AE8108 – Aircraft Turbine Engine
Project 2

Hypersonic Flight – Scramjet Propulsion

By: Aman Gilani
500879895

1.Introduction

Hypersonic flight is one of the emerging scientific innovations in the aviation sector amongst efficient aircraft engines and reusable rocket flights. Defined as flights speeds exceeding Mach 6[1], hypersonic flight offers a world of faster and efficient air travel with commercial, military and space applications. At the heart of this innovation lies the scramjet engines with the ability to fly higher altitudes at supersonic Mach numbers. Unlike a modern jet engine, although as the name ‘scramjet’ suggests, it is a jet engine that allows for supersonic and hypersonic airstream combustion in the burner section of the engine with no mechanically moving parts throughout. The engine uses its geometry to compress the incoming airflow to increase the burner efficiency. On the other hand, unlike the rocket engine which also fly at hypersonic speeds, the scramjet eliminates the need to carry oxygen cylinders by using the atmospheric oxygen and therefore having the ability to carry more payload weight. These features make the scramjet technology lighter, efficient and faster than the tradition commercial and rocket engines.

This report dives into the intricate function and operation of the scramjet engine technology, aiming to deliver a comprehensive knowledge about the principles of hypersonic flight. Though various propulsion systems have been used to achieve a hypersonic flight, rocket engines and orbital re-entry vehicles, the complex yet simplicity of a scramjet engines present various advantages over the others in terms of efficiency and fuel consumption. Some key topics important for a hypersonic flight discussed in this report are air flow management and thermo-acoustic management of the engine. The airflow management of a scramjet engine encompasses the design of a supersonic inlet and an isolator entrance section that can reject disturbances created during flight to avoid an engine unstart condition. On the other hand, the thermal management of the engine includes combustion stabilization techniques to ensure optimal thermal and burner efficiency. The high-speed combustion in the burner section generates enormous energy in order to efficiently fly at hypersonic speeds. However, at the same time, this poses a design problem for the engineers to choose an appropriate material for the engine or use active cooling techniques that can withstand intense temperature and pressure fluctuations in the engine.

2.Hypersonic Flight - History

The innovation in aviation began with the practical flight of Wright Brothers in 1903. In a very short time, the advancement in technology, science and engineering made it possible for the first ever hypersonic flight in 1949. The WAC Corporal flew approximately at 5 times the speed of sound in the New Mexico desert. Following this, in the year 1961, various countries including Russia, and the United States featured flights with hypersonic capabilities. In Russia, the Vostok I capsule entered the atmosphere at approximately 25 times the speed of sound. On the other side of the world, US air force flew the X-15 aircraft at Mach 5.3. In doing so, they became the first ever to set the record for the highest miles per hour in an aircraft reaching a velocity of 3600 mph. This record was only extended by the same test pilot later that year, flying the X-15 at Mach 6.[2]

From the beginning of aviation, engineers and scientists have strived harder and harder to make the aircraft fly as fast and efficient as possible. Starting with a 35-mph flight by the wright brothers, transitioning to 1200 mph flight by the X-15 experimental hypersonic aircraft and finally capped by the space shuttle with its Mach 25 re-entry into earth’s atmosphere. This trend illustrates massive advancements in aerodynamics, gas dynamics and thermal efficiency characteristics of an aircraft while exploring the extreme high-speed end of the spectrum. Another strong contender for sustaining hypersonic flight is a hybrid engine. These engines are usually a combination of multiple propulsive systems working in tandem or in stages. A two-stage-to-orbit vehicle design combines a hypersonic ramjet/scramjet engine for the first stage and a rocket powered orbiter for the second stage riding piggyback.[2]

A recent success in hypersonic flight came with the flight of the X-43 Hyper-X unmanned research vehicle. In late 2004, the X-43 became the first aircraft to have achieved a sustained Mach 10 flight for approximately 10 seconds. The vehicle was propelled by a scramjet engine developed by NASA, ATK GASL and Boeing.[3]

3.Scramjet Engine

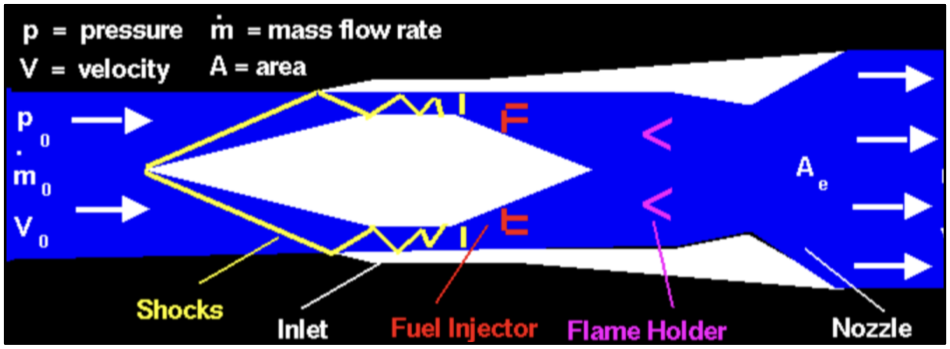

Figure 1: *Scramjet Engine Design.[4]*

A scramjet engine is a jet engine that flies at hypersonic speeds by burning the incoming airflow at supersonic speeds. The engine consists of a converging inlet, followed an isolator, a combustion chamber and finally a diverging nozzle. In the convergent inlet and the isolator section, the incoming flow undergoes a series of shocks thus increasing the airflow's pressure and temperature. This supersonic and compressed flow goes though the combustor chamber where in the fuel is injected and the combustion occurs. Since the inlet flow is hypersonic, the flow in the combustion chamber is also supersonic typically between Mach 2-3.[1] The heat produced in the convergent section expands in the diverging nozzle to produce enough thrust.

A scramjet engine usually consists of a combination of two airbreathing propulsive systems. A turbofan engine and a ramjet engine are combined for the aircraft to self-propel to higher altitudes and higher speed for the scramjet to function. The scramjet consists of a long hollow tube for the combustion to occur. This configuration of the engine doesn't contain any compressor fan blade to compress the incoming airflow. The flow is compressed by the shape of the inlet, the isolator and the forward speed of the aircraft. It is clear that the scramjet engine cannot function through itself as it requires high speeds and altitude. This is why, the scramjet engines are typically used as a second stage engine with a primary propulsive system to power the first stage of the vehicle.

The following table lists some of the important advantages and disadvantage of a scramjet engine.

Table 1: *Advantages and Disadvantages of a Scramjet Engine.[1]*

Advantages	Disadvantages
• Higher flight speeds with simple geometry and light weight engine.	• Can only be operated at high speeds and altitudes.
• Eliminates the need for an oxygen tank.	• Design and testing cost is high.
• Provides low-cost access to outer space.	• Engine cannot function from ground (at rest).
• It contains no moving parts, thus reducing mechanical complexity.	• Material selection that withstands high temperature fluctuations.

	• Insufficient air for fuel mixing at high altitudes.

4.Review of Existing Scramjet Engines

In the past, only a hand full of countries have been able to successfully demonstrate hypersonic flight using the scramjet engine technology. Countries such as, United States of America, Russia, China and India have contributed valuable data to the development of this technology by testing their hypersonic vehicles in the past decade. Boeing and United States Air Force's X-51 Waverider is one of the popular scramjet aircraft that demonstrated a sustaining hypersonic flight for up to five minutes. This section discusses the design of a scramjet engine whilst studying the popular X-43A and the proposed SR-72 scramjet engines.

4.1 X-43A Engine

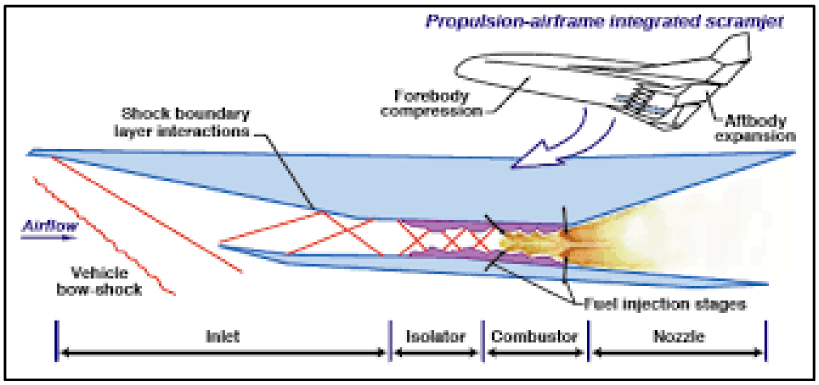

Figure 2: *X-43A Engine Design.[3]*

The Hyper-X research began in 1996, beginning with its conceptual design and wind tunnel testing. Three unpiloted aircrafts were built with identical physical dimensions with a lifting body that would flying only once and not to be recovered. However, certain aerodynamic and engineering differences were incorporated in all three to simulate variable engine geometry as a function of Mach number. While the first aircraft failed due to rocket malfunctioning, the second and third flights showed promising results. The second aircraft flew at Mach 6.8 in March 2004 while the third aircraft flew at Mach 9.6 in November 2004. The two flights began with being carried by the B-52B aircraft to reach an altitude of 40,000 ft. At this altitude the hypersonic aircraft strapped to a rocket booster was dropped. The rocket powered flight ascended the test aircraft up to 110,000 ft when the hypersonic aircraft was released by two pistons. The scramjet vehicle performed a preprogrammed engine burn and flew under its power and control for about 10 seconds. Following this, the aircraft went into hypersonic gliding for approximately 10 minutes to gather important aerodynamic data. As seen in figure 2, the X-43A aircrafts had a simpler design geometry as compared to any traditional aircraft engine. The inlet and the isolator section provided forebody compression for the incoming airflow to increase the flow's pressure and temperature. The compressed air travels through the combustor chamber at supersonic speed where the fuel is injected to energize the flow. The X-43A scramjet aircraft used gaseous hydrogen to provide for high-speed combustion. Lastly, the nozzle expands the airflow to produce maximum thrust required for a sustain flight. The two X-43A flights produced engine thrust that was very close to its design value.[3]

4.2 SR-72 Engine

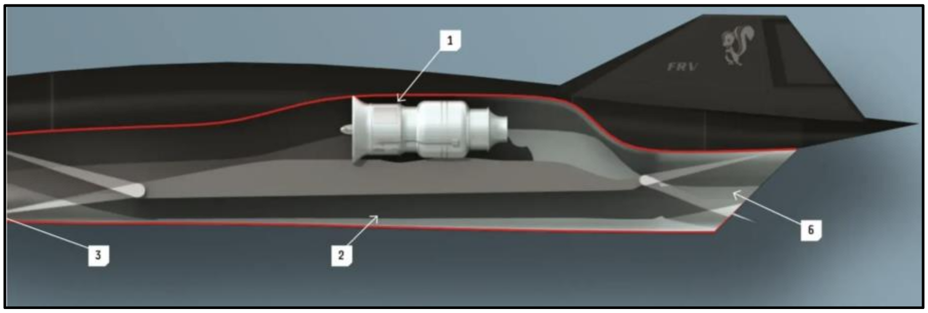

Figure 3: *SR-72 Engine Design.[5]*

The SR-72 dual mode scramjet is a conceptual design of a hypersonic aircraft proposed by Lockheed Martin in 2013 as a descendant to the Lockheed Martin SR-71 turbo-ramjet supersonic aircraft. The SR-72 propulsive unit is centered on a turbine based combined cycle. The SR-72 features a turbojet engine acting as a first stage propulsion system to accelerate the aircraft from takeoff to Mach3. The turbojet engine design is propositioned to be based on P&W J58 engine that propelled the SR-71 aircraft. The second stage of the hypersonic aircraft is propelled by a dual mode scramjet engine. The ramjet engine takes over from the turbojet engine from Mach 3 and flies up to Mach 5. Following this, the engine transitions to a scramjet engine to accelerate from Mach 5 to Mach 6. As seen in figure 3, the engine design combines the two engines with a common inlet section for the incoming airflow. In this section, the flow undergoes a series of shocks that provide for precombustion pressure and temperature rise. Following this, and depending on the flight speed, a flow flap directs the airflow into either of the engines. Under Mach 3, the flow is directed into a turbojet, where a mechanical compressor provides for further precombustion pressure rise. The burner section provides for air to fuel combustion and following this the exhaust nozzle expands the accelerating hot air to produce thrust.[5]

5.Inlet Optimization Techniques

This section of the report focusses on studying the inlet optimization techniques for a scramjet engine based on the relationships between high-speed aerodynamics and gas dynamics. The aim for utilizing optimization techniques is to maximize the total pressure recovery (TPR) for a designed cruise airstream Mach number. The design parameter used for inlet optimization is called shock on lip condition which warrants a maximum mass capture of the airflow with a minimum inlet length. As discussed earlier, the scramjet engine does not consist of any mechanically moving part and the precombustion pressure compression is provided by a series of shocks in the inlet and the isolator section. Therefore, the performance of the scramjet engine highly depends on the compression capabilities of the inlet. A scramjet inlet is typically designed selecting one of the three following methods of flow compression – Internal compression, external compression, and mixed compression. Amongst these, a mixed compression inlet design features lower drag, high pressure recovery and short inlet-isolator geometry. The mixed compression configuration features an external shock train in the forebody section of the inlet and an internal shock train in the inner body section of the isolator. This is illustrated in figure 4 below. Further, the inlet is optimized to maximize the total pressure recovery for a particular cruise Mach number. Therefore, to optimize for a range of Mach number in a flight envelope, the inlet geometry is designed to reject any shock and mass capture disturbances.

The preliminary design of the inlet can be completed using the Oswatisch criterion[6]. The criterion uses equations of gas dynamics and LaGrange multipliers to maximize the total pressure recovery. This is accomplished by equating the normal components for the series of oblique shocks to a terminating normal shock at the end, thus producing equal strength shocks. Another important criterion to be considered for the inlet design is the Kantrowitz limit along with the isolator entrance Mach number. The Kantrowitz limit is described mathematically as the ratio between the area at cowl lip to the area at isolator inlet. This factor prevents the inlet unstart condition. The isolator entrance Mach number is also crucial because it defines the separation of flow in the isolator section. If the Mach number at the isolator entrance is less than 50% at the inlet, the flow separation in the isolator is unavoidable. Several passive techniques, such as, air bleeding and blowing are used to prevent flow separation. Lastly, in accordance with the Oswatisch criterion, the cowl position must be designed so that the external oblique shock train meet at the cowl lip. The inlet geometry conferring to the above discussed parameters is illustrated in figure 4.

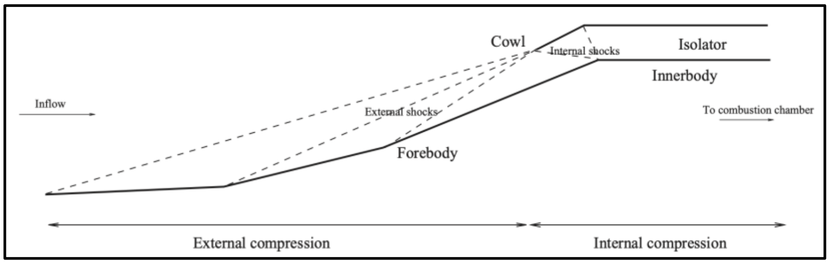

Figure 4: *Inlet Design Geometry.[7]*

As seen in figure 4, the number of internal shock (m) and external shocks (n) define the number of ramp angles. Using the Oswatisch theorem the ramp and shock angle are calculated iteratively using gas dynamics equations provided below. The free stream Mach number (M_1) is pre-defined, the Mach number at isolator entrance (M_{is}) is defined as half of free stream Mach number. The Mach number at the end of the final external shock wave (M_e) is also pre-defined as a design constrain. If this Mach number exceeds the prescribed value, the subsequent internal shock wave becomes a normal shock thus turning the flow subsonic. The initial assumption for Static Pressure Ratio (SPR) is 0.01 which is iteratively updated if a subsonic internal flow occurs. The initial assumption for the Total Pressure Ratio (TPR) is 1. The following equations are used to iteratively calculated the flow parameters given the number of internal and external shocks and the flight Mach number.

$$\beta = \sin^{-1}\left[\sqrt{\frac{\left((\mathrm{SPR}-1)\left(\frac{\gamma+1}{2\gamma}\right)\right)+1}{M_1^2}}\right],$$

$$\theta = \tan^{-1}\left[2\cot\beta\left(\frac{M_1^2\sin^2(\beta)-1}{M_1^2(\gamma+\cos 2\beta+2)}\right)\right], \qquad M_2 = \frac{\sqrt{\frac{\left(M_1^2\sin^2(\beta)+\frac{2}{\gamma-1}\right)}{\left(\frac{2\gamma}{\gamma-1}M_1^2\sin^2(\beta)-1\right)}}}{\sin(\beta-\theta)},$$

$$\mathrm{TPR} = \left[\left(1+\frac{\gamma-1}{2}M_2^2\right)^{\frac{\gamma}{\gamma-1}}\left(1+\frac{2\gamma}{\gamma+1}\left(M_1^2\sin^2(\beta)-1\right)\right)\left(1+\frac{\gamma-1}{2}M_1^2\right)^{\frac{-\gamma}{\gamma+1}}\right].$$

The figure 5 illustrates the results for the inlet optimization problem. For the given number of external and internal shocks the total pressure ratio (total pressure recovery ratio - TPR) is presented as a function of free stream Mach number. The results are also compared with historic reference data from **Smart**[8] to compare the optimization problem. The Smart optimization technique only maximizes one of the two parameters (maximizing TPR and optimizing Mach number) however the method presented in **Raj and Venkatasubbaiah**[7] optimizes for both the design parameters as discussed earlier. As seen, the TRP increases with the increase in the number of total external and internal shocks since, the shock strength decreases. Additionally, the percentage difference between the two methods is very significant. Moreover, as the number of external and internal shocks increase, the ramp angle decreases since less strength oblique shocks are now required to turn the flow. This causes more ramps and thus a longer inlet length. To mitigate the additional weight of the increased inlet length, a balance between the total pressure recovery ratio and the ramp angle needs to be further evaluated.

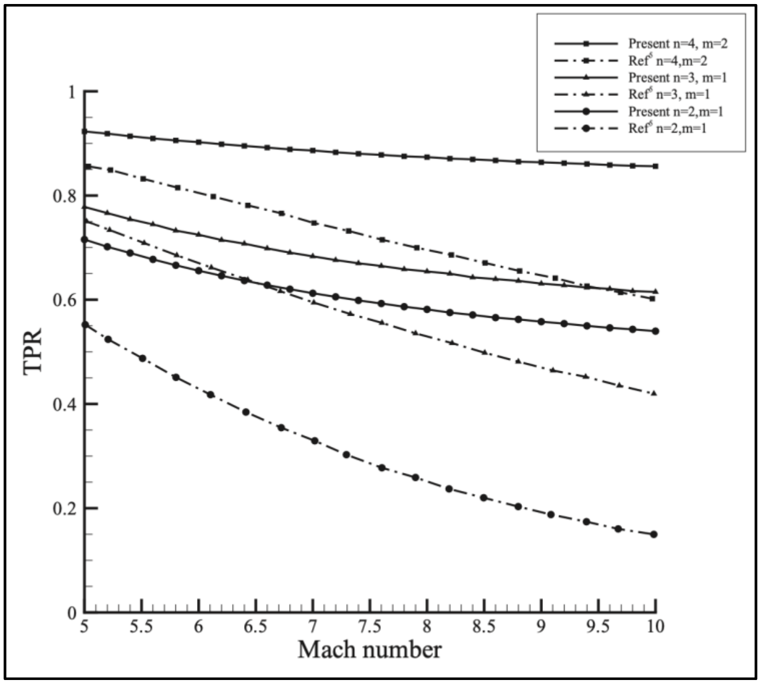

Figure 5: *Variation of TPR Vs. Mach number.[7]*

6.Supersonic Combustion Stabilization Techniques

The combustion process in an air breathing hypersonic vehicle occurs at supersonic speeds. Therefore, for a stable and efficient combustion, the air to fuel mixing process usually takes only a fraction of a second. The production of reliable thrust and high overall efficiency is highly dependent on the time scales of the airflow and the combustion process. Therefore, the coupling of thermo-fluid-acoustic dynamics of an engine is a significant factor in stabilizing the combustion process in the burner section of the engine. If the combustion process is not stabilized due to the increased system instability, it could cause an engine blowout, or the flame could propagate upstream and cause an engine unstart. In both cases, this phenomenon means engine malfunction and finally loss of thrust. Therefore, it is very important for an airbreathing hypersonic vehicle to be designed with active combustion stabilization and flameholder systems. The basic principle of flame stabilization dictates the combustion process to occur in the burner section itself. This process includes fuel jet injection, fuel-air mixing, fuel ignition, flame propagation, and combustion stabilization. The supersonic combustion stabilization incorporates a decrease in flow mixing time (τ_{mix}), increase in flow residence time (τ_{flow}) and reduction of the fuel combustion chemical reaction time (τ_{chem}). Therefore, the hypersonic combustion stabilization is dictated by the following equation: $\frac{\tau_{mix}+\tau_{chem}}{\tau_{flow}} \leq 1$[9].

The combustion stabilization technique is largely, however not solely, dependent on the flight Mach number. At low Mach numbers (Mach 5 to Mach 8) the engine sufferers through stabilization due to fuel ignition delays due to the low stagnation temperatures at the burner entrance. At moderate Mach numbers (Mach 8 to Mach 12) utilizing stabilization methods designed to address the above issue (at low Mach range) causes a significant loss in total pressure thus decreasing the engine performance and efficiency. The figure 6 illustrates various supersonic combustion stabilization techniques. These approaches are divided into diffusive and non-diffusive methods which are in turn a function of the flight Mach number. Therefore, to achieve efficient combustion for an airbreathing hypersonic vehicle, the process requires an optimum mixing of fuel and air at the molecular level along with overcoming the combustion activation energy to self-sustain the combustion chemical chain reaction.[9]

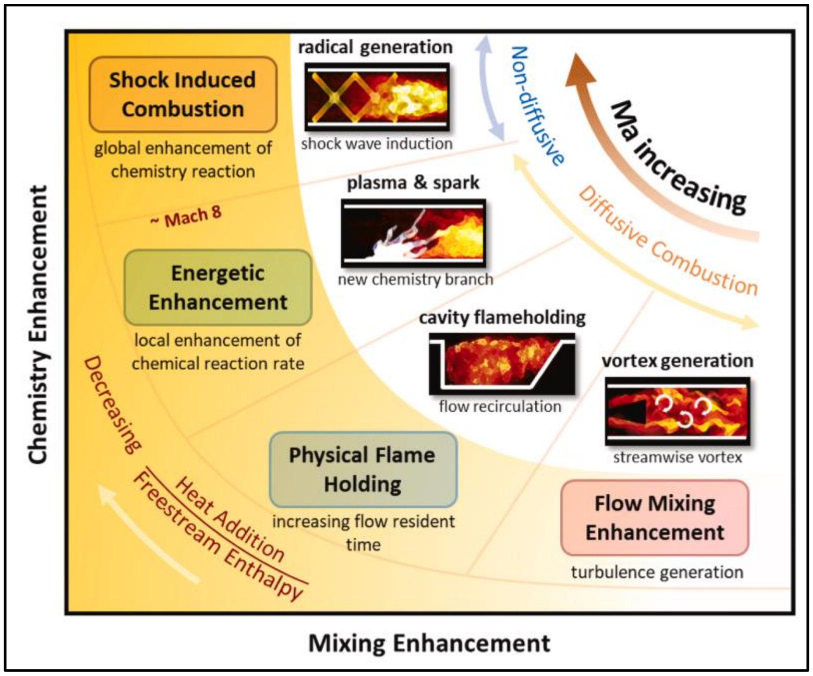

Figure 6: *Combustion Stabilization Techniques for Hypersonic Aircrafts.[9]*

The fuel to air mixing is usually achieved through causing turbulence in the combustion chamber that increases the interaction between the oxidiser and the fuel, thus increasing the diffusion rate. As seen in figure 6, the diffusion led scramjet engines are divided into active and passive control for fuel to air mixing. The active and passive controls are governed by the characteristic flow mixing time (τ_{mix}), and flow residence time (τ_{flow}). Some of the passive fuel mixing diffusion techniques include 3D jets, shock enhanced mixing, and axial vorticity generator. These techniques are also referred as large-scale structures that improves the mixing quality of the combustion by dragging large amounts of air (oxidizer) into fuel rich pockets of the engine. The active mixing techniques comprise of pulsed jet injection, pulsed detonation and energetic enhancement mixing. Energetic enhancement techniques include plasma supported mixing. This is incorporated in the engine when hydrogen fuel and jet-8 type fuel are used for combustion. The hot plasma helps increase the cold fuel's temperature to start the combustion, thus reducing the flow mixing time (τ_{mix}), and combustion chemical reaction time (τ_{chem}). While a scramjet engine might incorporate these mixing methods, the burner design also integrates flameholder techniques such as steps and cavities. These help in stabilizing the flow in the burner section by slowing down the flow and causing a recirculation region. This increases the flow residence time (τ_{flow}) of the air stream. However, these cavities and steps are not very efficient at moderate and high supersonic ranges since, they are a source of total pressure loss in the engine.[9]

The second requirement for an efficient combustion process is overcoming of the combustion activation energy. This requirement can be engineered by, firstly, increasing the static temperature of the fluid flow which would increase the reaction times in the burner and, secondly, creating radicals and excited species chemically to circumvent higher activation energy essential for starting the combustion chain reaction. These two factors increase the chemical chain reaction time, thus, decreasing the combustion chemical reaction time (τ_{chem}). At moderate and higher Mach number ranges, combustion stabilization methods for low Mach number range are very inefficient in generating enough thrust and utilising more fuel to combust the oxidizer. Therefore, the chemical reaction time (τ_{chem}) in the engine is reduced by exploiting a partially premixed flow. This method for combustion stabilization is known as shock induced combustion. In this scramjet engine design, the partially premixed flow is achieved through spraying fuel in the inlet/isolator entrance section of the engine. The upstream fuel injection provides for an additional length of the isolator for the fuel to mix and combust in the burner section. The shock and expansion wave train located in the inlet and the isolator section generates hot pockets of high pressure and temperature. These pockets are convected downstream into the engine where the combustion occurs in stage of two or more pockets. At high supersonic speeds, this reaction causes Oblique Detonation Waves (ODW) which causes fast combustion reaction. The use of ODW also leads to shorter combustion chambers since the fuel is premixed in the isolator section. Overall, this method for flame stabilization for hypersonic aircrafts flying above Mach 8 provides for a reduced flow mixing time (τ_{mix}), increased flow residence time (τ_{flow}) and decreased fuel combustion chemical reaction time (τ_{chem}).[9]

In addition to the enhancement of combustion stabilization through mixing and faster chemical chain reactions, different fuels and their injections also have a significant impact on causing a stable combustion. For example, droplet breakup and vaporization of liquid fuel spraying prior to entering the burner can enhance the fuel mixing quality of the combustion process. Using a kerosine fuel cavity can enhance flame-holding capability of a hydrogen piloted flame in the engine[9].

7.Future Implications

The optimization of scramjet inlet and combustion stabilization techniques have significant implication in the development of future hypersonic airbreathing aircrafts. Enhanced inlet designs have a substantial impact on engine performance in terms of higher inlet pressure recovery. On the other hand, the combustion stabilization techniques ensure complete fuel combustion maximizing engine thrust and efficiency. Scramjet inlet optimization and combustion stabilization techniques could increase the aircraft's speed and range. This development would revolutionize hypersonic flights usage into military, commercial and space applications. However, it's important to note that optimizing scramjet technology comes with its own set of challenges, including thermal management, material limitations, and safety considerations.

8.Conclusion

The report evaluates the inlet optimization and combustion stabilization techniques for the hypersonic air breathing aircrafts. The scramjet aircraft's inlet performance improves significantly with higher number of external and internal shocks with an increasing pressure recovery ratio. However, with the increased shocks the length of the inlet also increases therefore increasing the engine overall weight. The paper also explores and studies various flame/combustion stabilization techniques which are co-related with flight Mach number. These techniques are classified based on their ability to provide adequate mixing, enhance combustion rate and reduce the total pressure loss at occurs at Mach numbers greater than 8. These techniques include, physical flame holding using a cavity or step in the burner, active and passive flame mixing to increase the chemical burn rate and lastly shock induced stabilization for high supersonic speed to decrease flow mixing time (τ_{mix}), increase flow residence time (τ_{flow}) and reduce fuel combustion chemical reaction time (τ_{chem}).

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