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A Theoretical Study on the Characteristics of Scramjet

Vishnu Prakash B*, Shrutee Upganlawar

***Corresponding Author Email: vishnuprakash.aeroin@gmail.com**

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Abstract - This study aims to investigate the characteristics of scramjet engines in a theoretical manner that are indispensable for hypersonic flight. The study is focussed on the following topics- types of fuels used in scramjets, Brayton cycle for scramjet, the hypersonic air intake, speed for compression, the combustion chamber that enables combustion due to air-fuel mixing and the nozzle that propels exhaust. A thermodynamic and fluid dynamics related study has been done for investigating the parameters that affect the performance and efficiency of a scramjet. Further, some design characteristics have also been discussed such as inlet design, nozzle design, combustor geometry, etc.
Subsequently, with the aid of studies involving simulation tools to carry out CFD analysis, an understanding of how shock wave train, scramjet's operating envelope and mixing processes affect the efficiency has been presented.

Key Words: Scramjet technology, nozzle, combustor, hypersonic speed, air-fuel mixture

1.INTRODUCTION

An air breathing jet engine is a type of aircraft engine that uses atmospheric air to propel the aircraft. In this type of aircrafts, the atmospheric air acts as the exhaust gas required for the propulsion. These engines perform dual role of producing lift as well as maintaining it [1].
The aircraft intakes the air, starts compressing it and then gets mixed with aircraft fuel present in the combustion chamber of the engine. This air fuel combination produces exhaust gases which is expelled out thereby providing propulsion to the aircraft [2].

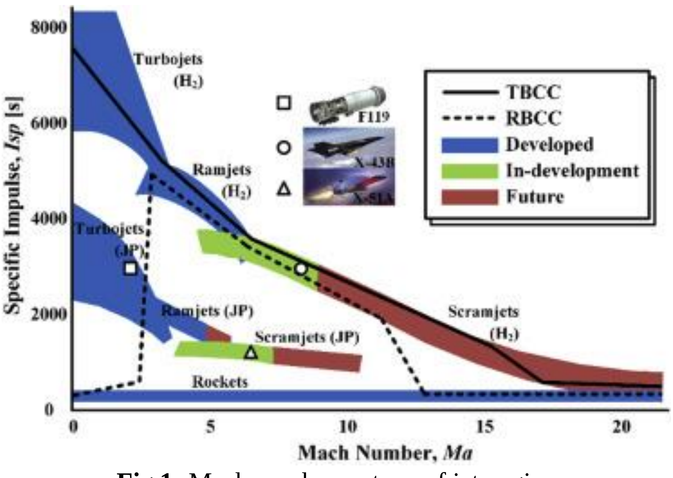

Fig 1- Mach number vs type of jet engine

TYPE OF AIR BREATHING JET ENGINE	FEATURE
Turbojet	Operates at subsonic speed
Ramjet	Does not contain a compressor and turbine with 3<M<6
Scramjet	M>6

Table 1: Features of some types of air breathing engines

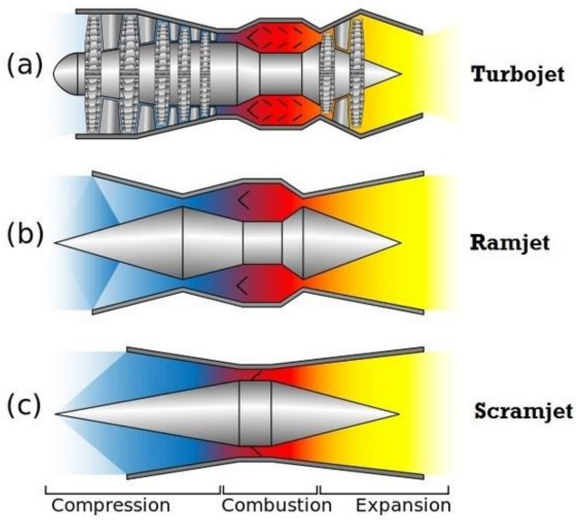

Fig 2- Diagram for engines in various parts

Scramjet stands for Supersonic Ramjet. Scramjets have emerged in the field of aerospace engineering owing to their ability of combusting the fuel at a speed greater than the speed of sound (hypersonic speed). The provision of air breathing technologies allows for more payloads carrying capacity to the aircraft and hence the ability to run at faster speeds compared to other jet engines [3].
Scramjet has several key features:

1. Air breathing: These engines take in atmospheric oxygen during flight thus considerably reducing the amount of propellant required which makes them more efficient.
2. Hypersonic speeds: They depend on the vehicle's forward speed itself to achieve a supersonic compression.

3. Fewer movable components: Scramjets differ from conventional jet engines using rotating compressors and turbines with minimal moving parts hence they are simpler and more reliable.
4. Supersonic combustion: Hypersonic flow ignites injected fuel within scramjet combustor. It is a process that occurs at very high speed compare to those of ramjets [4].

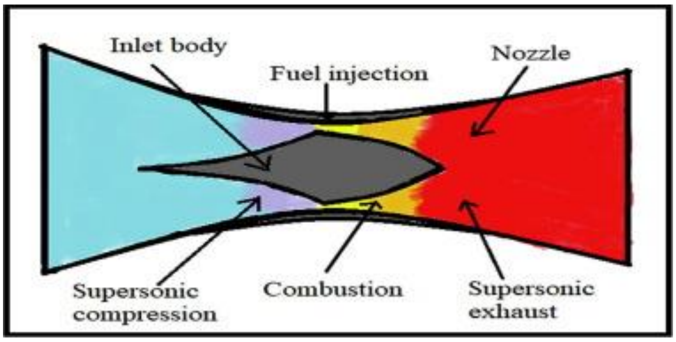

Fig 3- Scramjet engine

As seen in the figure 3, the incoming air is compressed in a tube-like chamber. The forward motion of the aircraft is used for compression. Then, this compressed air blows into the combustor where fuel is injected at precisely calculated moments creating an area of high-speed mixing. Combustion in this zone creates supersonic combustion which takes place when both fuel and air burn at hypersonic speeds producing high heat. The final stage occurs inside the well-designed nozzle of a scramjet. It is in this nozzle that the blazing hot, high-pressure mixture of gases will be channelled before it can be accelerated to even higher supersonic velocities. This rapid acceleration passes through the rear end of the engine where there is magic behind scramjet propulsion resulting into thrust for vehicle movement that travels at hypersonic rates [4].

2. THERMODYNAMIC AND FLUID DYNAMICS CHARACTERISTICS

2.1 Thermodynamic Cycles

Scramjet's thermodynamic cycle is based on the Brayton cycle/Joule cycle and consists of four main processes-

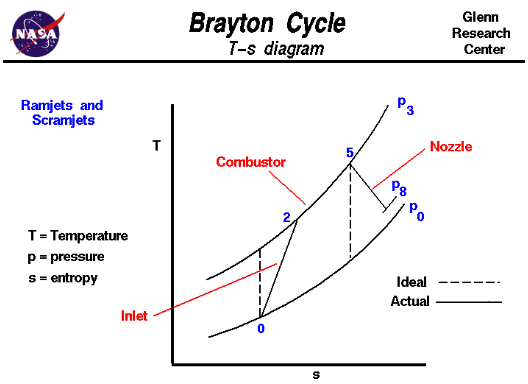

Fig 4- Brayton Cycle

It essentially consists of four steps-isentropic compression, constant pressure heat addition, isentropic expansion, and constant pressure heat rejection [5]. In aircrafts moving at hypersonic speeds, like that in scramjets, the cooling of scramjet poses a major issue. The flow rate of combustion should be higher than the fuel consumption rate of cooling. But with conventional regenerative cooling, this becomes difficult to maintain this required flow [6]. In regenerative cooling, the fuel absorbs the heat dissipated by the walls of engine but in scramjet, the fuel flow rate of scramjet is very less to cool the engine [6]. Researchers have found a method of having SCO_2 (supercritical carbon monoxide) for scramjet. Although initially this method increased the fuel consumption but by having different layouts by changing the location of split point, optimizing parameters of turbine, compressor, heat exchangers, etc. This also increased power output and reduced fuel consumption [7].

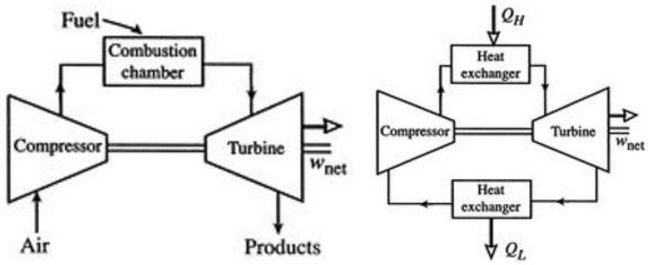

Fig 5- Open and Closed Brayton Cycle

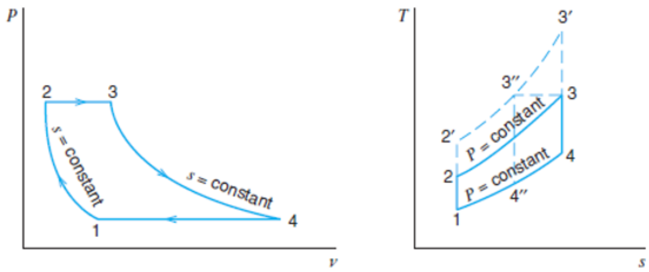

Fig 6- P-V and T-S diagram for thermodynamics of Brayton Cycle

The study conducted by Min Ou, Li Yan, Wei Huang and Xiao-qian Chen explored methods to enhance a Scramjet's performance using thermodynamic analysis. Their key findings were:
For scramjets, combustion is the optimal process to heat the air. This air expands rapidly and in order generates thrust. Hence, efficient fuel burning (combustion) significantly affects the overall performance of a scramjet.

1. Compound combustion was found to be the best combustion mode wherein the booster combustion, that is, burning of the propellant in booster itself, which in turn generates the huge amount of thrust to propel the LV during its ascent, was used at early stages. This thrust was subsequently converted into the ideally achieved highest temperature for the air fuel mixture considering no heat transfer.
2. Air fuel significantly affects the efficiency of a scramjet. The specific thrust (Fs) is found to be directly proportional to the air-fuel ratio.
3. Although increasing air-fuel ratio increases the Fs, but it also decreases ramjet's specific impulse (Specific impulse talks about the amount of thrust produced per unit of fuel). Hence a proper balance is needed to avoid the fuel consumption from crossing the thrust generation.

4. The paper concludes that finding the optimal air-fuel ratio that strikes a balance between achieving high thrust and maintaining good fuel economy is the key while maintaining the combustion efficiency [8].

2.2 Fluid Dynamics of Airflow Compressions and Combustion

In scramjet engines, due to high-speed airflow and combustion process, a sequence of disturbances that travel at a speed surpassing the speed of sound in that medium, called shock wave train are formed. They cause sudden change in the pressure, temperature, and density of the medium as they pass through it [9].
The study conducted by S. K Gugulothu and Prabhu Kishore Nutakki delved into the analysis of the performance of scramjet engine combustor in two modes- namely, cold flow (simulating engine without combustion) and engine ignition (initiating combustion in the engine through ignition). Various simulations were used to draw out the significance of injection temperature, pressure and movement of shock wave train. Turbulence models and conservation principles were solved to bring out the following theoretical investigations:
A shock wave is a disturbance that travels at a speed faster than the speed of sound in that medium. A series of such waves is termed as shock wave train. While in a cold flow, the shock wave train is at observed at a lower position than in engine ignition condition in the combustor. Additionally, when the injection pressure (the pressure with the fuel is passed out of the injector nozzle) increases, the shock wave trains are forced into the isolator.
The other factor to influence the fluid dynamics is the initial temperature of the injected fuel, technically named as, injection temperature. It affects the variation of pressure and Mach number in the broadening section of the combustor. Another aspect of increasing injection temperature is that it can lead transition from scramjet mode to ramjet mode. But while in cold flow, injection temperature plays a comparatively minimal role [10].

3. DESIGN AND OPTIMISATION CHARACTERISTICS
3.1 Inlet design for efficient air compressor in ramjet

Designing of the scramjet inlets is a challenging task because of the hypersonic airflow, high temperatures, and the need to efficiently compress the air before it enters the combustor, etc. It becomes important to make an efficient design for scramjet inlet because the later captures air from the atmosphere, slows it down supersonically and compresses it before it enters the combustor. Efficient compression increases the air density which leads to more efficient fuel burning and better thrust generation.
A study by Prof. Michael Smart on scramjet inlets has described three types of scramjet inlets:

1. External compression inlet which uses external compression surfaces that slow down and compress the airflow before entering the engine.
2. In Internal compression inlets, internal shocks slow down and compress the airflow.
3. Mixed compression inlets external surfaces to generate a preliminary wave. This slows down the airflow, followed by internal compression components to further compress the air.

Their study also highlighted the factors to be considered while designing a scramjet inlet:

1. Compression ratio: Higher compression ratios lead to better engine performance.
2. Mach number
3. Inlet efficiency: This refers to the amount of energy lost during the compression process. For optimal results, the inlet should compress the air with minimal energy loss [11].

3.2 Nozzle Geometry

In their paper, Rui Li, Jinglei Xu, Kaikai Yu, Zheng Lv and Kuangshi Cheng, addressed the problem of fuel injection in scramjets which interrupts the passage of air which adversely affects the performance of a scramjet's nozzle hindering thrust. The paper proposed a method that uses Rao's maximum thrust theory and the slip-line unit process to mitigate the negative influence of the internal contact discontinuity on the aerodynamic performance. The flow is divided into upper and lower region. Rao's maximum thrust theory focuses on maximising the axial thrust generated by the nozzle which propels the vehicle. This theory aims to achieve the maximum thrust possible under the given conditions. The theory states that the flow leaving the nozzle must be parallel to the axial direction in its entirety. The physics behind this is that the by aligning the nozzle with the axial direction ensures that all the flow from exhaust is used for generation of thrust hence mitigating any losses.
In Split theory, the material is divided in different regions depending on their flow properties and investigating the compatibility conditions among these regions. Now when the non-uniform flow enters the nozzle, along with flow properties of fuel and nozzle material, compatibilities are checked to find the factors for smooth flow, minimizing flow separation, alignment of the flow.
These two theories increase the axial thrust, enhances flow transition, pitching moment control (ability to manage aircraft's rotational movement around the pitch axis). Pitching moment is created when the lift created by the wings is not properly centred at the centre of gravity which in turn creates a torque. Pitching moment magnitude is defined as the distance between the centre of lift (point where the force acts) and the centre of gravity. Rudders and fins are used in addition with engine thrust to control the pitching moment. For the validation and testing, it was considered that there are no chemical reactions taking place in the flow. The aim was to compare the proposed methods with the truncated methods of analysing scramjet. The truncated methods include negligence towards non uniform flow at the inlet, ignorance towards the shock wave which are created due to high speed and complexity. Computational methods were carried out for the assessment of this comparison. The conclusion was that the proposed theories improve the performance reducing the impact of discontinuities [12].

3.3 Mixing and Transient Combustion Process

The research paper is based on usage of hypermixer to enhance the performance of scramjet combustor. Traditional injector

designs are incompetent in the complete mixing of fuel and air at hypersonic speeds and this leads to achieving lesser than the target amount of thrust. A new approach for using hypermixer was introduced in which the streamwise vortices are created within the combustor. Streamwise vortices are the regions in a fluid exhibiting rotational motion that are oriented parallel to the main flow direction. Streamwise vortices exhibit an axis parallel to the main flow direction.
They are created when-
1) When two fluids having different velocities flow adjacent to each other forming a shear layer leading to the formation of streamwise vortices.
2) Induction of such vortices due to curved geometries of various components.
3) Intended injection of a fluid sideways for specific applications.
Streamwise vortices affect the flow performance as:
1) They improve the mixing of fluids.
2) They help in the transfer of momentum among different parts of the flow.
3) When needed, they also create turbulence in the flow.
The paper involves using computer simulation to compare hypermixer with traditional scramjet engine. The simulation was based on the following factors:
1) Air-fuel mixture ratio.
2) Mixing efficiency of air and fuel.
3) Shock wave structure.
4) Mode of combustion.
5) Combustion efficiency.
The results showed that a hypermixer significantly enhances the efficiency of scramjet engine, mixing and combustion of fuel and air.
The numerical methods for computer simulation such as enhanced delayed detached eddy simulation (IDDES) coupled with the Thickened Flame Model and a seven-species, seven-reaction H2/air reaction mechanism was used [13].

4. FUEL TYPES

Jet fuels are the source of power for the aerospace vehicles. Decades of research have developed and found varied types of jet fuels for powering the jet engines. The constraints must be taken into consideration to optimise the performance of jet engines. It is found aircrafts are fed in with fuel volumetrically. This implies that the amount of air taken inside the cylinder will determine the efficiency of burning of fuel. This method is known as volumetric fuel consumption. Less dense fuels follow gravimetric energy density while the denser fuels follow volumetric density. Gravimetric density is simply the energy stored per unit mass of the fuel substance.

Following table summarises the various types of fuel and their properties [14]:

Table 2- Types of Fuels

TYPE OF FUEL	PROPERTIES	IMPLICATIONS
JP-7	High flash point, low votality, high density, low flammability, and excellent thermal stability	a. Requires an initiator for combustion. b. Emits CO and CO_2
JP-8	Low flash point, high volatility, low density, high flammability, and good thermal stability	a. Uses non-renewable hydrocarbons. b. Emits CO and CO_2.
H_2	High lower heating value, low density, high flammability, causes very less pollution,	a. Low density means more fuel is required.
Kerosene	High flash point, low volatility, high density, low flammability, good thermal stability, easy storage	a. Low density means more fuel is required.

There are various trade-offs between kerosene and H_2 as a fuel to be used in the scramjet engines. Due to its high enthalpy, high density and other factors, kerosene gets an upper hand. Kerosene shows effective thrust generation, low ignition delay, etc. Although it requires more fuel due to its low density.
On the other hand, H_2 fuel also ensures less delays in ignition, and better mixing at par with other hydrocarbon fuels. H_2 fuel enhances mixing rate in the combustor while also enhancing cooling of strut. However, they pose disadvantages of lower volumetric energy, difficulty in storage due to higher flammability, etc. Although, it has been noticed that the implications with H_2 fuel can be solved using H_2-hydrocarbon hybrid fuel [15].

5. CONCLUSIONS

- SCO_2 brayton cycle can be used for scramjets as it enhances the power output and reduces fuel consumption by changing various parameters of compressor, turbine, etc.
- Thermodynamics: Efficient fuel combustion is a precursor for optimal performance. Compound combustion, booster combustion, high temperature air fuel mixing. Finding the optimal balance of the air fuel mixture is crucial for achieving proper thrust, specific impulse, and fuel efficiency.
- Fluid Dynamics: Shock wave trains significantly affect the scramjet performance. Injection pressure, temperature, shock wave position are interdependent on each other.
- Design and optimisation: Inlet design plays a crucial effect on design efficiency of scramjet. Compression ratio, Mach number and inlet efficiency are important factors affecting the inlet design.
- Nozzle geometry: Fuel injection introduces discontinuities in the flow. Rao's maximum thrust theory and slip line unit process help in

minimising the discontinuities caused by the fuel injection.

- Mixing and transient combustion: Using a hyper mixer in scramjet engine improves the mixing and combustion efficiency by creating streamwise vortices that the traditional injector designs lack.
- JP-7, JP-8, H_2, Kerosene fuels are few of the most widely used jet fuels used in hypersonic aircrafts. Kerosene and H_2 are the most environment friendly and thermodynamically efficient fuels but comes with disadvantage of requirement of more fuel in accordance to their low density.

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The heading should be treated as a 3rd level heading and should not be assigned a number.

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