature rise associated with decelerating a supersonic flow to subsonic speeds, but this only goes so far: at near-hypersonic velocities, the temperature rise and inefficiencies discourage decelerating the flow to the magnitude found in ramjet engines. Scramjet engines operate on the same principles as ramjets, but do not decelerate the flow to subsonic velocities. Rather, a scramjet combustor is supersonic: the inlet decelerates the flow to a lower Mach number for combustion, after which it is accelerated to an even higher Mach number through the nozzle. By limiting the amount of deceleration, temperatures within the engine are kept at a tolerable level, from both a material and combustive standpoint. Even so, current scramjet technology requires the use of high-energy fuels and active cooling schemes to maintain sustained operation, often using hydrogen and regenerative cooling techniques. In a typical ramjet, the supersonic inflow of the engine is decelerated at the inlet to subsonic speeds and then reaccelerated through a nozzle to supersonic speeds to produce thrust. This deceleration, which is produced by a normal shock, creates a total pressure loss which limits the upper operating point of a ramjet engine. For a scramjet, the kinetic energy of the freestream air entering the scramjet engine is large comparable to the energy released by the reaction of the oxygen content of the air with a fuel (say hydrogen). Thus the heat released from combustion at Mach 25 is around 10% of the total enthalpy of the working fluid. Depending on the fuel, the kinetic energy of the air and the potential combustion heat release will be equal at around Mach 8. Thus the design of a scramjet engine is as much about minimizing drag as maximizing thrust. Usable dynamic pressures lie in the range 20 to 200 kilopascals (2.9 to 29 psi), where

$$q = \frac{1}{2}\rho v^2$$

Where,
q is the dynamic pressure of the gas
ρ is the density of the gas
v is the velocity of the gas

To keep the combustion rate of the fuel constant, the pressure and temperature in the engine must also be constant. Because air density reduces at higher altitudes, a scramjet must climb at a specific rate as it accelerates to maintain a constant air pressure at the intake. This optimal climb/descent profile is called a "constant dynamic pressure path". It is thought that scramjets might be operable up to an altitude of 75 km. Fuel injection and management is also potentially complex. One possibility would be that the fuel be pressurized to 100 bar by a turbo pump, heated by the fuselage, sent through the turbine and accelerated to higher speeds than the air by a nozzle. The air and fuel stream are crossed in a comb like structure, which generates a large interface. Turbulence due to the higher speed of the fuel leads to additional mixing. The minimum Mach number at which a scramjet can operate is limited by the fact that the compressed flow must be hot enough to burn the fuel, and have pressure high enough that the reaction be finished before the air moves out the back of the engine.

IV. CURRENT SCRAMJET ENGINE CHALLENGES

There are three main areas that these problems lay in, namely Air Inlet, Combustor, and Structures and Materials. Problems within these areas vary from inlet starting problems to the inherent difficulty of the ignition of the fuel in a supersonic flow, as the possibility of failure exists anywhere from the fuel not igniting to the possibility that the ignition could take place outside of the combustor due to the extraordinary velocity of the air in the engine. Additionally, structures that can withstand the extreme temperatures experienced during hypersonic flight combined with the additional temperatures experienced during combustion are necessary. Despite the wide range of applications possible with scramjet technology, the vehicle must first be propelled to a high enough Mach number for the scramjet to start. This requires, depending on the needed application, one or two additional propulsion systems to propel the vehicle to the needed scramjet start velocity. Current scramjet designs target the start of supersonic combustion to be between Mach 5&6. However, if the necessary scramjet starting Mach number is reduced, a reduction in the number of required additional propulsion systems is possible, as the gap is bridged between the maximum possible velocity of the low speed engine(s) and the scramjet start velocity. This would have direct advantages from the resulting reduction in overall vehicle weight, the lower mass fraction required for the propulsion system (thereby resulting in more available payload weight), and fewer systems that must work in succession reliably, thereby increasing overall vehicle safety. The focus of this project is to address this issue of reducing the starting Mach number.

Unstart in Scramjet engine is characterized by the formation of a strong normal shock wave in the combustor. This shock wave propagates upstream towards the inlet and eventually reduces significantly the mass flow rate and the thrust generated by the engine. Another expected result is that unstart is more likely if the incoming stream is at a lower Mach number. For the amount of fuel burnt, parameterized by K_c (Fraction of completed combustion); although obviously high values of K_c are more likely to lead to thermal choking, few unstarted realizations with $K_c < 0{:}85$ were observed. Unstart in a scramjet engine is also characterized by the following reasons: Firstly, since when a supersonic flow is compressed it slows down, the level of compression must be low enough (or the initial speed high enough) not to slow the gas below Mach 1. If the gas within a scramjet goes below Mach 1 the engine will "choke", transitioning to subsonic flow in the combustion chamber. This effect is well known amongst experimenters on scramjets since the waves caused by choking are easily observable. Additionally, the sudden increase in pressure and temperature in the engine can lead to an acceleration of the combustion, leading to the combustion chamber exploding. Secondly, the heating of the gas by combustion causes the speed of sound in the gas to increase (and the Mach number to decrease) even though the gas is still travelling at the same speed. Furthermore forcing the speed of air flow in the combustion chamber under Mach 1 in this way called "thermal choking".

V. SOFTWARES USED

The software's used in this project are GAMBIT and FLUENT. **Gambit** is the program used to generate the grid or mesh for the CFD solver whereas **Fluent** is the CFD solver which can handle both structured grids, i.e. rectangular grids with clearly defined node indices, and unstructured grids. Unstructured grids are generally of triangular nature, but can also be rectangular. In 3-D problems, unstructured grids can consist of tetrahedral (pyramid shape), rectangular boxes, prisms, etc. Fluent is the world's largest provider of commercial computational fluid dynamics (CFD) software and services. Fluent covers general-purpose CFD software for a wide range of industrial applications, along with highly automated, specifically focused packages. FLUENT is a state-of-the-art computer program for modelling fluid flow and heat transfer in complex geometries. FLUENT provides complete mesh exibility, including the ability to solve your own problems using unstructured meshes that can be generated about complex geometries with relative ease. Supported mesh types include 2D triangular/quadrilateral, 3D tetrahedral/ hexahedral/ pyramid/ wedge/ polyhedral, and mixed (hybrid) meshes. FLUENT is ideally suited for incompressible and compressible fluid-flow simulations in complex geometries.

VI. PROBLEM DESCRIPTION AND SCOPE OF CURRENT WORK

A critical path issue in scramjet development is for scramjet operability to be extended to lower Mach numbers. Specifically, scramjet start should be reduced to "Mach 3.50 while maintains performance at higher Mach numbers within the same flowpath" with minimal variable geometry features and the use of hydrocarbon fuel. A turbojet engine can provide for thrust from takeoff to a speed of Mach 3 or 4. Therefore, if a scramjet were designed with a starting Mach number of about 3.50, presumably only two propulsion systems would be needed for the entire mission, whether that is up to Mach 8-10 for a hydrocarbon-powered scramjet or up to Mach 15-20 for a hydrogen-powered scramjet. The advantage of this technology is the resulting reduction in overall vehicle weight, lower mass fraction required for the propulsion system, and fewer systems that must work in succession reliably, thereby increasing overall vehicle safety. The method best suited for the current project is then selected.

A. *Scramjets: Options for Lowering the Starting Mach Number*

The project seeks to lower the starting Mach number to 3.50 and to determine the main factors influencing this ability. There are a number of possible ways to lower the starting Mach number of the scramjet. The methods discussed in the literature are listed and briefly explained here in turn. The method best suited for the current project is then selected.

i. Variable Geometry

In a variable geometry scramjet, the flowpath is changed according to the freestream Mach number to ensure high performance values throughout a wide range of Mach numbers. An example of a program which employed this technique is the HRE program which developed a flight-weight hydrogen-fuelled scramjet designed to operate from Mach 4 to 7 using variable geometry. Though this technique ensures high performance, it is highly complex and instills a high level of inherent risk, as it relies on a large number of moving parts which require large actuation forces.

ii. Hypersonic Dual-Combustor Ramjet (DCR)

The concept of this type of scramjet engine is that a portion of the captured air in the engine is "diverted to a small, embedded subsonic dump combustor into which all of the fuel is injected". The fuel and air are then mixed to a sufficient level in the subsonic combustor, which, essentially, acts as a "hot, fuel-rich gas generator for the main supersonic combustor".

iii. Manipulation of "Pure" Scramjet Engine Key Design Parameters

There are a few key parameters of the "pure" scramjet engine—that is, a scramjet with one combustor and a non-variable flowpath—that are able to be varied and manipulated to perhaps lower the starting Mach number of a scramjet. For instance, as the cycle static temperature ratio (T_3/T_0) increases, the Mach number of the flow entering the burner (M_3) decreases. Thus, T_3/T_0 directly affects the free stream Mach number (M_0) at which the flow entering the burner (M_3) becomes supersonic. Due to this, it is possible that the manipulation of T_3/T_0 would yield a lower free stream Mach number at which supersonic combustion can occur. Additionally, the key design parameters of fuel selection and fuel-to-air ratio (f) for the scramjet may have an impact on the starting scramjet Mach number. A minimal variable geometry features should be used; therefore, exploring the use of variable geometry as a solution to the problem is not an option. Though the concept of the DCR engine may prove effective at lowering the starting Mach number of the scramjet, determining whether the starting Mach number of a "pure" scramjet can be accomplished should be the first task. Therefore, of these three possible avenues for investigation, the manipulation of the pure scramjet's key design parameters is the best approach for the current project.

B. Analysis of Key Design Parameters to Reduce Scramjet Starting Mach No.

The goals of this section are as follows: determine what impact the driving design parameters for a scramjet have in lowering the starting Mach number and assess whether a starting Mach number of 3.50 is currently possible or feasible in the future. Table 1 lists the one-dimensional stream thrust performance analysis inputs and how they are determined. As seen in the table, the vast majority of the inputs are set by the freestream Mach number, are properties that remain constant for air, earth, etc., or are assumed based on reasonable values within a typical range. The values for the constant and assumed inputs can be seen in Table 2 below. These values are used throughout the paper for all analysis calculations as needed unless otherwise noted. All assumed values were chosen based on recommendations from reference paper 1. Additionally, all constants were determined based on information in reference paper 1.

Table 1: Performance Analysis Inputs and Corresponding Determination Methods

Performance Analysis Inputs	*How Determined*
M_0, V_0, T_0, p_0	Set by Mach Number
C_{pc}, R, C_{pb}, C_{pe}, h_f, g_0	Constant
V_{fx}/V_3, V_f/V_3, $C_f(A_w/A_3)$, η_c, η_b, η_e, T^o, p_{10}/p_0, γ_c, γ_e, γ_b	Assumed
T_3/T_0, f, h_{pr}	Variation

For one-dimensional flow analysis, there are only three inputs that are able to be varied to alter performance results. These are the cycle static temperature ratio (T_3/T_0), the fuel selected, and the fuel-to-air ratio (*f*). But here we are concentrating only on cycle static temperature ratio (T_3/T_0).

Table 2: Stream Thrust Inputs: Values for Constant and Assumed Values

Constants [1]		
C_{pc}	1090.00	J/kgK
R	289.3	$(m/s)^2/K$
C_{pb}	1510.00	J/kgK
C_{pe}	1510.00	J/kgK
h_f	0.00	
g_0	9.81	m/s^2
Assumed Values [1]		
V_{fx}/V_3	0.50	
V_f/V_3	0.50	
$C_f{}^*A_w/A_3$	0.10	
η_c	0.90	
η_b	0.90	
η_e	0.90	
T^0	222.00	K
p_{10}/p_0	1.40	
γ_c	1.362	
γ_e	1.238	
γ_b	1.238	

C. Preliminary Calculation of Cycle Static Temperature Ratio T_3/T_0 Necessary for Starting Mach Number of 3.50

Due to the large design impact of T_3/T_0, this subsection will present the theory and governing equations that the preliminary investigation of this parameter requires. The largest factor in changing the freestream Mach number at which supersonic combustion begins is the cycle static temperature ratio, T_3/T_0. As T_3/T_0increases for a given freestream Mach number (M_0), the Mach number of the flow entering the combustor decreases. Thus, T_3/T_0 directly affects the M_0 at which the flow entering the burner (M_3) becomes supersonic. So, with a range of freestream Mach numbers, the necessary $T_{3/}T_0$ can be determined based on M_0 and the ratio of specific heats at compression (γ_c) where M_3=1 by the following equation.

$$M_3 = \sqrt{\frac{2}{\gamma_c - 1}\left\{\frac{T_o}{T_3}\left(1+\frac{\gamma_c - 1}{2}M_o{}^2\right)-1\right\}} \quad \ldots$$

(1)

The following subsection will detail methods which will more accurately weigh all of the design parameters' influences.

D. Analysis: Variation Of Cycle Static Temperature Ratio Influence: Impact on Lowering the Starting Scramjet Mach Number

The cycle static temperature ratio (T_3/T_0) has a powerful impact on the starting Mach number of a scramjet. As Equation 1 shows, T_3/T_0, the ratio of specific heats during compression (γ_c), and the freestream Mach number (M_0) are the only variables which determine the burner entry Mach number (M_3). The specific heat ratio can be considered constant in the compression component. With the requirement that M_3>1 to ensure supersonic combustion, lowering M_0 can apparently be achieved by lowering T_3/T_0. Therefore, T_3/T_0 has perhaps the greatest impact on whether it is possible to lower the scramjet starting Mach number. Thus, it is necessary to determine what the required value of T_3/T_0 is to achieve a starting scramjet Mach number of 3.50. Using Equation 1 with a range of freestream Mach numbers, and γ_c=1.36, the necessary T_3/T_0 for each freestream starting Mach number can be determined where $M_3 \geq 1$. According to the calculations in the reference papers, with generic values chosen for the fuel properties and the fuel-to-air ratio, the maximum T_3/T_0 for a scramjet with a starting Mach number of 3.50 to maintain supersonic combustion is 1.25 (with no available margin), which hardly requires any compression at all. Although a T_3/T_0 value exists for lowering the starting scramjet Mach number to 3.50, the overall performance values are quite low. Though scramjet overall efficiencies are commonly around 50%, and are often as low as 30%, the overall efficiency here is only 9%. This is a very low efficiency and one that severely impedes any possible benefits for starting the scramjet at M_0=3.50. Also, the values of specific impulse and specific thrust are significantly reduced with a value of T_3/T_0 this low. Therefore, this section has shown that further investigation of the remaining design parameters is needed to aid in lowering the scramjet starting Mach number, so that the T_3/T_0 value may be selected at a higher value closer to the value of 2.75. On the other hand, it is found out that a Mach no. of 4.00 is both feasible and practicable. Hence we take Mach 4.00 as the free stream Mach no. and carry out our analysis.The design of compression systems is characterized by the cardinal number of oblique shock waves available to produce a specified cycle static temperature ratio at a specified Mach number and in the cases when more than one shock wave is specified, all oblique shock waves must provide equal amounts of geometric turning of the flow. The compression sequence is assumed to begin at the leading edge of the vehicle. The input values are M_0, T_3/T_0, γ, and the number of desired oblique shock waves. The number of oblique shock waves has a direct impact on the compression efficiency (η_c). It is from these values and plotting the graph that an educated guess can be made as to how many shock waves are necessary based on the M_0, T_3/T_0, and the desired compression efficiency. It should be noted that the higher the number of oblique shock waves, the longer the compression system will be. Also, with more oblique shocks, more off-design complications will exist.

VII. DESIGN OF A SCRAMJET WITH STARTING MACH NUMBER OF 4.00

It is from the calculations from previous equations that concluded that a scramjet with a starting freestream Mach number of 4.00 is both currently feasible and worthwhile. The scramjet will be designed to operate from Mach 4.00 to Mach 10. Though Mach 3.50 would provide more of a margin, a Mach 4.00 starting scramjet is still a feasible choice, as a turbojet engine is capable of providing "thrust from takeoff up to a Mach of 3-4". Therefore, the benefits of having a lower starting Mach number scramjet would still be possible as a vehicle using this system would only require two propulsion systems, therefore reducing overall vehicle weight and complexity. Mach 10 is still used as the upper limit for the design of the flowpath. Waltrup states that the "maximum freestream Mach number of a hydrocarbon-fuelled scramjet-powered vehicle flying at 47.88 MN/m^2 trajectory would be between Mach 9 and 10". Therefore, in order to ascertain the overall vehicle performance of a Mach 4.00 starting scramjet across the entire possible performance range, Mach 10 is used as the upper limit of the flight path. This section will detail the design process for the flowpath of a scramjet with a starting M_0=4.00, T_3/T_0=2.80 obtained from reference papers. The design process includes the design of the compression system, isolator, combustion system, and expansion system. This section will detail the theory and equations behind the design process conducted for inlet/compression system of the scramjet engine component. The combustion system and expansion system are not in the scope of this project as this project only deals with the inlet part. The values and other data are directly taken from reference papers. The inlet part will be discussed here, and the other data are directly taken from other reference papers.

A. Compression System and Inlet Design

The goal of the compression system in a scramjet engine is to "provide the desired cycle static temperature ratio (T_3/T_0) over the entire range of vehicle operation in a controllable and reliable manner with minimum aerodynamic losses (i.e., maximum compression efficiency or minimum entropy increase". This compression, for the one-dimensional analysis used throughout this project, relies on oblique shock waves. Normal shock wave compression is reserved for ramjets as it is able to offer "reasonable performance for $0 < M_0 < 3$," whereas for Mach numbers greater than 3, the "normal shock losses become unacceptably high and oblique shock compression becomes necessary".

There are three options for the application of oblique shock waves in a scramjet, as listed and defined below: *Internal Compression:* All oblique shock compression waves occur inside of the engine's inlet. This is difficult to design and complex flows are produced at off-design Mach numbers *External Compression:* All oblique shock compression waves occur outside of the engine's inlet, utilizing the vehicle's forebody. The waves generally focus on and terminate at the cowl lip. *Mixed Internal and External Compression:* Mixtures of internal and external oblique shock compression waves are used. Compared to external compression, this method has, in general, less of an entropy increase, but the overall length required for the shock system is greater. This method "decouples[s] the engine cowl angle from the amount of compression and can result in a cowl that is parallel to the freestream flow". As an internal compression system is highly complex in design, the choice for this project is between an external compression system and a mixed internal and external compression system. The decision between these two options is generally based on practical integration issues. Since this project is a preliminary analysis based on one-dimensional flow and integration issues are not yet visible, mixed internal and external compression will be used as it allows for a cowl that is parallel to the free stream flow. Due to the complex nature of flow in a compression system, CFD analysis or physical experiments are often needed. However, for a preliminary study, estimation will suffice. Therefore, the following assumptions are made for the compression system design process: **1.** One-dimensional flow; boundary layer is represented only by its average effect on flow properties. **2.** Air is represented as a calorically perfect gas. **3**. Heat transfer to or from the wall will be neglected. With these assumptions, the software tool HAP (Gas Tables) can be used to calculate the performance of the resulting compression system. This tool accompanies the Reference 1 text and calculates the compression system's oblique shock wave configuration for the given number of oblique shock waves, the freestream Mach number, and the static cycle temperature ratio specified. The output is the resulting properties at the exit of the compression system (Station 2), the required turning angle for each shock wave to turn the flow through to accomplish the overall required compression, the static pressure ratio, the adiabatic compression efficiency, and the kinetic energy efficiency.

VIII. SCRAMJET DESIGN WITH FREESTREAM STARTING MACH NO. 4.00

The starting Mach number also serves as the on-design case or the engine flowpath as it is the limiting operation Mach number. This section will integrate the three components of the scramjet engine

Inlet Compression System Height and Length

Determining the height of the compression system as it varies axially is found by using two equations. Before these two equations are discussed, however, please refer to Fig-3 for the coordinate axes convention utilized for all ensuing equations and calculations.

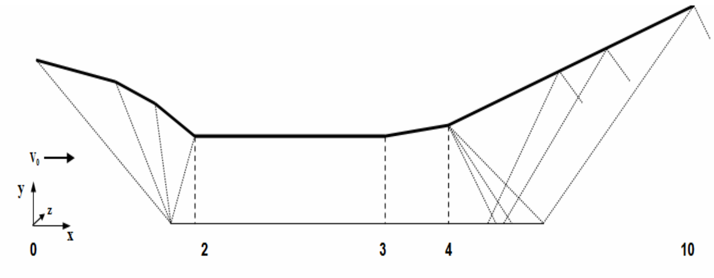

Fig 3: Coordinate Axes Convention for Scramjet Engine Designed & Conceptual Diagram of Four Oblique Shock System for Scramjet

With this convention in place, it is possible now to display the equations used for calculating the height *h* along the y-axis as it varies axially, that is, along the x-axis.

$$h_n = \frac{A_n}{A_2}(h_2) \quad \ldots (2)$$

Where, n = point on the x-axis;A = area.

Equation 3 is valid when the depth into the page (*d*) is constant for the length between two given station numbers. In other words, it is valid when $d_2 = d_n$ along the z-axis due to the following:

$$\text{For} \quad \frac{A_n}{A_2} = \frac{h_n d_n}{h_2 d_2},$$

when $d_2 = d_n$,

$$\frac{A_n}{A_2} = \frac{h_n}{h_2} \quad (3)$$

Therefore, using Equation 2**,** it is possible to calculate the height of the inlet at any given point along the compression system if the ratio of the area at that point to the area at the beginning of the isolator (A_n/A_2) is known. In the design of the inlet compression system, an output parameter produced by HAP (Gas Tables) is the area ratio of the area after each oblique shock to the inlet area at Station 0 (A_n/A_2). This information can be used to generate A_n/A_2 *after* each oblique shock using Equation 4 below.

$$\frac{A_n}{A_2} = \frac{A_n/A_0}{A_2/A_0} \quad (4)$$

With the value of A_n/A_2determined, the height of the compression system as it varies axially can therefore be determined by using Equation 2 above and the value of h_2, which is equal to 0.152 m, a value determined during the combustor design process.

The determination of the compression system length is an approximation using simple geometry and the properties of the compression system as depicted in Figure 3

The first three oblique shocks converge on the cowl lip of the engine, as seen in Figure 3 above. The value of $x_0$as depicted in the figure provides a good estimation of the length of the first three oblique shocks at M_0=4.00 using Equation 5

$$x_0 = h_0 \tan(90 - \beta_1) \quad \ldots (5)$$

Where, β_1 = wave angle of first oblique shock;
h_0 = height of engine inlet.

In order to find the best estimate of the length of the compression system, the length covered by the fourth and last oblique shock must be determined. This is done by Equation 6 below.

$$x_1 = \frac{h_0}{\sin \delta} \quad \ldots (6)$$

Where, δ = degrees each oblique shock turns flow through

Once x_0 and x_1 have been determined, the total estimated length of the compression system can be determined by summing these two values. The axial distance after each shock wave along the flowpath can then be determined by simple geometry, using the results for the height as described above. Performing the necessary calculations for both the height and length of the compression system, the data in Table 3 is obtained.

Table 3: Inlet Compression System Axial Height and Length for a Design Point of Mach 4.00

i	x (m)	A/A_2	h (m)
0	0.000	7.622	1.159
0a, after OS 1	2.534	3.679	0.559
0b, after OS 2	3.017	2.087	0.317
0c, after OS 3	3.149	1.355	0.206
0d, after OS 4	3.190	1.000	0.152

Plotting the height as a function of axial location shows the two-dimensional view of the scramjet's inlet compression system.

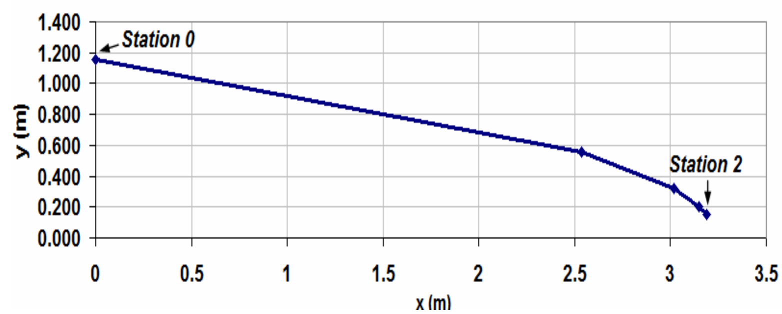

Figure 4: Inlet Compression System Two-Dimensional Schematic for a Design Point of Mach 4.00

IX. CFD METHOD

Modelling is the representation of a physical system by a set of mathematical relationships that allow the response of the system to various alternative inputs to be predicted. In Computational Fluid Dynamics, we model the physical system involving fluid flow within the definite boundaries by the set of mathematical equations usually in differential form and obtain the numerical solution of these governing equations describing the fluid flow by the use of computational methods. The governing equations may include: the set of the Navier-Stokes equations, continuity equation, and any additional conservation equations, such as energy or species concentrations. The fluid flow is modelled by the governing equations, which show the effect of the governing phenomena on the fluid flow. These governing phenomena may include: conduction, convection, diffusion, turbulence, radiation and combustion. The following is brief description of the governing equations.

A. Governing Equations

Continuity Equation

Considering the law of conservation of mass the continuity equation,

$$\frac{\partial \rho}{\partial t} + u.\mathrm{div}\,(\rho) + \rho.\mathrm{div}\,(u) = 0 \qquad \text{----- (7)}$$

In the given equation the first term is the rate of change of density. In the second and the third terms the divergence div is the flux density or flux/volume. The first two terms show the two ways the density of the fluid element changes. If we assume the incompressibility condition i.e. density of the fluid is constant, the above equation reduces to, div (u) =0.

Momentum Equations

Also known as Navier and Stokes equations, these are derived for a viscous flow and give the relationships between the normal/shear stresses and the rate of deformation (velocity field variation).We can obtain these equations by making a simple assumption that the stresses are linearly related to the rate of deformation (Newtonian fluid), the constant of proportionality for the relation being the dynamic viscosity of the fluid. The Navier and Stokes equation for i-th coordinate direction can be stated as

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + F_i \qquad \text{----- (8)}$$

Where τ_{ij} is the viscous force tensor and F_i represents a body force in the *i*-th coordinate direction. In practical situations of combustion, all fluids are assumed to be Newtonian and the viscous stress tensor is:

$$\tau_{ij} = \mu \left\{ \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right\} - \frac{2}{3}\mu \delta_{ij} \left\{ \frac{\partial u_k}{\partial x_k} \right\} \qquad \text{----- (9)}$$

Where μ is the molecular viscosity which depends on the fluid.

The Kronecker delta is δ_{ij} =1, if i = j, 0 otherwise.

k-ε Turbulence Model

Turbulent flows are characterized by fluctuating velocity fields. These fluctuations mix transported quantities such as momentum, energy, and species concentration, and cause the transported quantities to fluctuate as well. The simplest of "complete models" of turbulence are two-equation models in which the solution of two separate transport equations allows the turbulent velocity and length scales to be independently determined. The standard k-ε model in FLUENT falls within this class of turbulence model and has become the workhorse of practical engineering flow calculations in the time since it was proposed by Launder and Spalding. Robustness, economy, and reasonable accuracy for a wide range of turbulent flows explain its popularity in industrial flow and heat transfer simulations. It is a semi-empirical model, and the derivation of the model equations relies on phenomenological considerations and empiricism. The standard k-ε model is a semi-empirical model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε). The model transport equation for '*k'* is derived from the exact equation, while the model transport equation for 'ε' was obtained using physical reasoning and bears little resemblance to its mathematically exact counterpart. These two quantities are related to the primary variables and can give a length scale and time scale to form a quantity with dimension of v_T , thus making the model complete (no more flow-dependent specifications are required).

The turbulence kinetic energy, k, and its rate of dissipation, ε, are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \qquad \text{----- (10)}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S_\varepsilon - C_2\rho\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \qquad \text{----- (11)}$$

- G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy,
- Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
- $C_{1\varepsilon}$, $C_{2\varepsilon}$ and$C_{3\varepsilon}$ are constants. σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively. S_k and S_ε are user-defined source terms.

X. GAMBIT MODELLING AND FLUENT ANALYSIS OF SCRAMJET ENGINE WITH STARTING MACH NUMBER OF 4.00

The analysis is carried out by initially creating the design in "Gambit" and meshing in the same and then is transferred to "Fluent" for analysis..The model which was obtained, will be created in GAMBIT by the regular procedure. The model in this project is a 2-d model. In Gambit the key thing for analysis is meshing. The meshing had to be dense near the inlet of the engine when compared to the rest of the domain. For creating a model, the tables 3 & 4 will help us create the Inlet and Combustion sections. The height of the exhaust as discussed earlier is 2.8175m. The length of the exhaust is also mentioned in that section as 8.15m and therefore the data for modelling the main (upper) part of the engine is done. Now for the other part of the engine (lower part), it extends from the end of x_0 and beginning of x_1 in the inlet part in figure 5 to the point where $l_4$culminates and where l_{10}in the exhaust part starts as shown in figure 6**.**

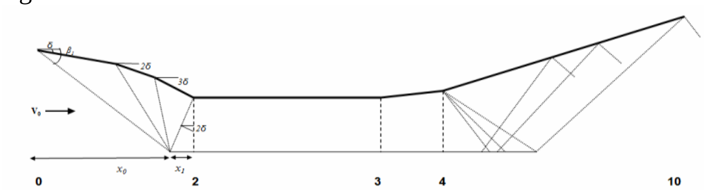

Fig 5: Conceptual Diagram of Four Oblique Shock System for Scramjet

The length x_1 is calculated using geometrical relations for 2δ, x_1 and h_2. Using geometry, we can write the relation as:

Tan 2δ = x_1/ h_2 … (12)

We know that δ value is 17.52 from θ-β-M relations for β=30°. And the value of β is derived geometrically from the figure 5 as the heights of h_0 and h_1 are known to us. Using the 2δ value, we substitute in equation 12 and we derive x_1.

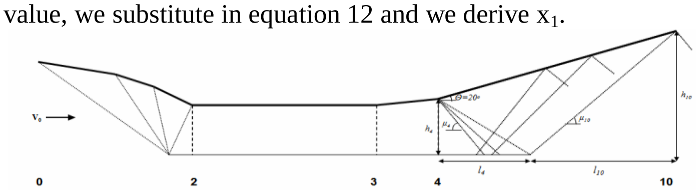

Fig 6: Expansion System Conceptual Diagram for Calculating Length

Thus as we know the values, with the help of tables derived earlier, we can summarize the values for the geometry as:

- INLET VALUES:

Upper Body:
1. (X, y): (0, 1.159)
2. (X, y): (2.534, 0.559)
3. (X, y): (3.017, 0.317)
4. (X, y): (3.149, 0.206)
5. (X, Y): (3.190, 0.152)

Lower Body:
1. (X, y): (3.1138, -0.3)
2. (X, y): (8.5190, -0.3)
3. (X, y): (4.4651, -0.8)
4. (X, y): (7.1677, -0.8)

- COMBUSTOR VALUES:

1. (X, y): (3.190, 0.152)
2. (X, y): (4.104, 0.152)
3. (X, y): (4.107, 0.152)
4. (X, y): (5.019, 0.283)

- EXHAUST VALUES:

1. (X, y): (13.169, 2.8175)

INLET RAMPS

Four different models are created in the analysis, namely: Single Ramp, Double Ramp, Tri Ramp and Four Ramps. The ramp angles were obtained in the analysis part in earlier and the ramps are varied in the following way: For a Single ramp engine model, all inlet values will not be considered, inlet values (upper body) of 1 and 5 will directly be joined and values 2, 3 and 4 are not taken into account. 1 and 5 points are directly joined and the line joining points 1 and 5 is the single ramp of the engine model. For Double ramp engine model, inlet values (upper body) of 1, 2 and 5 are joined and values 3 and 4are not taken into account. Lines joining points 1-2, 2-5 form two ramps of the engine model. For a Tri ramp engine model, inlet values (upper body) of 1, 2, 3 and 5 are joined and 4th value is not considered. Lines joining the points 1-2, 2-3, 3-5 form three ramps of the engine model. For Four ramp engine model, all inlet values (upper body) are joined. Lines joining 1-2, 2-3, 3-4 and 4-5 form four ramps of engine model.

Using these values, we create the desired model, domain and mesh it. The lower part of the inlet is same for all the models, be it Single/Double/Tri/Four ramp model. The denser the mesh is, the more precise is the result we achieve. As this project is on the inlet part of the engine, we dense the mesh more on the inlet part than in other areas of the domain. Few domains were tried out in the process and a couple of them were found to be appropriate for the project. The final product of the design in GAMBIT is transferred to FLUENT. Results are captured for mach numbers, pressure and temperature. The efficiency and performance of the models are discussed based on Compression efficiency and temperature ratio (T_3/T_0).

CFD ANALYSIS

Initially analysis was done with less dense mesh in Gambit and the results were not in any way closer to the analytical values. Therefore in order to get more precise values, we mesh the model denser to around 100,000 elements for all the four ramps individually.

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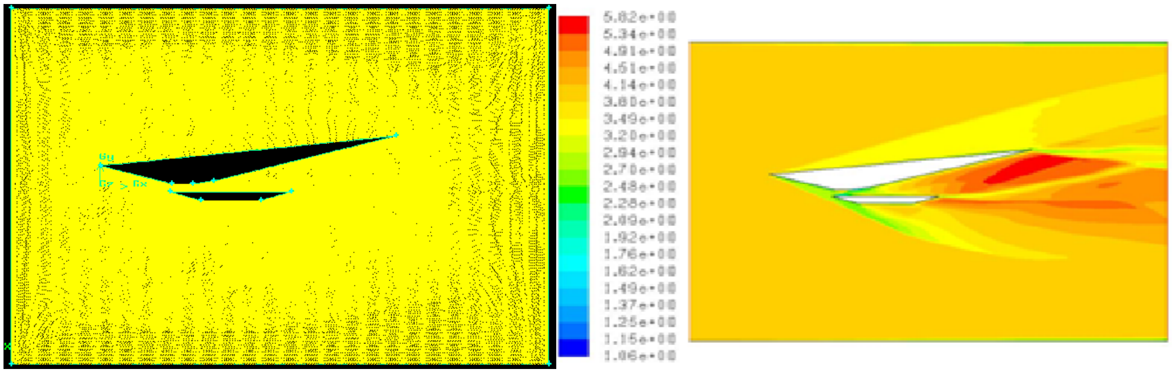

Fig 7: Model for Single Ramp with around 100,000 elements in GAMBIT &Velocity Contour for the above model in FLUENT

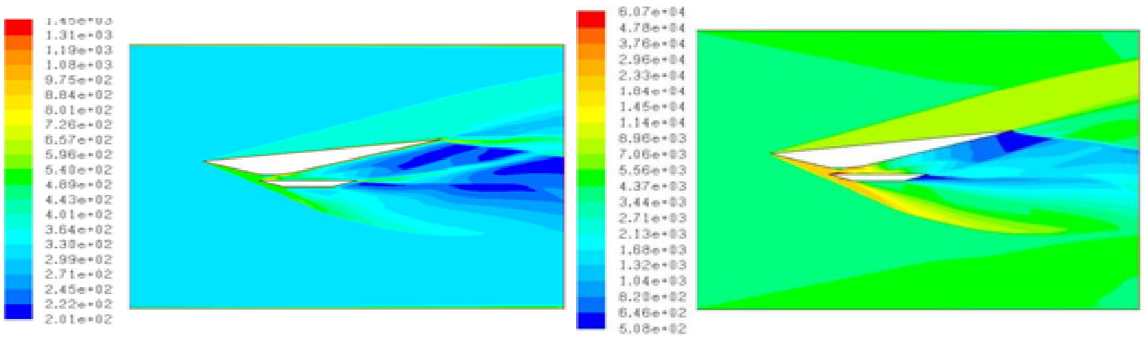

Fig 8: Temperature & Pressure Contour for single ramp for above model

From the above four figures shocks can be visualised due to which the change in flow parameters like Mach number, pressure and temperature can be obtained. The above model is with single ramp such that single shock is obtained but the compression efficiency is very less. So, to increase the compression efficiency it is desired to increase the number of oblique shocks by increasing the number of ramps. The next model is with double ramp to get two shocks. After analysing the following flow contours have been captured .

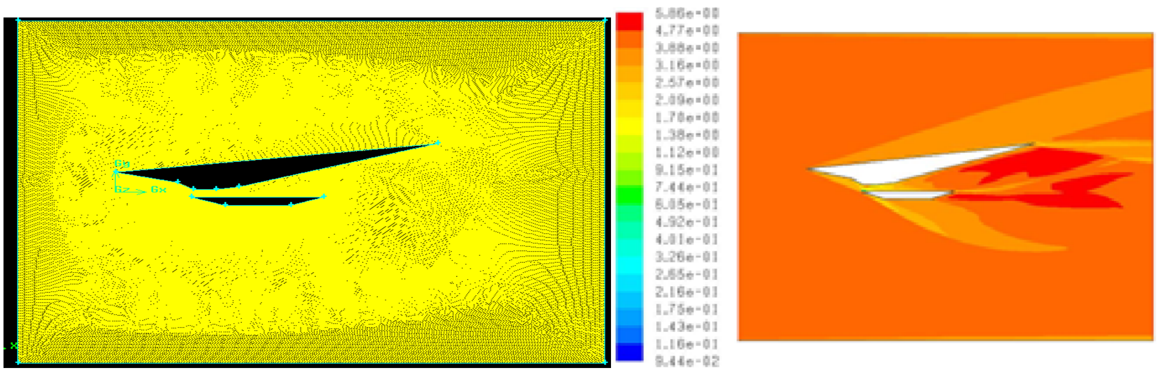

Fig 9: Model for Double Ramp with around 100,000 elements in GAMBIT and Velocity Contour for the above model in FLUENT

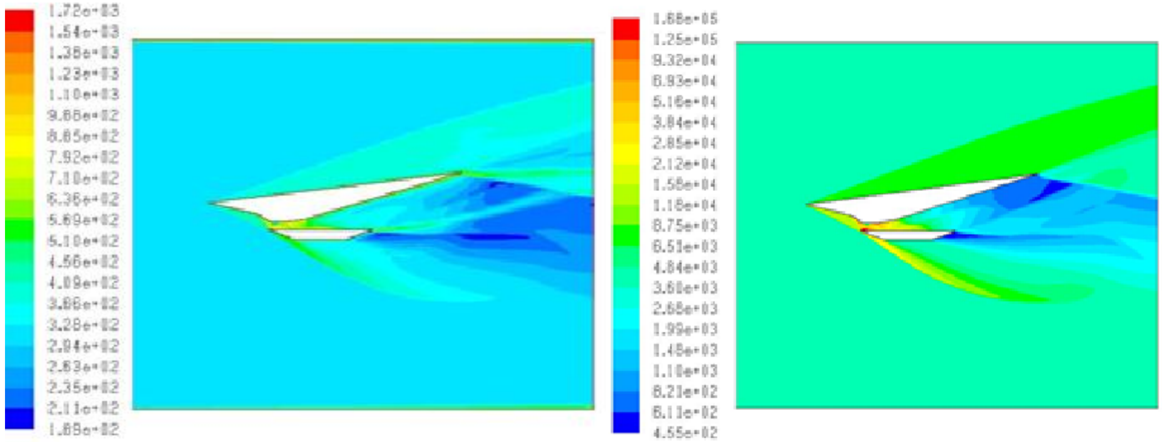

Fig 10: Temperature & Pressure Contour for double ramp for above model

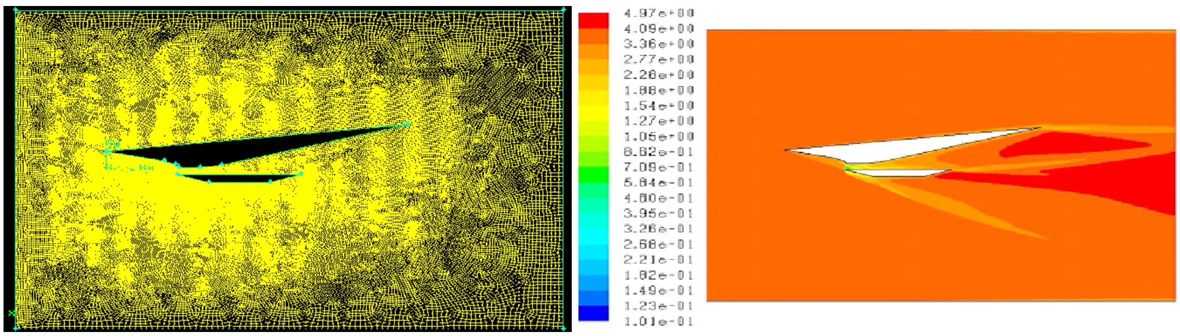

Fig 11: Model for Tri Ramps with around 100,000 elements in GAMBIT and Velocity Contour for tri ramp for above model.

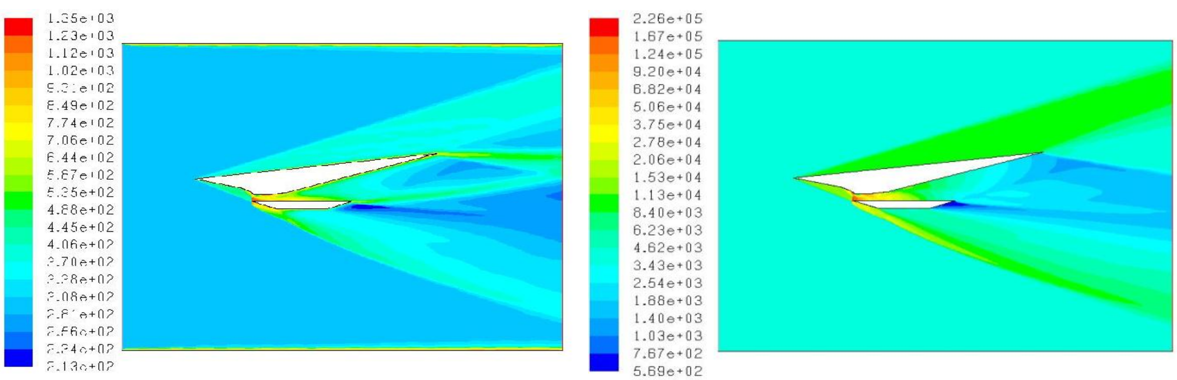

Fig 12: Temperature & Pressure Contour for tri ramp for above model

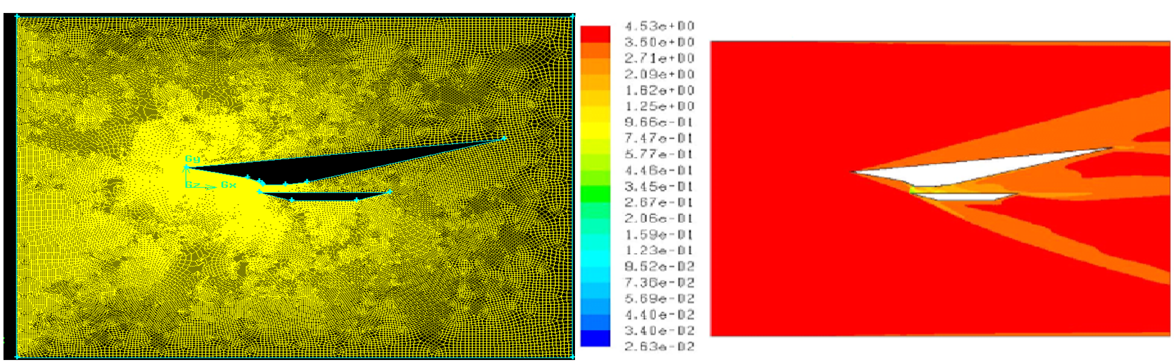

Fig 13: Model for Four Ramps with around 100,000 elements in GAMBIT and Velocity Contour for four ramp for above model

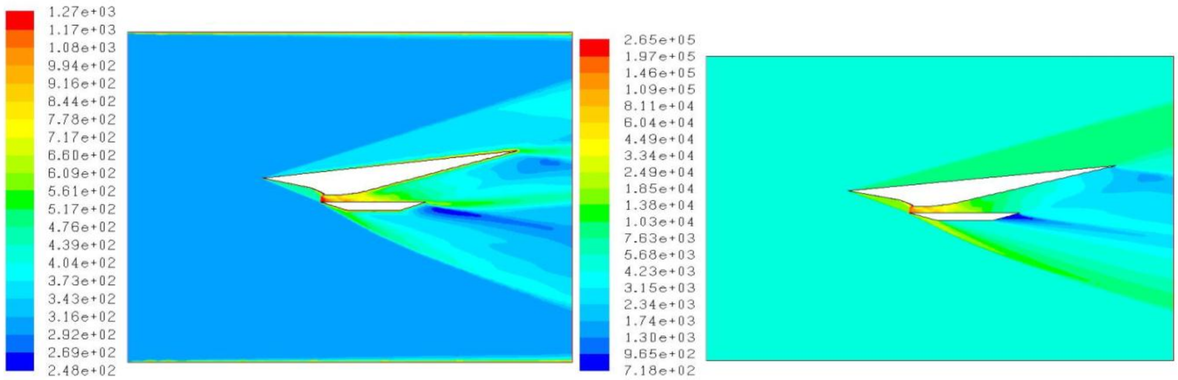

Fig 14: Temperature & Pressure Contour for four ramp for above model

The results of all the above models are tabulated in the table 4 below. Further discussions are made after the table

Table 4: Result Summary of all the models discussed above

Ramps	Mach No. CFD	Mach No. Analytical	T_3/T_0 CFD	T_3/T_0 Analytical	P_3/P_0 CFD	P_3/P_0 Analytical
Single	2.62	3.1	2.07	1.41	13.4	8.3
Double	2.21	2.45	2.25	1.86	21.8	19.7
Tri	1.81	1.93	2.64	2.32	29.23	29.4
Four	1.51	1.47	2.85	2.8	35.4	34.69

We can observe that the final model, i.e., four ramp model with around 175,000 elements is very close to the theoretical result of M_3=1.58. It was evident from the analysis that results were better achieved with four ramps amongst all tried ramps. As discussed earlier, a turbojet engine can provide thrust from take off to a speed of Mach 3 or 4. Therefore, if the scramjet is designed applied to a hypersonic cruiser it could presumably allow for a reduction in total propulsion system. The analysis done also supports the theory with concrete evidence in the results tabulated above with small difference in values. Off-design conditions were also checked out with four ramp model with Mach Numbers 3,6,8,10 but the results were not desirable and moreover, Mach number 3 and 10 gave unstart related problems.

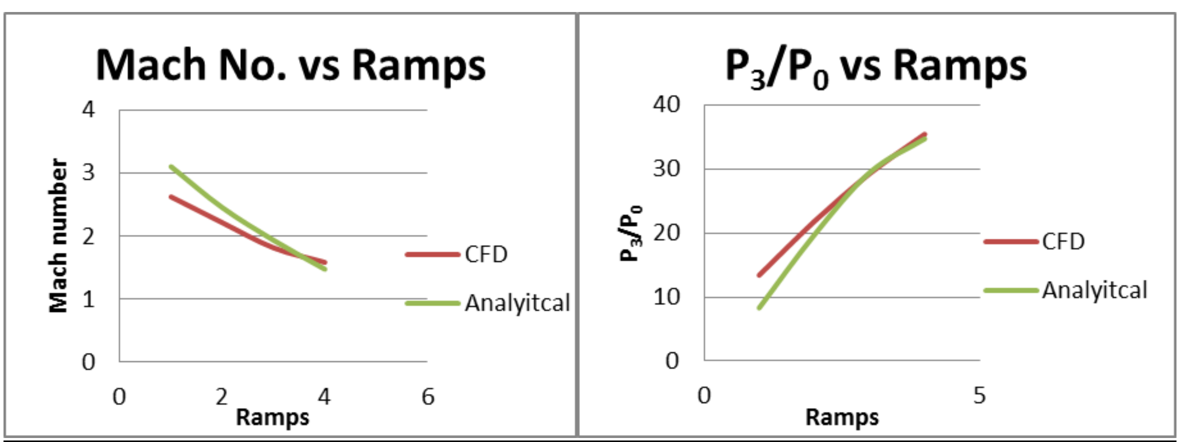

Fig 15: Mach number vs Ramps & P_3/P_0 vs Ramps

XI. CONCLUSION& RECOMMENDATIONS

The purpose of this paper was to determine at which lower freestream Mach number the Scramjet Engine will start so as to reduce the weight of the craft by eliminating one of the propulsion system while performance is maintained in the same flowpath at the higher, off-design Mach numbers and to define how it could be accomplished. Hence, a Scramjet engine was then modelled in GAMBIT and analysis was carried out in FLUENT for the same with different design models. It was found out that a model with starting Mach number of 4.00 was feasible as it matched the theoretical values with CFD values. Amongst all designs, a design with four ramps yielded better results than the other designs. By this Analysis we can conclude the "K-epsilon turbulence model exactly simulates the flow field characteristics in supersonic and hypersonic conditions" in capturing shocks at leading edges and shock trains in the isolator and etc. The present analysis shows that with this design Starting Mach number of Scramjet can be reduced to Mach number 4 but with the same design Scramjet is facing the unstarting conditions for off design Mach number of 3 and 10.

At the closing of this report, it is evident that there are important areas which call for future research and analysis. The first of these is that analysing three dimensional scramjet inlet and the next is application of a fully designed expansion system employing the use of method of characteristics or CFD codes. This will enable more precise calculations of performance, as well as provide more realistic overall engine lengths to be obtained, as the nozzle does not have to be fully expanded to freestream conditions to gain a satisfactory amount of thrust. As for the practical design of this scramjet, the use of cavity-based fuel injectors should be explored. Additionally, the method of fuel-air mixing, combustion time required, and overall potential benefit of cooling scramjet with the fuel should be explored. For the next step in the design of this particular scramjet, higher fidelity analysis methods should be employed, to ensure that frictional effects would prove interesting and provide direction towards the application of this engine.

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