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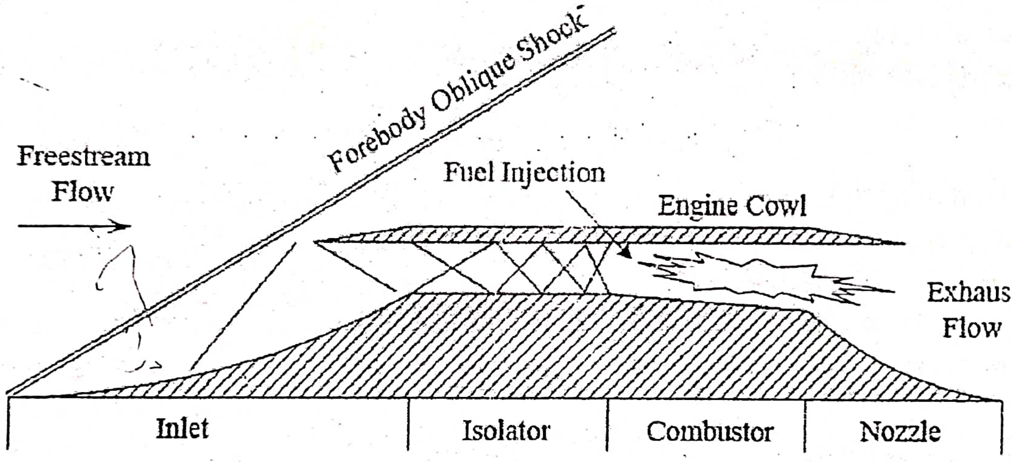
SCRAM JET ENGINE

A **Scramjet** engine is a ***supersonic combusting ramjet engine*** in which combustion takes place in a supersonic airflow. Generally ramjet decelerates the air to subsonic velocities before combustion, where as airflow in a scramjet is supersonic throughout the entire engine. This allows the scramjet to operate efficiently at extremely high speeds.

Scramjet engines operate on the same principles as ramjets, but do not decelerate the flow to subsonic velocities. Rather, a scramjet combustor is supersonic speed.

As in ramjet, a scramjet relies on high vehicle speed to forcefully compress and decelerate the incoming air before combustion (hence called ramjet), but whereas a ramjet decelerates the air to subsonic velocities before combustion, airflow in a scramjet is supersonic throughout the entire engine. The Scramjet is composed of three basic components:

1) *A CONVERGING INLET*, where incoming air is compressed and decelerates.
2) *A COMBUSTER*, where gaseous fuel is burned with atmospheric oxygen to produce heat.
3) *A DIVERGING NOZZLE*, where the heated air is accelerated to produce thrust.



Due to the nature of their design 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, rail gun, or rocket engines.

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.

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

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.

A scramjet relies on high vehicle speed to forcefully compress and decelerate the incoming air before combustion. But ramjet decelerates the air to subsonic velocities before combustion and airflow in a scramjet is supersonic throughout the entire engine. This allows the scramjet to efficiently operate at extremely high speeds

Advantages

- Does not have to carry oxygen tank.
- No rotating parts makes it easier to manufacture.
- Less weight and simple design.
- As the hydrogen is used as a propellant and combustion is carried out at supersonic velocity with the help of oxygen from the atmosphere.
- As a result of that, steam (H2O) is being exhaust gas which is eco-friendly in nature.

Disadvantages

- A Scramjet cannot produce efficient thrust unless boosted to high speed, around Mach 5.
- As a result additional propulsion systems are required.
- Lack of stealth.
- Testing difficulties.

History

During World War II, a tremendous amount of time and effort were put into researching high-speed jet engine and rocket-powered aircraft, predominantly by the Germans. After the war, the US and UK took in several German scientists and military technologies through Operation to begin putting more emphasis on their own weapons development, including jet engines.

In the 1950s and 1960s a variety of experimental scramjet engines were built and ground tested in the US and the UK.

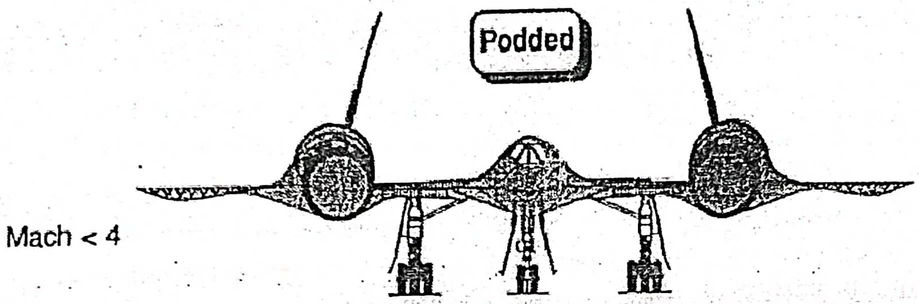
In 2000s, significant progress was made in the development of hypersonic technology. In June 15, 2007, the US Defense Advanced Research Project Agency (DARPA), in cooperation with the Australian Defence Science and Technology Organisation (DSTO), announced a successful scramjet flight at Mach10 using rocket engines to boost the test vehicle to hypersonic speeds.

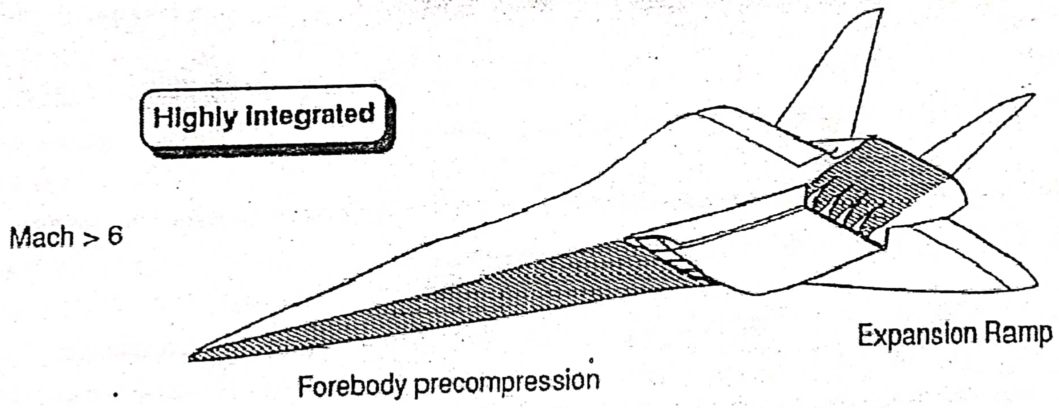
On 22 and 23 March 2010, Australian and American defence scientists successfully tested a (HIFiRE) hypersonic rocket. It reached an atmospheric velocity of "more than 5,000 kilometres per hour

- The theoretical projections place top speed of scram between Mach 12 and Mach 24, which is near orbital velocity.
- The fastest air-breathing plane is a SCRAMJET design, the NASA X-43a which reached Mach 9.6 or 12,144 km/h, on 16 Nov 2004.

A summary of the integration aspects of airbreathing engines in hypersonic vehicles & launchers concludes this section:

- Aerodynamic shape and propulsion system have to be **optimized together**
- **Main elements** of the airbreathing engine are precompression, intake and diverter system, nozzle and afterbody integration
- **Trade-offs** are needed for "thrust-minus-drag", moment characteristics, structural mass, fuel filling factors, aerodynamic complexity and etc.
- The most critical item is the **hypersonic intake**: high pressure recovery and air capacity characteristics, safe operation (prevention of intake un-start), and favourable compatibility parameters for the wide range of flight Mach numbers (temperatures and pressures) built from light weight structure
- A further promising feature is **base pressurisation** by heated bleed air ("external burning")
- Reduction of **engine size** by increasing engine numbers leads to physical integration





An airframe integrated scramjet propelled vehicle has advantages for application to several missions. In its simplest form, such a vehicle will combine the features of quick reaction, low vulnerability to counter attack and better propulsion efficiency.

The Supersonic Combustion Ramjet (SCRAMJET) engine has been recognized as the most promising air breathing propulsion system for the hypersonic flight (Mach number above 5). In recent years, the research and development of scramjet engine has promoted the study of combustion in supersonic flows. Extensive research is being carried out over the world for realizing the scramjet technology with hydrogen fuel with significant attention focused on new generations of space launchers and global fast-reaction reconnaissance missions. However, application for the scramjet concept using high heat sink and hydrogen fuels offers significantly enhanced mission potential for future military tactical missiles. Scramjet being an air-breathing engine, the performance of the missile system based on the scramjet propulsion is envisaged to enhance the payload weight and missile range.

Supersonic combustion ramjet engine for an air-breathing propulsion system has been realized and demonstrated by USA on ground and in flight. X-43 vehicle used hydrogen fuel. Hydrocarbon fuel scramjet engine is still under study and research. Mixing, ignition and flame holding in combustor, ground test facilities and numerical simulation of Scramjet engine are the critical challenges in the development of scramjet engine.

Scramjet engine - Technological challenges

One of the greatest advantages is the simplicity of design. A scramjet has no moving parts and the main part of its body is constituted by continuous surfaces. This admits relatively low manufacturing costs for the engine itself. Another significant difference between airbreathing engines and rockets, both of them able to fly at hypersonic speeds, is the fuel for combustion that they have to carry on board. While a rocket must carry the oxidizer on board, a scramjet collect it from the atmosphere; thus, this last would be lighter and hopefully capable of carrying more payload, since in a rocket the 75 percent of the total start weight is the oxidizer. So, that would be a great advantage too.

On the other hand, a scramjet engine has a major inconvenience. It cannot produce thrust if it is not first accelerated to a high velocity around Mach 5-6. This requires one or two additional propulsion systems to propel the vehicle to the needed scramjet start velocity. Therefore, various structures are needed for the suspension of these engines as well as all necessary control systems. All secondary equipment necessary to bring the vehicle to velocities suitable for the scramjet operation makes the whole vehicle heavy, in contrast to what has been mentioned previously. Then, the loss in the dry mass and, consequently, the gain in the payload mass are not so significant. In order to minimize the weight and complexity of having multiple propulsion systems, a dual-mode ramjet/scramjet is often proposed.

The current challenges in the development of the scramjet engine can be gathered in three main areas: air inlet, combustion, and structures and materials.

Air inlet

The overall performance of a scramjet is largely dictated by the aerodynamic performance, geometric size, and weight of the hypersonic inlets. Commonly, hypersonic inlets have a wide Mach number range, but the shock-onlip condition can be met only at the design Mach number, since shock angles vary with the upstream Mach numbers. Thus, at Mach numbers higher than the design one, the ramp shocks move inside the inlet and evolve into a strong incident shock, causing strong slip layers, remarkable total pressure loss, boundary-layer separation, and possible engine unstart. At Mach numbers lower than the design one, the ramp shocks move away from the cowl lip, causing loss of the precompressed airflow and the so-called spillage drag. To avoid these performance penalties at offdesign conditions, the control of the ramp shock system is needed. Hence, variable geometric approaches for ramp shock control are widely considered and studied.

Mixing, Ignition and flame holding in a scramjet combustor

Among the three critical components of the scramjet engine, the combustor presents the most formidable problems. The complex phenomenon of supersonic combustion involves turbulent mixing, shock interaction and heat release in supersonic flow. The flow field within the combustor of scramjet engine is very complex and poses a considerable challenge in design and development of a supersonic combustor with an optimized geometry. Such combustor shall promote sufficient mixing of the fuel and air so that the desired chemical reaction and thus heat release can occur within the residence time of the fuel-air mixture. In order to accomplish this task, it requires a clear understanding of fuel injection processes and thorough knowledge of the processes governing supersonic mixing and combustion as well as the factors, which affects the losses within the combustor. The designer shall keep in mind the following goals namely,

- Good and rapid fuel air mixing
- Minimization of total pressure
- High combustion efficiency.

The ignition delay time of a fuel-air mixture continues to be the limiting factor for all scramjet engines designs. Decreasing the delay time allows for shorter combustors and/or higher flight velocities. Initially, the ignition delay time of a fuel is fixed for a given set of conditions and the type of fuel. Increasing the temperature of the fuel and/or air stream reduces this time. Pressure plays a somewhat more complex role. Increasing the pressure, usually, but not always, improves the combustion conditions. Increasing pressure usually reduces the ignition delay time, but there exists a critical value of pressure, above which, the delay time increases dramatically, followed by a slow decrease. So, it is not always advantageous to increase the pressure. The equivalence ratio does not strongly affect the ignition delay time, except for equivalence ratios below 0.3, where the delay time increases sharply. Hydrogen has very low ignition delay time compared with hydrocarbon. Therefore, all these effects need to be considered in designs.

Perhaps the largest problem associated with combustion is the mixing between free stream air and fuel. If fuel cannot be properly injected and mixed into the air stream it will not ignite, regardless of pressure, temperature or equivalence ratio. Due to compressibility effects, fuel injection presents challenging obstacles. The air stream is at such a high pressure and velocity, that fuel injected into the stream has a tendency to be pushed against the wall and rendered ineffective. In addition to the problem of mixing, ignition and flame holding at these high velocities is extremely difficult. To overcome these challenges, several solutions have been proposed like plasma torches, ramps and wedges, or recessed cavities.

Another challenge to increase the performance is the need of a variable geometry combustion chamber. A fixed geometry combustor associated to a variable capture area air inlet does not benefit from the enhanced efficiency of the air inlet. A fully variable geometry – air inlet + combustion chamber – can increase the performance by comparison with the previous concept, but cannot take all the benefit of the complexity related to a fully variable geometry system because of the fixed minimum section of the inlet (equivalent to the fixed section of the combustion chamber entrance). So other concepts have been studied, which consist in modifying at the same time the minimum section of the air inlet and the geometry of the combustion chamber. Moreover, for such concepts, having at disposal a variable minimum section for the air inlet avoids the need of large variation of the air inlet capture area (i.e.

increase when the Mach number increases) and permits high efficiency in a wide Mach number range.)

Structures and materials

Unlike a rocket that passes nearly vertically through the atmosphere on its way to orbit, a scramjet would take a more levelled trajectory. Because of the thrust-to-weight ratio of a scramjet being low compared to modern rockets, the 26 scramjet needs more time to accelerate. Such a depressed trajectory implies that the vehicle stays a long time in the atmosphere at hypersonic speeds, causing atmospheric friction to become a problem. This is not only for space launch applications but also in missile or commercial transport applications. Heat addition produced by the combustion at these high velocities and temperatures is another significant factor to take into account. Therefore, the materials chosen for the structure must have good properties and be adequate in front of these phenomena. Furthermore, cooling of the engine's structure by fuel or radiation is essential.

Applications for a scramjet engine

There is a range of possible applications for scramjet engines, including missile propulsion, hypersonic cruiser propulsion, and part of a staged space access propulsion system. Before going into details, the need for a scramjet engine hydrogen-fuelled to propel a vehicle at Mach 5 or higher will be justified. Figure 9 displays the approximate performance range in terms of engine specific impulse and Mach number for various types of propulsion systems. It can be seen that at Mach numbers higher than approximately 6-7, the only available propulsion systems are rockets and scramjets. Compared to rockets, scramjets have much higher specific impulse levels (because they do not have to carry on board the oxidizer as they are airbreathing engines and collect oxygen from the atmosphere); therefore, it is clear why it is advantageous to develop the scramjet, if for this reason only. There are other reasons that highlight the advantages of the scramjet development as well. Airbreathing engines produce higher engine efficiency, have longer powered range, possess the ability for thrust modulation to ensure efficient operation, have higher versatility, and are completely reusable.

Space launch applications

Space launch is one of the potential applications of scramjet engines that have raised the most attention for the past two decades. Airbreathing vehicles,capable of hypersonic speeds, can transform access to space, just like turbojets transformed the airline business. The benefits of using a scramjet for a Single-Stage-to-Orbit (SSTO) vehicle are improved safety, mission flexibility, vehicle design robustness, and reduced operating costs. A SSTO vehicle takes off and lands horizontally like an ordinary aircraft but has the capability to bring payload to lower earth orbits without releasing pieces of its own structure, for example fuel tanks or burn-out rockets.

Safety benefits result from characteristics such as enhanced abort capability and moderate power density. Horizontal takeoff and powered landing allows the ability to abort over most of the flight, both ascent and decent. High lift/drag (L/D) allows longer-range glide for large landing footprint. Power density, or the quantity of propellant pumped for a given thrust level, is 1/10 that of a vertical takeoff rocket due to lower thrust loading (T/W), lower vehicle weight and higher specific impulse. Power density is a large factor in catastrophic failures. Recent analysis indicates that safety increases by several orders of magnitude are possible using airbreathing systems. Mission flexibility results from horizontal takeoff and landing, the large landing (unpowered) footprint and high L/D.

Utilization of aerodynamic forces rather than thrust allows efficient orbital plane changes during ascent, and expanded launch window. Robustness and reliability can be built into airbreathing systems because of large margins and reduced weight growth sensitivity, and the low thrust required for smaller, horizontal takeoff systems. Cost models indicate that about one-order magnitude reduction in operating cost is possible. Attributes for selected airbreathing assisted launch systems categorized by staging Mach number and reusable or expandable second stage are listed in Table 1. What it might be observed is that increasing staging Mach number plus adding a reusable second stage, increases the payload fraction and reliability, and reduces both loss of the vehicle and operating cost. The most significant benefit is in safety, quantified by the attribute "Loss of Vehicle/Payload".

Military applications

The vehicle that could most quickly benefit from current scramjet research is the cruise missile, as it is explained in the following points:

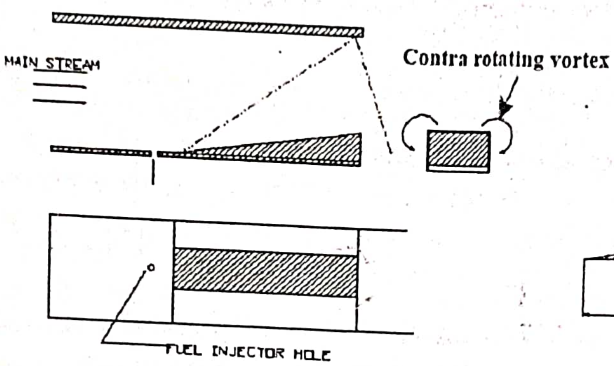
- The space application draws maximum benefit from airbreathing propulsion when using it up to Mach 10-12, in order to optimize the staging of the different propulsion modes. On the contrary, the military interest of high speeds can be reached significantly below this domain. Mach 8 should not be very far from the upper limit for missile applications.
- In its whole flight envelope, the space launcher has to provide a very large acceleration, which is one of the key parameters to provide sufficient payload performances into orbit. A cruising military system has naturally less needs in terms of acceleration capability at high speed.
- Test facilities, developed in some programs, were designed to test components of the propulsion system of a launcher at much reduced scale and in a limited flight Mach number conditions range, but they nearly enable to test a missile engine at full scale. This situation contributes to reduce the uncertainties remaining after ground tests to get to flight tests
- Finally, it is clear that if a flight demonstration was made using a vehicle whose size would have been chosen minimal for together preserving the demonstration interest of the operation, and limiting the cost, this minimal size would probably be not very far from the size of a missile. Consequently, the success of the flight demonstration would validate the methodology used to develop the experimental vehicle, so that this methodology would also be applicable for any kind of vehicle of similar size and level of integration.Then, different possible military applications can be proposed:
- Tactical missile when penetration is the key factor or when pure speed is necessary against time targets
- High speed reconnaissance drone with improved mission safety and response time capability
- Global range rapid intervention system based on previously mentioned missiles and drones
- Global range military aircraft or UCAV
- Short response time space launching system

Civil applications

On the other hand, for civil applications, a hypersonic cruiser aircraft that is an alternative to traditional turbojet or turbofan transportation could also be a not-too-distant possibility. The urge to always fly faster and higher might contribute to develop a scramjet vehicle for a commercial hypersonic flight. However, due to all the problems present in the scramjet technology and the remaining uncertainties, today this possibility stays very far from being a reality.

Ramp injectors

One of the strategies to solve the aforesaid problems of mixing is generation of axial vortices. Axial vortices possess a better far field mixing characteristics. Also they are being propagated to a considerable distance, even with the suppressing characteristics of the supersonic core flow. Ramp injectors are considered to be a key feature to generate axial vortices. Figure 4 & 4A depicts some of the characteristics of Ramp injectors flow field. The following are the characteristics of the ramp injectors.



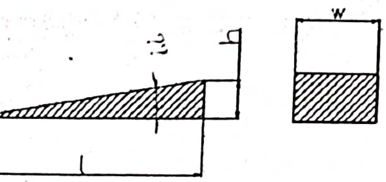
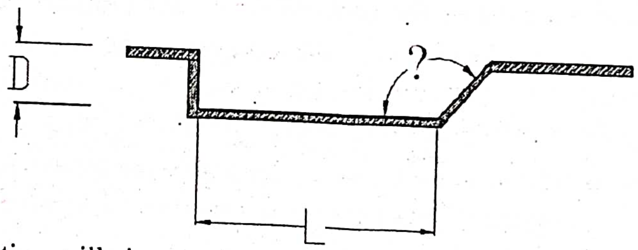


Fig4: Ramp injector Flow field ating Fig4A: Ramp injector geometry

- Pre-compression by the Ramp face produces favorable region for injection.
- Stagnation region near the leading edge of the Ramp injector improves ignition.
- The strength of the spillage vortices increase with increase of core flow mach no, thus retaining the performance at higher operating conditions.

Cavity Based Injection:



Generation of acoustic oscillations is also considered to be a better candidate to achieve better mixing. Unsteady shear layers generate acoustic oscillations. Wall mounted cavities generates these oscillations to aid the mixing enhancement. The Cavity parameters in figure 5. Cavities are characterized by their L/D ratio. There are three regimes of cavity behavior, categorized by the shear layer separation and its reattachment. For cavities of L/d less than 1, the shear layer reattaches way past the trailing edge of the cavity it generates transverse oscillations. These cavities are called as 'Open Cavities'. This type of oscillations aid in penetration of fuel For L/D more than 2, the separated shear layer attaches to the bottom wall of the cavity, it generates longitudinal oscillations, which aid in flame holding characteristics. The third type of cavities is square and transition cavities, where L/D is one or close to one. They exhibit a very low level of oscillations

Combination of Ramp and cavity injectors

The overall performance of ramp and cavity injectors can be improved by combining them properly. The combination of cavities and ramps generate a three dimensional flow field and turbulence for better mixing and combustion. Ramps will enhance the fuel penetration in to the core and cavities will enhance the flame holding characteristics. The ramp generated axial vortices can be utilized to scoop out the hot gases generated at cavities to improve the combustion efficiency. Thus Ramp and cavity combination shows promising characteristics for better scramjet combustor performance.

The following table shows the design criterion.

S.No	Parameter	Criterion
	Ramp Injector	
1	Length (L)	Evaporation length of droplets
2	Wedge angle (?1)	Compression and shock strength
3	Ramp base width (w)	Area blockage by ramp
4	Ramp Spacing (w1)	Minimum the blockage area-distribution
	Cavity Injector	
1	Length (L)	Ramp Base height
2	Cavity depth (D)	L/D ratio needed
3	Trailing edge angle (?)	Shock strength at the Trailing Edege

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Recent Advances in Scramjet Fuel Injection - A Review

K.M.Pandey, *Member IACSIT* and T.Sivasakthivel

***Abstract* - Fuel injection techniques into scramjet engines are a field that is still developing today. The fuel that is used by scramjets is usually either a liquid or a gas. The fuel and air need to be mixed to approximately stoichiometric proportions for efficient combustion to take place. The main problem of scramjet fuel injection is that the airflow is quite fast, meaning that there is minimal time for the fuel to mix with the air and ignite to produce thrust (essentially milliseconds).Hydrogen is the main fuel used for combustion. Hydrocarbons present more of a challenge compared to hydrogen due to the longer ignition delay and the requirement for more advanced mixing techniques. Enhancing the mixing, and thus reducing the combustor length, is an important aspect in designing scramjet engines. There are number of techniques used today for fuel injection into scramjet engines.**

***Index Terms* – Fuel injection, Mach number, Scramjet, Thrust**

I. INTRODUCTION

The desire for faster response times or cheap access to space drives both government program requirements and industry driven innovation in propulsion. Applications such as rapid transportation, ballistic missile defence, long range strike, or air breathing access to space continue to push the envelope in terms of altitude and airspeed. Today, turbine engines power most high speed aircraft, but they can no longer be expected to provide the primary source of air-breathing propulsion as speed and altitude requirements increase. Supersonic combustion ramjet (scramjet) propulsion provides a method of achieving this higher performance. Unlike their low-speed counterparts, scramjet designers must contend with supersonic velocities through the entire engine which results in minimal time to burn fuel before the flow exits the engine. Aerospace propulsion varies over an enormously wide range of speeds from zero velocity before takeoff all the way to escape velocity for space access. Considering only air-breathing propulsion, one potential path through this airspeed spectrum, as shown in Figure 1, starts with the familiar turbine engine for flight Mach numbers less than three, moving to the ramjet for Mach numbers up to approximately five, and ending with the supersonic combustion ramjet. Nothing special defines these Mach number boundaries.

Turbine engine designs could operate above a Mach number of three; they would just do so less efficiently. Turbine engines compress air using a rotating compressor to take low pressure, high-speed air and convert it into a high pressure, slow moving flow favorable for combustion. The hot products of this combustion expand through a turbine and out a nozzle to produce thrust. Eventually, as speed increases, the ram effect of the incoming flow suffices to compress the air for combustion eliminating the need for mechanical compressors. This compression provides the basis for ramjet engines. The air in a ramjet engine still decelerates to subsonic speed and to a higher pressure suitable for combustion. The flow then accelerates through a nozzle to provide thrust, but without the inefficiencies and mechanical complexity associated with rotating machinery. At even faster speeds, the high static pressures and temperatures that result from decelerating air above Mach numbers of approximately five to subsonic speeds for combustion may lead to molecular dissociation of the incoming flow and unacceptable material stresses. Scramjets provide one approach to achieving these higher speeds, where air decelerates for combustion yet remains supersonic through the entire engine. Refs [1-2] provide an excellent overview of the mechanics and evolution of scramjet propulsion outlined above.

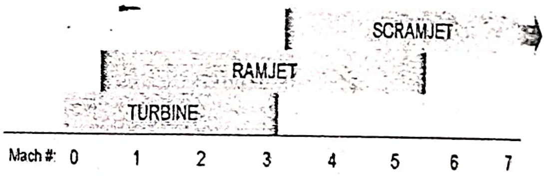

Figure1. Approximate Mach number regimes

II. SCRAMJET FUEL INJECTORS

There are several key issues that must be considered in the design of an efficient fuel injector. Of particular importance are the total pressure losses created by the injector and the injection processes that must be minimized since the losses reduce the thrust of the engine. The injector design also must produce rapid mixing and combustion of the fuel and air. Rapid mixing and combustion allow the combustor length and weight to be minimized, and they provide the heat release for conversion to thrust by the engine nozzle. The fuel injector distribution in the engine also should result in as uniform a combustor profile as possible entering the nozzle so as to produce an efficient nozzle expansion process. At moderate flight Mach numbers, up to Mach 10, fuel injection may have a normal component into the flow from the inlet, but at higher Mach numbers, the injection must be nearly axial since the fuel momentum provides a significant portion of the engine thrust. Intrusive injection devices can provide

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K.M.Pandey, Member IACSIT, Department of Mechanical Engineering, N.I.T Silchar, Assam, India(email: kmpandey2001@yahoo.com).

T.Sivasakthivel, M.Tech - Thermal Engineering, Department of Mechanical Engineering, N.I.T Silchar, Assam, India(email: sivasakthivel.t@gmail.com).

good fuel dispersal into the surrounding air, but they require active cooling of the injector structure. The injector design and the flow disturbances produced by injection also should provide a region for flame holding, resulting in a stable piloting source for downstream ignition of the fuel. The injector cannot result in too several local flow disturbance, that could result in locally high wall static pressures and temperatures, leading to increased frictional losses and severe wall cooling requirements. A number of options are available for injecting fuel and enhancing the mixing of the fuel and air in high speed flows typical of those found in a scramjet combustor. Some traditional approaches for injecting fuel are described below.

A. Parallel, Normal and Transverse Injection

Early scramjet research focused on either parallel or normal fuel injection in relation to the main flow of the engine to create mixing areas just upstream of the combustion. As in Figure.2. Parallel fuel injection consists of fuel flowing parallel to the air in the engine but separated by a splitter plate. When the splitter plate ends, a shear layer is created due to the different velocities of the fuel and air. The shear Layer is the primary source of mixing the fuel with the air so that proper combustion can be achieved. When parallel fuel injection was tested with a hydrogen-fluorine fuel in air, the growth rate of the shear layer was reduced compared to theoretical rates. The reduction in growth rate is argued to be caused by the reduction of turbulent shear stress at the core of the shear layer due to the density change caused by the heat released from the combustion process. [3, 4].

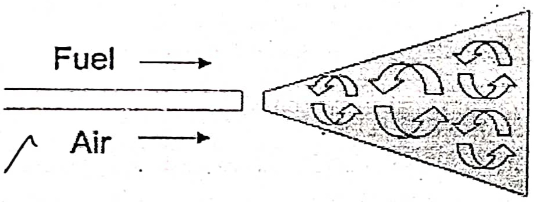


Figure 2: Parallel fuel injection

Normal fuel injection consists of an injection port on the wall of a scramjet. The port injects the fuel normal to the flow of air in the scramjet. Normal fuel injection creates a detached normal shock upstream of the injector which causes separation zones upstream and downstream of the injector as in Figure 3. The separation zones cause increased total pressure losses which affect the efficiency of the engine. However, the downstream separation regions can be used as a flame holder. Research conducted to minimize the total pressure loss displayed low combustion efficiency due to poor mixing [5].

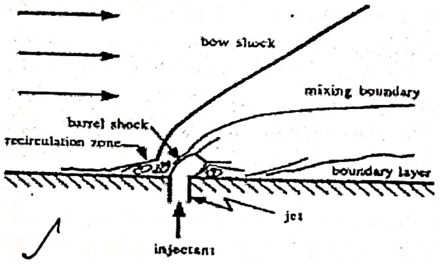


Figure 3: Normal fuel injection

Transverse fuel injection is a combination of parallel and normal fuel injection. In a transverse injector, the fuel is injected at an angle between normal and parallel to the flow. Transverse injection reduces some of the negatives to normal injection, but requires a larger injection pressure to achieve the same penetration height into the air flow. The increase in the injection pressure increases the total pressure loss of the scramjet which decreases the efficiency of the engine. Since these injection techniques do not meet the needs in a scramjet, more complex mixing methods were evaluated

B. Ramp Injectors

Using the results from parallel injection, it was theorized [6] that adding axial velocity to the parallel injection may increase the mixing. To add axial velocity to the flow near fuel injection, ramps were added with fuel injectors on the trailing edge of the ramp injecting fuel parallel to the flow. The flow over the ramps created counter-rotating vortices that increased the mixing. Due to the supersonic flow in the scramjet, the ramps also create shocks and expansion fans which cause pressure gradients that also increase mixing. Two types of ramps were used; compression ramps are elevated above the floor while expansion ramps create troughs in the floor (Figure 4).

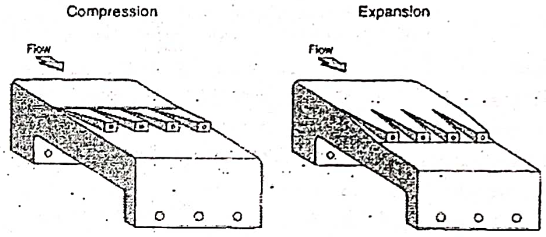


Figure 4: Ramps used for mixing

Research compared several different compression and expansion ramp geometries [7]. The shock formation in the ramps depended on the type. In compression ramps the shocks formed at the base of the ramp and in expansion ramps the shocks formed in the recompression region at the bottom of the trough. Due to the difference in the shock locations, the combustion efficiency and mixing for the two ramp styles differed. The results showed that compressor ramps created a stronger vortex and increased the fuel/air mixing, but expansion ramps had the higher combustion efficiency. Combustion efficiency requires mixing at the smaller scales that the expansion ramps provide, and the strong vortex generated by the compression ramps degrades the small scale mixing. Another interesting result was that the expansion ramps reached their maximum combustion efficiency in less distance than compression ramps, which would allow for shorter combustion sections and thereby minimizing weight. While ramps did improve the mixing caused by parallel injection, the ramps are placed along the wall of the combustion section which limited the fuel penetration into the combustion section. In order to achieve penetration throughout the flow field, a more intrusive method was required.

C. Strut injector

Research into strut mixing devices covers a wide range of designs and includes both normal and parallel injection methodologies. Most struts consist of a vertical strut with a wedge leading edge. The strut is connected to both the bottom and top of the combustion section. Since it is across the whole combustion section, fuel injection occurs at several locations and allows the fuel to be added throughout the flow field. Research [8] compared three mixing techniques for scramjet combustion: transverse injection in a cavity, two-stage normal and transverse injection, and a strut consisting of a vertical wedge front with fuel injection in the back side of the trailing edge as seen in Figure 5. Results showed that a strut was the only technique that affected the entire flow field but had a higher pressure loss than the other techniques. The researchers suggested that more interest should be paid to the design of the strut to minimize the pressure loss while maintaining the ability to affect the flow field.

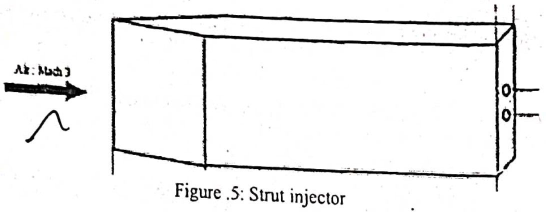


Figure .5: Strut injector

Many researchers [9, 10, and 11] looked at modifying the trailing edge of the vertical strut to increase mixing. The basic strut design was similar in that the strut was connected to the top and bottom of the test section and the leading edge was a wedge. The difference came from the trailing edge designs as seen in Figure 6. The different trailing edges, called alternating wedge designs, create either co-rotating or counter-rotating vortices that are used to enhance the mixing. All of these designs use parallel fuel injection at the trailing edge of the strut so that the fuel is entrained into the vortices which cause the increased mixing in the combustion section. The results from this research concluded that the alternating wedge design created a more uniform mixing region, but the overall combustion performance is similar to that of

A strut with a flat trailing edge and causes a larger total pressure loss.

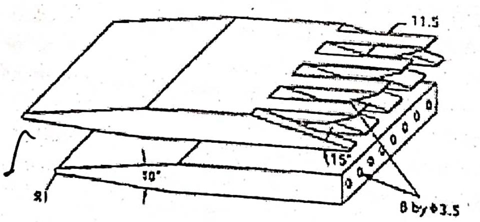


Figure 6: Alternating Wedge strut

NASA conducted research at the Lewis Research centre on struts and studied the effects of the geometric parameters of the strut on the drag in the combustion section. The drag that develops in the combustion section must be balanced by the thrust produced by the engine. Therefore, the drag should be low for more efficient scramjet designs. The struts used in this experiment had a diamond shaped cross section, Figure 7, instead of the wedge leading edge and box shaped body. Unlike the struts used in previous research, these struts did not connect to the top and bottom of the test section. These struts used normal injection at the thickest part of the strut. NASA compared nine different struts with variations in the position of maximum thickness, thickness, leading edge sweep and length. The largest contributor to the drag was the thickness of the strut, a slight decrease in the thickness lead to a 50% reduction in the drag. Also, increasing the leading edge sweep decreased the drag of the strut.

Research conducted by the Air Force Research Lab [12] examined three different strut shapes and their effect on the combustion in a Scramjet chamber. These struts are similar to the NASA struts in that they are not connected to the bottom and top of the test chamber and have a leading edge sweep angle, but did not have the diamond body of the NASA struts, as in Figure 7. Unlike previous research, these struts are place directly in front of the combustion cavity used for holding the same of the combustion. The three struts tested had slightly different trailing edges, a at trailing edge, a 45 degree trailing edge similar to a tapered airfoil, and the third had an extension that went into the combustion cavity. Testing was done in a supersonic research facility using a continuous air flow at a Mach number of 2. Their research showed an increase in maximum temperature and mixing, as well as moving the center of combustion into the main section of the flow as compared to a cavity without a strut. As in previous research, the strut included fuel injection into the flow, but here the fuel was injected from the leading edge of the strut.

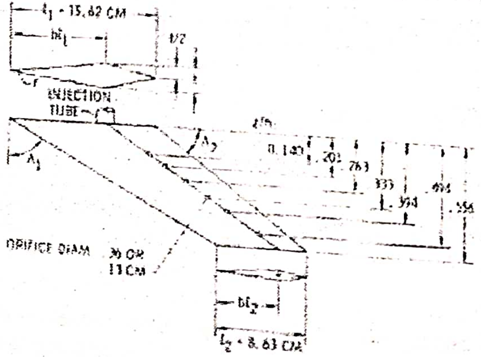
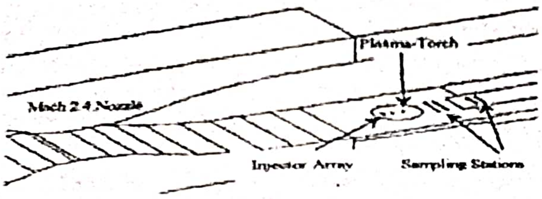


Figure 7: Diagram of basic strut

D. Plasma Ignitor

Another fuel injection system developed by Jacobsen et al. [13] is a fuel injection and flame holding system consisting of an aerodynamic ramp injector and a DC plasma torch for scramjet operating between Mach 4 and Mach 8. The injector consists of four holes placed upstream and a plasma torch downstream operated with methane and nitrogen. The set up is shown in Figure 8. The toe-in angle of the injector holes was varied, and it was found that increasing the toe-in angle increased the mixing efficiency and penetration of the fuel into the flow. This is due to the uneven rotation and hence vorticity created due to fuel injection from these elliptic shaped holes. The same configuration was developed with a ramp set up, and it was found that the ramp configuration provided better mixing than a flat injector with injection holes. Further development suggested by Jacobsen et al. include the incorporation of a flame holding device somewhere between or downstream of the fuel injector array. The plasma torch used in this set up allows the fuel to be ignited in the cross flow. Increasing the oxygen content at the plasma/fuel-plume has also shown to produce an increase in ignition and flame distribution.



Supersonic wind tunnel and test section.

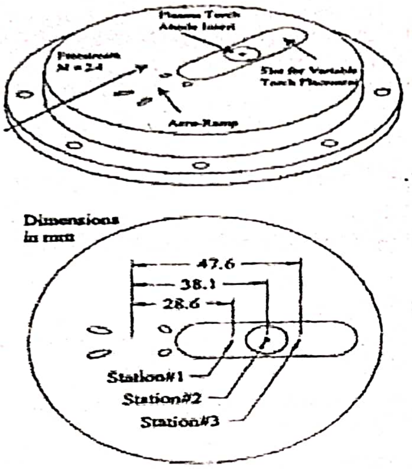


Figure 8: Plasma torch ignition arrangement with injection ports

E. Pylon Injection

Pylon injection is essentially injection behind a tall, narrow in-stream body, such as shown in Figure 9. Injection may be axial, normal, or at some other angle relative to the free stream. Many shapes and angles of injection have been investigated. Vinogradov et. al. [14] experimented with gaseous fuel injection far upstream behind a swept, thin pylon with a various cross sectional pylon shapes. The results showed much improved mixing and penetration, improved flame holding, and a lack of pressure losses and pronounced edge shocks. These results are not typical of earlier work referenced by Paull and Stalker [15], where an advantageous system of shocks from the pylon helped improve mixing but at the sacrifice of pressure losses.

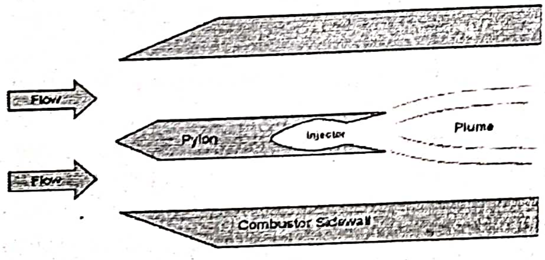


Figure 9: Central Pylon Fuel Injection

F. Upstream Injector

Another type of fuel injection method is upstream injection, as tested by Gardner et.al [16]. This basically involves injecting the hydrogen fuel from the intake into the flow from portholes upstream prior to combustion. This method is for a two dimensional scramjet engine. The main advantage this method has is that it allows for a shorter combustion chamber, thus a reduction in skin friction drag. It has been determined that drag in the combustion chamber is one of the main contributors to inefficiency in a scramjet [17]. The injection port consists of four holes placed flush on the intake ramp, as shown in Figure 7. The main problem with this technique is possible ignition of the fuel in the portholes or near the wall due to the high temperatures within the boundary layer. It was also determined that a fuel jet from a smaller hole would penetrate further than fuel from a larger hole, and a hole at a greater angle to the wall would allow for more fuel to be moved away from the wall. Proper set up of the ramps and intake allows for combustion to occur in the combustion chamber, with no burning in the free stream flow within the intake.

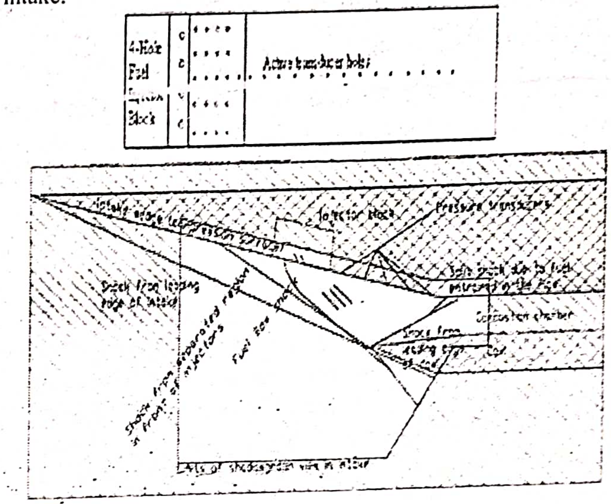


Figure 10: Upstream injection

G. Barbotage Injection System

Effervescent atomization is a phenomenon in which gas has to be introduced into the liquid with a very low velocity, leading to turbulent two-phase flow that can improve penetration and vaporization of the fuel jet spray. The difference in the densities of liquid and the gas, the interaction between the two phases are helping in breaking the liquid to smaller droplets and reducing the flow dimensions for the liquid which helps in injecting the liquid fuel as very fine droplets. Barbotage injection with liquid Kerosene and Hydrogen/Air has a definite advantage in terms of breakup of droplets for better mixing with the supersonic air stream and combustion enhancement. Also using hydrogen as the barbotaging gas creates favourable conditions for the kerosene combustion also. The basic configuration of the barbotage injection unit is shown in the Fig 11. The kerosene is injected through a central tube into a mixing zone, to which the Hydrogen flows through the annular gap around the kerosene tube. In the mixing zone, gas bubbles into the liquid. Then the two-phase flow is injected into scramjet combustor through the injection orifices.

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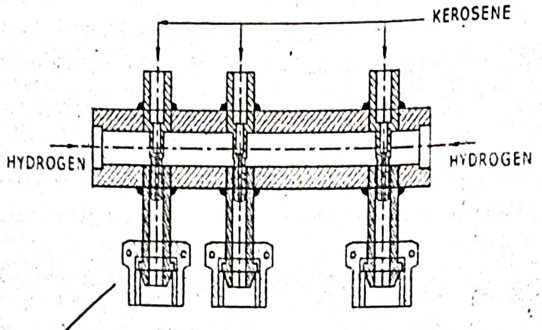

Figure 11: Barbotage system

H. Pulsed Injector

Another type of fuel injection is pulsed injection [18] conventionally; fuel is injected as a continuous stream from injection ports into the combustion chamber where it ignites. This type of injection injects the fuel in a series of pulses, which allows for greater mixing between the fuel and air. Combustion occurs more rapidly as well as more efficiently, thus producing a greater thrust output. The time between pulses is dependent on the free stream conditions, and is coordinated to achieve near stoichiometric combustion. An advantage of this method is that combustion always remains in a transient state, and never reaches a steady state condition. Transient combustion further enhances fuel-air mixing, as well as allowing for a greater dispersal of the heat load on the combustor. The injector plate consists of a four-by-eight matrix of injectors, as shown in Figure 8. Eight portholes (consisting of two or three diagonal rows) operate simultaneously at different intervals, and since only eight of the thirty-two injectors are functioning simultaneously at a given time, the pulses can be of a lower flow rate. This reduces the need for higher-pressure fuel lines. Since the positions of the fuel injection ports constantly change, the shock waves and vortices will be constantly moving though out the combustion chamber, which has a favourable effect on the mixing of the fuel and air.

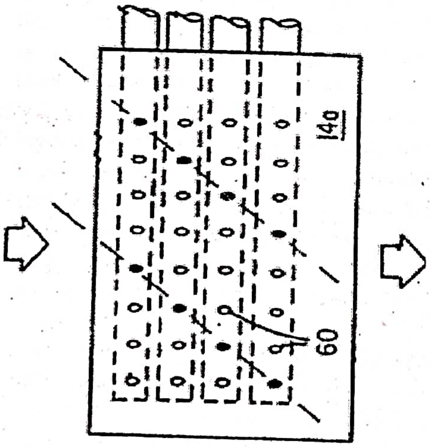

Figure 12: Pulsed fuel injection

I. Cavity Flame holders

Another fuel injection system uses a backward-facing step to induce recirculation, with fuel injected upstream of this cavity. This cavity would also provide a continuous ignition point or flame holder with little pressure drop, and hence sustained combustion. The advantage is that the drag associated with flow separation is less over a cavity than over a bluff body. The two main disadvantages are the losses in stagnation pressure due to this step, as well a reduction in total temperature. Also, the wall injection method limits the penetration of the fuel into the airflow. This means that a broad application of this method is not possible, since the ignition heavily depends on the Mach number. An injection with a cavity set up is shown in Figure 13.

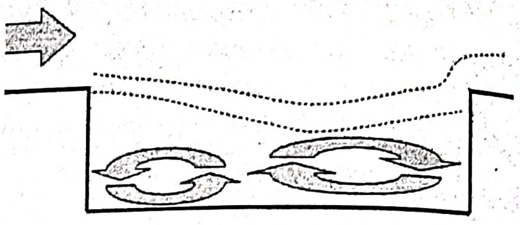

Figure 13: Rectangular cavity flame holder

With a cavity installed downstream of the fuel injection point, it was observed that the mixing efficiency as well as the combustion was greatly improved, since the mass and heat movement along the shear layer and inside the cavity are greatly increased. The depth of the cavity determines the ignition time based on the free stream conditions, while the length of the cavity has to be chosen to sustain a suitable vortex to provide sufficient mixing inside the cavity. There needs to be sufficient time for the injected fuel and free stream air to mix and ignite. An increase in the wall angle of the cavity produces greater combustion efficiency, but also a greater total pressure loss. It is also to be noted that if the injector is comparatively far from the leading edge of the cavity, the cavity forms small vortices because the mixture entering the cavity is insufficient. However, if the injector is relatively close to the cavity, the injected fuel does not penetrate into the free stream due to the flow turning into the cavity.

J. Cavity-Pylon Flame holder

Intrusive devices can enhance the interaction between a cavity-based flame holder and a fuel-air mixture in the core flow [19]. A pylon placed at the leading edge of the cavity provides such a mechanism by increasing the mass exchange between the cavity and free stream [16] and improving mixing due to pylon vortex/shock interactions [19]. Low pressure behind the pylon draws fluid out of the higher pressure cavity and into the main flow which leads to increased mass exchange between the cavity and main flow compared to a cavity-only case [20,21] (see Figure 13). Supersonic expansion at the pylon edges, as represented in the two-dimensional example in Figure 14, results in low pressure behind the pylon .The pressure differential between the cavity and pylon base should result in a flow of cavity fluid upward behind the pylon. This Upward flow will lie between a pair of stream wise counter-rotating vortices that form as the flow over the top of the pylon spills over each side. The vortices generated by a ramp fuel injector produce a similar effect. This additional stream wise vorticity should enhance mixing of the fluid behind the pylon and the main flow.

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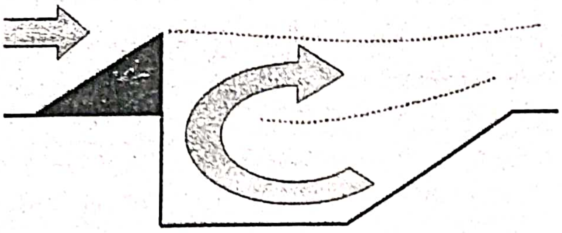

Figure 13. Cavity flame holder with inclined downstream ramp and leading edge pylon (on centerline)

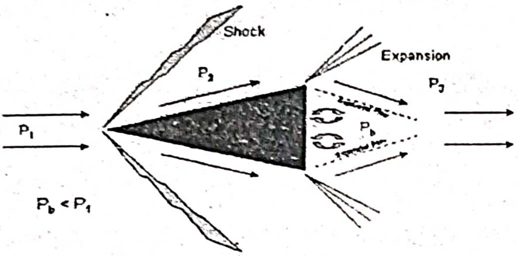

Figure14: Two-dimensional pylon shock/expansion system

K. Conventional-scale bluff-body flame holders

There is an extremely large body of work investigating combustion stabilization in conventional combustors in both subsonic and supersonic flows. The low velocity associated with subsonic flows favors the formation of very steady Recirculation zones, where hot products can heat the incoming fuel-air mixture, and in so doing provide conditions conducive to stable combustion. Bluff bodies such as vee-gutters and cylinders, illustrated above in Figure 15, are commonly used to generate these recirculation zones.

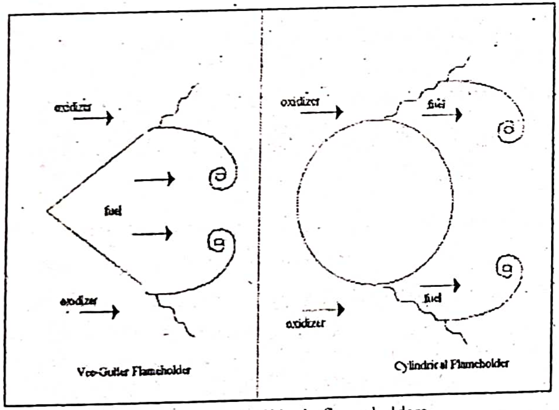

Figure 15: bluff-body flame holders

Much of the early combustion stabilization research was conducted in the 1950's. In 1956, Cornell et al. [22] investigated the flow behind a vee-gutter cascade in a gas turbine combustor. They compared their experimental results with the predictions of a theoretical model was able to successfully predict the wake shape, the total pressure loss, and the drag force of high blockage cascades of vee-gutter profiles. In the same year, Ames et al. [23] investigated interference effects between multiple bluff-body flameholders, and showed that the maximum blow-off velocity decreased as the number of flameholders increased due to increase in the blockage ratio.

L. Micro-flame holder

A micro-flame holder designed for achieving ignition and flame holding in a scramjet combustor has been previously built and tested experimentally by Mitani et al. in 2001 [24]. The micro-igniter was constructed from copper and measured 15cm in length and 5mm in width, with injector port diameters of 1.4mm and 2.5mm. Using a hydrogen-oxygen, mixture Mitani et al. showed experimentally that the micro-flame holder could successfully promote ignition in a Mach 2.5 air cross flow. The ignition performance of the micro-flame holder was found to be comparable to that of an oxygen plasma ignition torch; however, a much larger energy input was required for the operation of the micro-igniter. One micro flame holder arrangement is shown below in Figure16, where an array of micro- Flameholders is integrated into the upper portion of a rearward facing step or 'dump'. The idea is to create a locally well-mixed nearly stoichiometric region near the top of the 'dump' that burns stably and serves as a low-drag pilot to ignite and stabilize combustion in the bulk combustor flow. The micro-burner array consists of three layers: a top layer, which acts as a cover plate; a middle layer, in which fuel and air streams mix; and a bottom layer containing the fuel and air reservoirs.

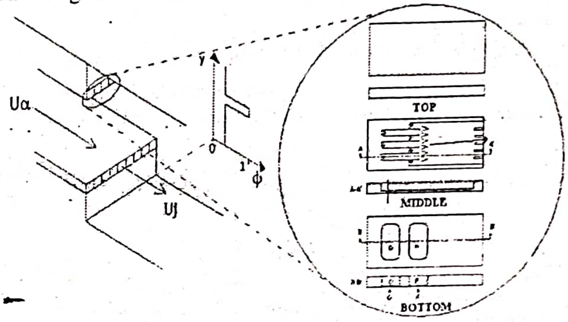

Figure 16. Schematic of scramjet micro-flame holder

An analogous flame holding concept could also be applied to combustion-based micro-power systems. A schematic of a micro-flame holder suitable for use in a micro-power device is illustrated below in Figure 17. Mixing is accomplished by the transverse injection of fuel into an air cross flow through multiple, opposed fuel injection ports integrated into a rearward facing step, 'dump' combustor configuration.

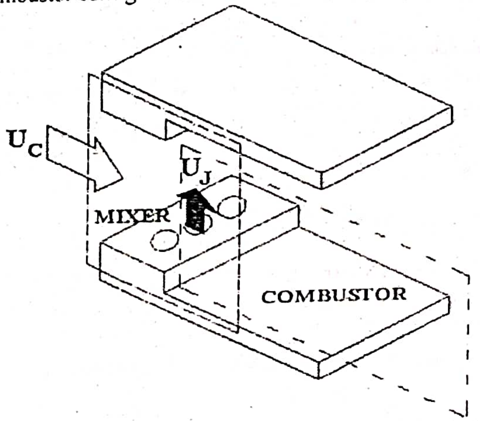

Figure.17 Schematic of micro-power system micro-flame holder

Despite the different appearance of the two micro-flame holder designs shown in Figure 16 and Figure 17, it is important to recognize that the physical problem is essentially the same in each case. In both concepts mixing is achieved via the injection of fuel into an airflow, inside a passage with small dimensions. The major difference, however, between the scramjet and micro-power system flame holder designs, is in their function. In the former case, the aim of the mixing process is to ignite and stabilize a pilot flame which in turn stabilizes combustion in the bulk flow of the combustor. In contrast, in the latter case the fuel-air mixture leaving the flame holder is directly burned in the micro-combustor. The similarities and differences present analogous as well disparate design challenges which are discussed in the next section.

M. Cantilever Fuel Injectors

Parent and Sislian [25] conducted numerical studies of mixing efficiencies of cantilevered ramp and Waitz ramp injector [26]. For the analysis the authors used Favre averaged Navier–Stokes equations for multiple species with κ–ω turbulence model. The study shows the mixing efficiency variation with convective Mach number. Cantilevered design has the advantage that shock is formed under the injectors providing contiguous shock surface span–wise direction of the injector array, which will increase the baroclinic effect and hence larger mixing efficiency. Figure.18 gives the geometry and compares the mixing efficiency of planar, free and cantilevered jets.

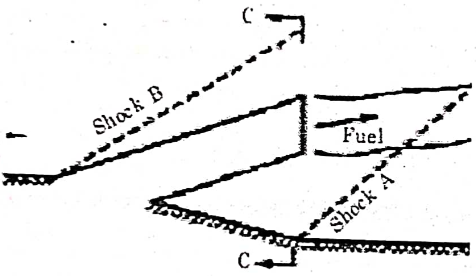

Figure 18: Geometry of Cantilever Fuel Injectors

The cantilever injection geometry is considered that is thought to embody the characteristics of both injection techniques. Shock B is responsible for the cross–stream shear, and shock A for the baroclinic effect, both of which generate strong longitudinal vortices. However, in the present design, in addition to the side wall vortices generated by the cross–stream shear, strong vortices will be produced behind the 'bluff–body' of the injector, as in the case of a low–angle wall fuel injector. These vortices will further enhance the mixing process. Although it can be considered as a candidate for fuel injection in scramjet combustors, the proposed cantilevered ramp injector is primarily considered for use in shock–induced combustion ramjets, where fuel–air mixing should take place without combustion until a specific location in the propulsive duct of the engine.

III. Some Recent Review on Sudden Expansion of Nozzle

K.M.Pandey[27] worked on the topic of "Wall Static Pressure Variation in Sudden Expansion in Flow through De Laval Nozzles at Mach 1.74 And 2.23: A Fuzzy Logic Approach" and his findings are - The analysis of wall static pressure variation with fuzzy logic approach to have smooth flow in the duct. There are three area ratios chosen for the enlarged duct, 2.89, 6.00 and 10.00. The primary pressure ratio is taken as 2.65 and cavity aspect ratio is taken as 1 and 2. The study is analyzed for length to diameter ratio of 1, 2, 4 and 6. The nozzles used are De Laval type and with a Mach number of 1.74 and 2.23. The analysis based on fuzzy logic theory indicates that the length to diameter ratio of 1 is sufficient for smooth flow development if only the basis of wall static pressure variations is considered. Although these results are not consistent with the earlier findings but this opens another method through which one can analyze this flow. This result can be attributed to the fact that the flow coming out from these nozzles are parallel one. K.M.Pandey [28] worked on the topic of "Wall Static Pressure Variation in Sudden Expansion in Cylindrical Ducts with Supersonic Flow: A Fuzzy Logic Approach" and his findings are - The analysis of wall static pressure variation with fuzzy logic approach to have smooth flow in the duct. Here there are three area ratios chosen for the enlarged duct, 2.89, 6.00 and 10.00. The primary pressure ratio is taken as 2.65 and cavity aspect ratio is taken as 1 and 2. The study is analyzed for length to diameter ratio of 1, 2, 4 and 6. The nozzles used are De Laval type and with a Mach number of 1.74 and 2.23 and conical nozzles having Mach numbers of 1.58 and 2.06. The analysis based on fuzzy logic theory indicates that the length to diameter ratio of 1 is sufficient for smooth flow development if only the basis of wall static pressure variations is considered. K. M. Pandey et.al [29] worked on the topic of "Studies on Pressure Loss in Sudden Expansion in Flow through Nozzles: A Fuzzy Logic Approach" and there findings are - Minimum pressure loss takes place when the length to diameter ratio is one and it is seen that the results given by fuzzy logic formulation are very logical and it can be used for qualitative analysis of fluid flow in flow through nozzles in sudden expansion. K. M. Pandey and E.Rathakrishnan [30] worked on the topic of "Influence of Cavities on Flow Development in Sudden Expansion" and there findings are - Flow from nozzles expanding suddenly into circular pipes with and without cavities was experimentally investigated for a Mach number range of 0.6 to 2.75. The research indicates that the introduction of secondary circulation by cavities reduces the oscillatory nature of the flow more in subsonic region than in supersonic region.

IV. Conclusion

The major types of fuel injection used in scramjet technology today are Parallel, Normal, Transverse Injection, ramp, and strut, Cavity-Pylon Flame holder, Cavity Flame holders, barbotage injection, Pylon Injection, upstream and pulsed injection. With these, there can be variations, such as the use of a plasma ignitor or a cavity. Each method has its advantages and disadvantages. The main issue to consider in scramjet injection is the flow ~~speed, which~~ has an effect on the mixing efficiency of the fuel and air. However, greater mixing can be achieved at the expense of pressure loss. A

4. Develop a hypersonic airbreathing sensitivity analysis code with appropriate flow physics to generate multiple parametrics of performance quantities within a defined design space based on high-fidelity CFD solutions. Implement a computational and, perhaps, corresponding experimental program to validate the methodology for complex configurations under unpowered and powered conditions.

5. Conduct a study to investigate full flowpath designs which utilize stream-traced forebody shapes and rectangular-to-elliptical transition inlets. This includes analytical and computational studies to investigate: Combustor designs; internal and external nozzle shapes; transition mechanisms from elliptical combustor cross sections to contoured nozzle shapes; methods for efficient integration with airframe and control surfaces; and the effects of multiple module interactions.

6. Implement an experimental and analytical program to investigate alternative mechanisms, such as thrust vectoring, to improve the controllability of scramjet-powered vehicles while minimizing trim drag and associated performance penalties.

7. Conduct analytical and computational studies to investigate issues associated with the integration of multiple-flowpath engine systems, such as RBCC and TBCC designs. This should include component interaction effects between systems, placement of flowpaths and engine nacelles, interaction of multiple plumes and unsteady effects of mode transitions. Advanced concepts, such as the use of rocket modules for scramjet fuel injection or enhanced controllability by tailoring fuel delivery, may also be examined.

8. A computational and experimental program to investigate Reynolds number scaling issues from ground test to flight conditions, and geometric scales, including the effects of boundary layer transition on flowpath and integrated vehicle performance.

9. An experimental and computational program to investigate the effects of inlet unstart on vehicle performance, stability and control.

10. A computational and experimental study to investigate alternative nacelle placements on vehicle performance.

3.4.5 Ignition and Flameholding

Ignition and flameholding devices in hypersonic airbreathing engines have a 1960's "subsonic pedigree," but largely result from trial and error engineering design processes - despite the fact that recent detailed chemical kinetics, numerical simulations of nonpremixed combustion, and several nonintrusive combustion diagnostic tools are available to transform this activity into systematic scientific study. Blunt-body fuel injector arrays and backward-facing-step fuel-injection configurations are typically analyzed using "calibrated" turbulent mixing codes, and highly simplified chemistry inadequate for the description of "ignition turning points." Designs are refined by trial and error to maximize mixing with minimal losses, and (hopefully) retain flameholding over a required range of conditions. The empirical design goal is to provide just enough reactivity/residence time for combustion initiation, propagation and radical mass transport through injection-stagnation and recirculation flows, while minimizing shocks and flow stagnations, and resultant drag, surface heating and thrust penalties. Thus, although ignition and flameholding are highly critical, they stem from empirical trial-and-error processes which may be far from optimum.

Where do we need to go in next 10 years? We need to apply (and refine) recent comprehensive and reduced kinetic schemes, in combination with nonpremixed numerical simulation tools and diagnostic techniques, to attack these problems more scientifically – e.g., as very recently done in some highly detailed computational/experimental studies that explain the lifting-stabilization-mechanism of jet diffusion flames. Needs include: detailed calculations and characterizations of free-radical initiation/production rates in reaction kernals (without and with air contaminants); residence-time distributions; localized shock and convective heating effects; cavity resonance frequencies; transport rates of free radicals to the primary supersonic flow; detailed sensitivities (partial derivatives) of ignition delays to imposed pressure/temperature fields and injector/flameholder geometric variables; and analyses to unravel complex diffusive/convective stabilization mechanisms that can maintain efficient unsteady combustion without flameout.

The AAAC should focus on long-term development and support of fundamental computational and experimental efforts as described above, with the goals of developing new mapping and optimization strategies for ignition and flameholding. Most importantly, this and similar high-risk and long-term research activities need to be conducted independently of project funding (e.g. Hyper-X or Future-X, etc) while maintaining adequate mechanisms for significant interchange of technical information.

The most significant engineering problem associated with ignition and flameholding in our present scramjet design methods is that we lack engineering prediction tools and methodology for accurately predicting engine light-off and blowout limits in clean air or in vitiated air. While some very old emipirical correlations exist [5, 6] to define these limits for subsonic flows using certain specific geometries (steps, wall jets, etc) the local flow residence time, pressure, temperature and flow composition must be known or estimated in order to use these correlations. In the complex flowfields or flameholding regions of "real" scramjet combustors these quantities are quite uncertain. Present codes which have some ability to predict light-off and flame-out behavior are either too time consuming for use in engineering design, or require specification of uncertain parameters, as in the empirical methods. Presently these limits are found through extensive tests of complex engine models, and are dependent on model scale, facility, and test conditions in many cases which results in highly uncertain "scalability" of results. The lack of a tool and/or methodology to predict light-off and flame-out results in conservative combustor and flameholder designs and is a significant liability in future test and analysis programs which seek to obtain "scalability".

If effective prediction tools and methodology could be developed to predict scramjet engine light-off and flame-out, designers could reduce engine length, drag (reduced flameholders), engine heat load, and increase engine operating margins, and thrust/weight ratios.

Therefore, engineering methods should be developed that are capable of predicting and measuring the required flow parameters in the flameholding region, with and without combustion, for complex "real" scramjet flowfields — so that existing experimental results for engines can be better correlated and "scaled". Ultimately, a unified predictive engineering code must be developed that will adequately predict light-off and flame-out limits for real engines as a function of flow composition, scale and combustor inflow conditions.

3.5 Testing Requirements and Facilities

During the NASP program a renewed interest in hypersonic flow phenomena led to the reactivation and upgrade of some older hypersonic test facilities and the building of new ones for the study of high enthalpy fluid dynamics, and specifically airbreathing propulsion flowpaths. These facilities, generally of the pulse type in which test gas is heated by the passage of a strong shock wave, can deliver a test gas flow at stagnation enthalpy equal to the energy of an aerospace vehicle in atmospheric flight up to orbital speeds. Pulse facilities can operate as either a reflected-shock tunnel (RST) or a shock-expansion tunnel (SET). For airbreathing propulsion testing, RST's are generally best between Mach 7 to 12 flight enthalpy duplication, with the upper limit based on avoidance of excessive dissociation of O_2 in the stagnated air test gas in the nozzle plenum. The SET's are more appropriate

- Finally, it is clear that if a flight demonstration was made using a vehicle whose size would have been chosen minimal for together preserving the demonstration interest of the operation, and limiting the cost, this minimal size would probably be not very far from the size of a missile. Consequently, the success of the flight demonstration would validate the methodology used to develop the experimental vehicle, so that this methodology would also be applicable for any kind of vehicle of similar size and level of integration.

Then, different possible military applications can be proposed:

- Tactical missile when penetration is the key factor or when pure speed is necessary against time targets
- High speed reconnaissance drone with improved mission safety and response time capability
- Global range rapid intervention system based on previously mentioned missiles and drones
- Global range military aircraft or UCAV
- Short response time space launching system

- **Civil applications**

On the other hand, for civil applications, a hypersonic cruiser aircraft that is an alternative to traditional turbojet or turbofan transportation could also be a not-too-distant possibility. The urge to always fly faster and higher might contribute to develop a scramjet vehicle for a commercial hypersonic flight. However, due to all the problems present in the scramjet technology and the remaining uncertainties, today this possibility stays very far from being a reality.

3.4. Current scramjet engine technology challenges

This section will expose some of the most important pros and cons of the scramjet technology as well as some technical challenges.

One of the greatest advantages is the simplicity of design. A scramjet has no moving parts and the main part of its body is constituted by continuous surfaces. This admits relatively low manufacturing costs for the engine itself. Another significant difference between airbreathing engines and rockets, both of them able to fly at hypersonic speeds, is the fuel for combustion that they have to carry on board. While a rocket must carry the oxidizer on board, a scramjet collect it from the atmosphere; thus, this last would be lighter and hopefully capable of carrying more payload, since in a rocket the 75 percent of the total start weight is the oxidizer. So, that would be a great advantage too.

On the other hand, a scramjet engine has a major inconvenience. It cannot produce thrust if it is not first accelerated to a high velocity around Mach 5-6. This requires one or two additional propulsion systems to propel the vehicle to the needed scramjet start velocity. Therefore, various structures are needed for the suspension of these engines as well as all necessary control systems. All secondary equipment necessary to bring the vehicle to velocities suitable for the scramjet operation makes the whole vehicle heavy, in contrast to what has been mentioned previously. Then, the loss in the dry mass and, consequently, the gain in the payload mass are not so significant. In order to minimize the weight and complexity of having multiple propulsion systems, a dual-mode ramjet/scramjet is often proposed.

The current challenges in the development of the scramjet engine can be gathered in three main areas: air inlet, combustion, and structures and materials.

- **Air inlet**

The overall performance of a scramjet is largely dictated by the aerodynamic performance, geometric size, and weight of the hypersonic inlets. Commonly, hypersonic inlets have a wide Mach number range, but the shock-on-lip condition can be met only at the design Mach number, since shock angles vary with the upstream Mach numbers. Thus, at Mach numbers higher than the design one, the ramp shocks move inside the inlet and evolve into a strong incident shock, causing strong slip layers, remarkable total pressure loss, boundary-layer separation, and possible engine unstart. At Mach numbers lower than the design one, the ramp shocks move away from the cowl lip, causing loss of the precompressed airflow and the so-called spillage drag. To avoid these performance penalties at offdesign conditions, the control of the ramp shock system is needed. Hence, variable geometric approaches for ramp shock control are widely considered and studied.

Spills ~~the~~ air outside instead of compr

Rectangular plate like device with air intake the engine designed to generate No. of shock waves and the inlet compressing sonic speed air crossing each shock layer the Mach No. increase pres

- **Combustion**

Although the concept of scramjet engines appears simple, supersonic combustion remains a complex field of study. Supersonic combustion is very difficult to maintain and continues to be a formidable task.

The ignition delay time of a fuel-air mixture continues to be the limiting factor for all scramjet engines designs. Decreasing the delay time allows for shorter combustors and/or higher flight velocities. Initially, the ignition delay time of a fuel is fixed for a given set of conditions and the type of fuel. Increasing the temperature of the fuel and/or air stream reduces this time. Pressure plays a somewhat more complex role. Increasing the pressure, usually, but not always, improves the combustion conditions. Increasing pressure usually reduces the ignition delay time, but there exists a critical value of pressure, above which, the delay time increases dramatically, followed by a slow decrease. So, it is not always advantageous to increase the pressure. The equivalence ratio does not strongly affect the ignition delay time, except for equivalence ratios below 0.3, where the delay time increases sharply. Hydrogen has very low ignition delay time compared with hydrocarbon. Therefore, all these effects need to be considered in designs.

PSD.7
n

Perhaps the largest problem associated with combustion is the mixing between freestream air and fuel. If fuel cannot be properly injected and mixed into the air stream it will not ignite, regardless of pressure, temperature or equivalence ratio. Due to compressibility effects, fuel injection presents challenging obstacles. The air stream is at such a high pressure and velocity, that fuel injected into the stream has a tendency to be pushed against the wall and rendered ineffective. In addition to the problem of mixing, ignition and flame holding at these high velocities is extremely difficult. To overcome these challenges, several solutions have been proposed like plasma torches, ramps and wedges, or recessed cavities.

Another challenge to increase the performance is the need of a variable geometry combustion chamber. A fixed geometry combustor associated to a variable capture area air inlet does not benefit from the enhanced efficiency of the air inlet. A fully variable geometry – air inlet + combustion chamber – can increase the performance by comparison with the previous concept, but cannot take all the benefit of the complexity related to a fully variable geometry system because of the fixed minimum section of the inlet (equivalent to the fixed section of the combustion chamber entrance). So other concepts have been studied, which consist in modifying at the same time the minimum section of the air inlet and the geometry of the combustion chamber. Moreover, for such concepts, having at disposal a variable minimum section for the air inlet avoids the need of large variation of the air inlet capture area (i.e. increase when the Mach number increases) and permits high efficiency in a wide Mach number range.

- **Structures and materials**

Unlike a rocket that passes nearly vertically through the atmosphere on its way to orbit, a scramjet would take a more levelled trajectory. Because of the thrust-to-weight ratio of a scramjet being low compared to modern rockets, the scramjet needs more time to accelerate. Such a depressed trajectory implies that the vehicle stays a long time in the atmosphere at hypersonic speeds, causing atmospheric friction to become a problem. This is not only for space launch applications but also in missile or commercial transport applications. Heat addition produced by the combustion at these high velocities and temperatures is another significant factor to take into account. Therefore, the materials chosen for the structure must have good properties and be adequate in front of these phenomena. Furthermore, cooling of the engine's structure by fuel or radiation is essential.

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4. Parts of a scramjet engine

In this chapter are described the different parts of a scramjet engine: air inlet, isolator, combustor and nozzle. With the actual technology, as it is mentioned in Chapter 3, the scramjet engine must be integrated with the fuselage of the aircraft, specially the air inlet and the nozzle. Part of the forebody aircraft fuselage makes the function of air inlet compressing the freestream air, and similarly, the aftbody acts as a nozzle expanding the gases from the combustion.

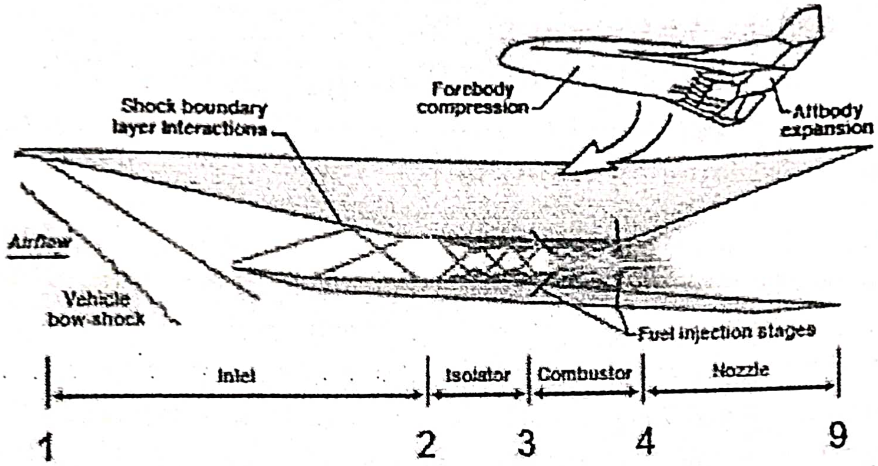


Figure 11. Propulsion-airframe integrated scramjet with station numbering

The flowpath through a scramjet engine follows a Brayton thermodynamic cycle. The air is compressed, after that combustion takes place to increase the flow temperature and pressure, and finally, the products from the combustion are expanded. Next, the different parts of a scramjet in charge of these processes are described.

4.1. Air inlet

The air inlet can be considered as a diffuser in which takes place the compression of the freestream air gathered. This compression is achieved by successive shock waves.

For an oblique shock wave (see Figure 40 of Annex C), the flow is always deflected towards the shock wave, and the flow properties vary as

$$
\begin{array}{lll}
M_{2n} < 1 & M_2 < M_1 & \\
T_{t2} = T_{t1} & p_{t2} < p_{t1} & \rho_{t2} < \rho_{t1} \\
T_2 > T_1 & p_2 > p_1 & \rho_2 > \rho_1
\end{array}
$$

Here the subscript 1 and 2 corresponds respectively just before and just after the shock wave.

Therefore, at the exit of the air inlet, the supersonic freestream air has reduced its velocity and has raised its static temperature and pressure. Furthermore, the total temperature through the air inlet is constant and the total pressure changes

$$\frac{T_{t2}}{T_{t0}} = 1 \qquad \frac{p_{t2}}{p_{t0}} < 1$$

The subscript 0 represents freestream conditions before forebody compression.

The ratio between the total pressure at the station 0 and 2 (π_d) characterizes the inlet's pressure performance and consists of two contributions

$$\pi_d = \pi_{d_{max}} \eta_r \tag{4.1}$$

$\pi_{d_{max}}$ represents the part due to viscosity effects, while η_r is called recovery factor and characterizes the contribution of compressibility effects. Both factors imply total pressure losses within the inlet.

The performance of the air inlet compression can be separated into two key parameters: capability, or how much compression is performed, and efficiency, or what level of flow losses does the inlet generate during the compression process. A common parameter used to quantify the efficiency of the forebody/inlet compression is the kinetic energy efficiency η_d. The definition of η_d is the ratio of the kinetic energy the compressed flow would achieve if it were expanded isentropically to freestream pressure, relative to the kinetic energy of the freestream

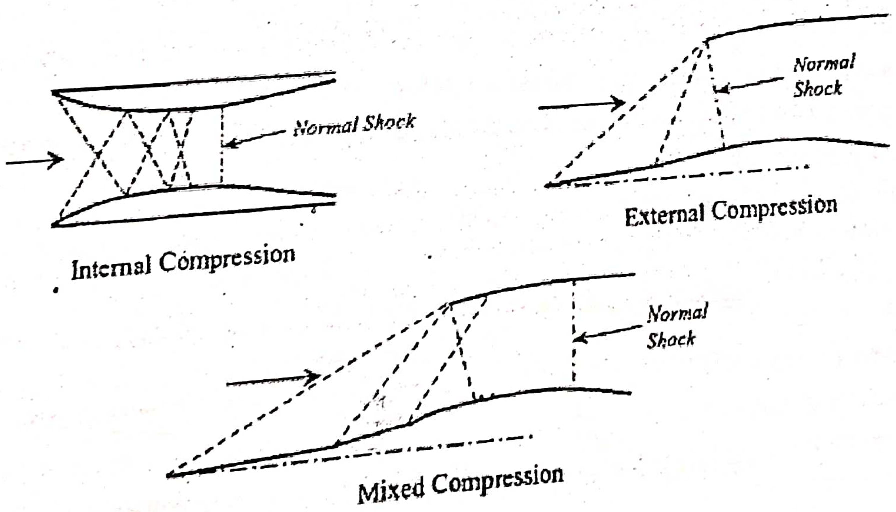
$$\eta_d = \frac{\frac{1}{2} u'^2_2}{\frac{1}{2} u_0^2} = \frac{u'^2_2}{u_0^2} \tag{4.2}$$

Both parameters, total pressure ratio and kinetic energy efficiency, can be related through the expression

$$\pi_d = \left[1 + (1 - \eta_d)\frac{\gamma - 1}{2} M_0^2\right]^{\frac{-\gamma}{\gamma - 1}} \tag{4.3}$$

See Annex C for more details on this expression, as well as on the equations governing shock waves.

Hypersonic inlets used in scramjets fall into three-different categories, based on the type of compression that is utilized. These three types are: external compression, mixed compression and internal compression. A schematic of these types is shown in Figure 12. In the external compression all the compression is performed by flow turning in one direction by shock waves that are external to the engine. These inlet configurations have large cowl drag, as the flow entering the combustor is at a large angle relative to the freestream flow; however, external compression inlets are self-starting and spill flow when operated below the design Mach number (this is a desirable feature for inlets that must operate over a large Mach number range). In a mixed compression inlet the compression is performed by shocks both external and internal to the engine, and the angle of the external cowl relative to the freestream can be made very small to minimize external drag. These inlets are typically longer than external compression configurations, but also spill flow when operated below the design Mach number. Depending on the amount of internal compression, however, mixed compression inlets may need variable geometry in order to start. In internal compression inlet the compression is performed by shock waves that are internal to the engine. This type of inlet can be shorter than a mixed compression inlet, but it does not allow easy integration with the vehicle. It maintains full capture at Mach numbers lower than the design point, but its most significant limitation is that extensive variable geometry is always required for it to start.



Internal Compression

External Compression

Mixed Compression

Figure 12. Types of supersonic air inlets

4.2. Isolator

At flight speeds below Mach 8, combustion in a scramjet engine can generate a large local pressure rise and separation of the boundary layer on the surfaces of the combustion duct. This separation, which can feed upstream of fuel injection, acts to further diffuse the core flow in the duct, and will affect the operation of the inlet, possibly causing an unstart of the engine. The method use to alleviate this problem is the installation of a short duct between the inlet and the combustor known as an isolator. In some engines (those which operate in the lower hypersonic regime between Mach 4 and 8) the combination of the diffusion in the isolator and heat release in the combustion decelerate the core flow to subsonic conditions, in what is called dual-mode combustion. At speeds above Mach 8 the increased kinetic energy of the airflow through the engine means that the combustion generated pressure rise is not strong enough to cause boundary layer separation. Flow remains attached and supersonic throughout, and this is termed pure scramjet. In this case an isolator is not necessary.

The structure of the supersonic flow in confined ducts under the influence of a strong adverse pressure gradient is of interest in the design of scramjet isolators. As shown in Figure 13, a pressure gradient is imposed on the incoming supersonic flow, and with the presence of a boundary layer, a series of crossing oblique shocks are generated. This phenomenon, known as pseudo shock or shock-train, is characterized by a region of separated flow next to the wall, together with a supersonic core that experiences a pressure gradient due to the area restriction of the separation and forms the series of oblique shocks mentioned before. Finally, the flow reattaches at some point and mixes out to conditions that match the imposed back-pressure. Being able to predict the length scale of this flow structure is the key component of isolator design for dual-mode scramjets.

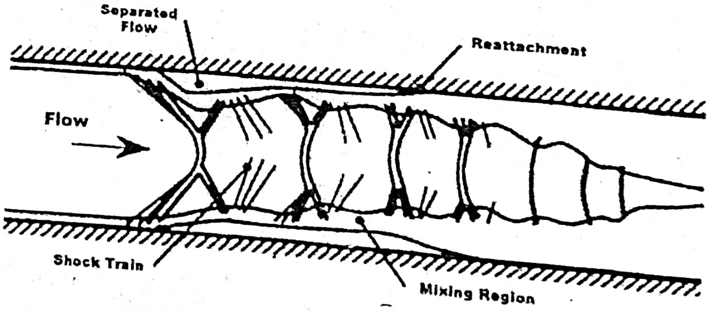


Figure 13. Schematic of flow structure in an isolator

4.3. Combustor

The combustor chamber is a duct where the combustion between freestream air and fuel takes place. This combustion is supersonic, so there are some aspects that require more attention on the contrary of the conventional combustion. Next, these aspects will be commented.

At very high velocities, a properly fuel injection and mixing could be a problem, as well as flame holding. That is why over the past decades a lot of different configurations have been studied and developed. Some techniques used today for fuel injection in scramjet engines are: wall, ramp, strut, pylon and pulsed injectors. And for keeping the combustion, there is a technique quite used called cavity flame holders.

Another significant aspect to take into account is the dissociation. At the entrance of the combustor the flow static temperature and pressure are very high, and with the heat release due to chemical reactions, the temperature and pressure could reach extremely high values which involve dissociation of combustion products.

Because of the heat addition, the velocity or Mach number decreases while the static temperature and pressure increases. The total temperature is raised and the total pressure is reduced. The total pressure loss is proportional to the square of Mach number; hence, it is better to have a small combustor inlet Mach number, on the contrary for the dissociation phenomenon. In Section 4.4 there is a discussion about the optimum Mach number at the entrance of the combustor.

Finally, the fuel used in scramjet engines is hydrogen or hydrocarbons. Hydrogen is most used because it has more advantages in front of hydrocarbons. The reason for using liquid hydrogen for scramjet fuel rests with its high specific impulse and its potential for cooling parts of the vehicle. The heat value (which represents the amount of energy released when a fuel is combusted) for hydrogen is two and a half times that of hydrocarbons. Hydrogen is also extremely flammable and it has a wide flammability range (it can burn when it occupies between 4 - 74% of the air volume). Another advantage over hydrocarbons is that hydrogen is a clean fuel as it doesn't produce any harmful pollutants like carbon monoxide (CO) or carbon dioxide (CO_2) during the combustion process. The only product from its combustion is water, which can be safely exhausted into the atmosphere.

Although it may appear that hydrogen is the ideal fuel for scramjet propulsion it does present some drawbacks. Liquid hydrogen is not a dense fuel, having a density of only 0.09 kg/m^3. For example, JP-8 on the other hand has a density of 800 kg/m^3 in similar conditions, very much higher. Having a low density does save weight; however, a large volume is needed in order to store enough chemical energy for practical use.

Even with the above limitations hydrogen has been the clear choice for many scramjet researchers due to its versatility and performance, and it is also clear that hydrogen will be the preferred fuel for future projects and developments using scramjet technology.

4.4. Nozzle

The nozzle is a divergent duct that accelerates the supersonic flow and at the same time expands it reducing its static temperature and pressure. The expansion process converts the potential energy of the combusting flow to kinetic energy and then it results in thrust. An ideal expansion nozzle would expand the engine plume isentropically to the freestream pressure assuming chemical equilibrium. Nevertheless, loss mechanisms are present in real expansion processes and are due to under-expansion, failure to recombine dissociated species, flow angularity and viscous losses.

The weight of a fully-expanded nozzle would be prohibitive at most hypersonic flight conditions; hence under-expansion losses are usually traded against vehicle structural weight. Dissociation losses result from chemical freezing in the rapid expansion process in the nozzle, essentially locking up energy that cannot be converted to thrust. Flow angularity losses are product of varying flow conditions in the nozzle, and viscous losses are associated with friction on the nozzle surfaces.

The flow enters the nozzle in a highly reactive state. As it expands to lower pressure and temperature, chemical reactions will occur toward the completion of combustion, with consequent additional heat release. If the expansion is slow enough chemical equilibrium is approached, but in most cases, due to the high velocities reached in a scramjet, the flow composition freezes and becomes fixed. Two limiting cases can be treated fairly easily: equilibrium flow, where equilibrium is maintained through all nozzle length, and frozen flow, where the flow doesn't change its composition from the combustor exit. The true situation lies between these two cases.

The choice of combustor inlet Mach number is a key aspect for the performance of the scramjet and it is related to the nozzle expansion. If the static temperature at the combustor entrance is too high, dissociation will be present and then chemical energy is not available as thermal energy for conversion to kinetic energy in the nozzle. So, the question to be dealt with quantitatively is then what static temperature, or what combustor inlet Mach number, is best for any given flight Mach number. The existence of such an optimum M_3, which depends on finite chemical reaction rates, can be seen by comparison of the specific impulse for two limiting cases: one which chemical equilibrium is assumed throughout the flow, and another in which the flow is assumed to be in equilibrium up to the combustor exit but frozen at that composition during the nozzle expansion.

As it can be seen in Figure 14, for equilibrium nozzle flow there is no optimum M_3, the specific impulse increases continuously as M_3 decreases. This is not surprising, because for equilibrium flow the chemical energy invested in dissociation is recovered as thermal energy and then kinetic energy as recombination occurs in the nozzle, and the lower the combustor Mach number the lower the entropy increase in the combustor. Therefore, independently on the flight Mach number interests a low combustor inlet Mach number.

In contrast, for frozen nozzle flow (Figure 15), there is a clear optimum M_3 for flight Mach numbers above about 10. It is defined by the envelope, drawn as a dashed line. The optimum value of M_3 depends on the extent to which recombination occurs in the nozzle, as well as on the degree of dissociation at the combustor exit. For a very high flight Mach number, if the flow is decelerated to a very low M_3, the total pressure loss will be small but then losses of dissociation will be too high, and in the opposite case, if the flow is slowed to a relative high M_3, dissociation losses will be small but the total pressure loss will be very elevated. So, balancing each term it can be found an optimum combustor inlet Mach number.

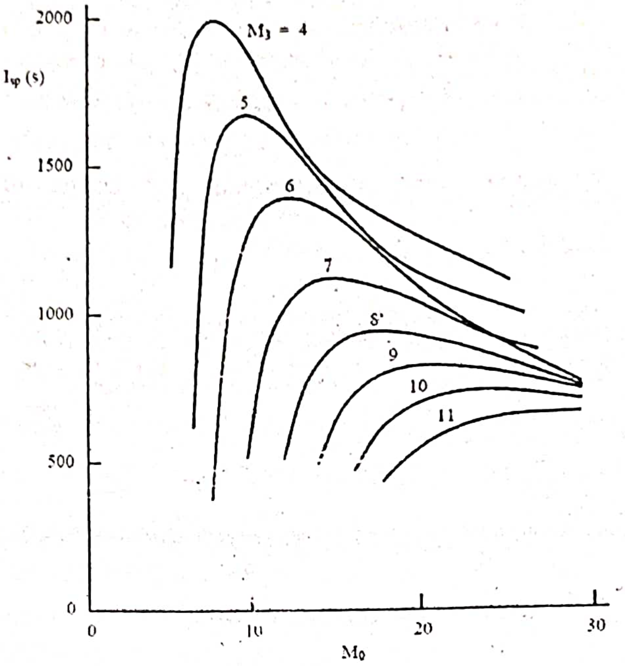


Figure 14. Specific impulse for equilibrium nozzle flow (combustor pressure fixed at 1 atm)

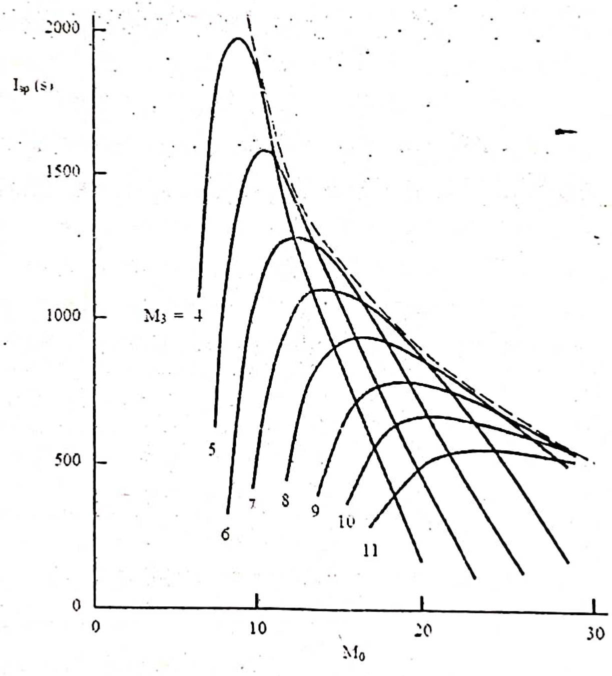


Figure 15. Specific impulse for frozen nozzle flow (combustor pressure fixed at 1 atm)