Recent Advances in Scramjet Fuel Injection - A Review

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***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.

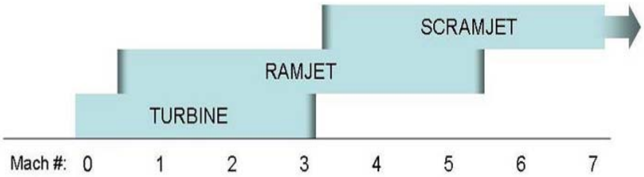

Figure1. Approximate Mach number regimes

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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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].

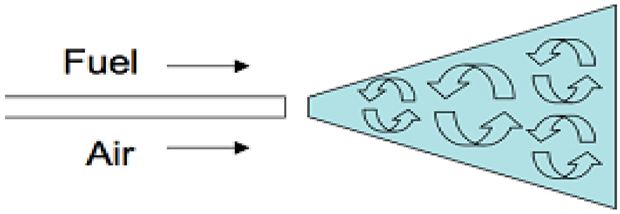

Figure 2: Parallel fuel injection

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].

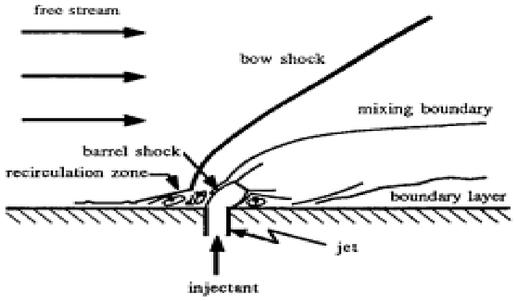

Figure 3: Normal fuel injection

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).

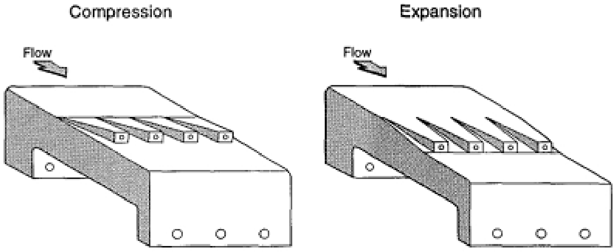

Figure 4: Ramps used for mixing

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.

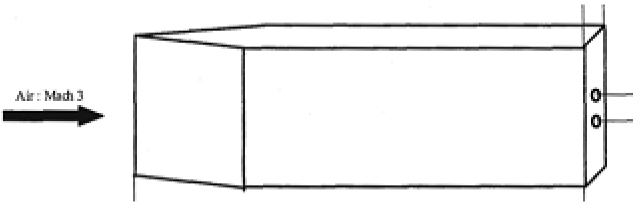

Figure .5: Strut injector

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.

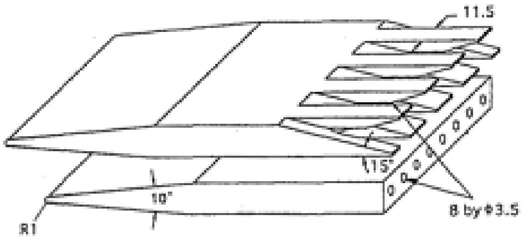

Figure 6: Alternating Wedge strut

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.

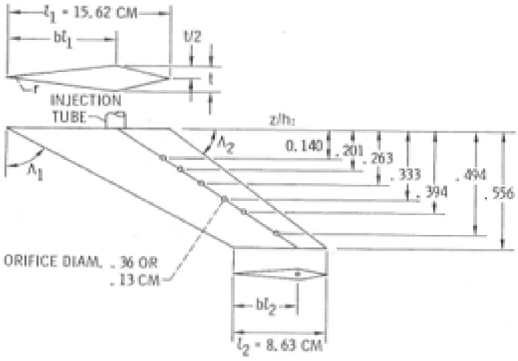

Figure 7: Diagram of basic strut

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.

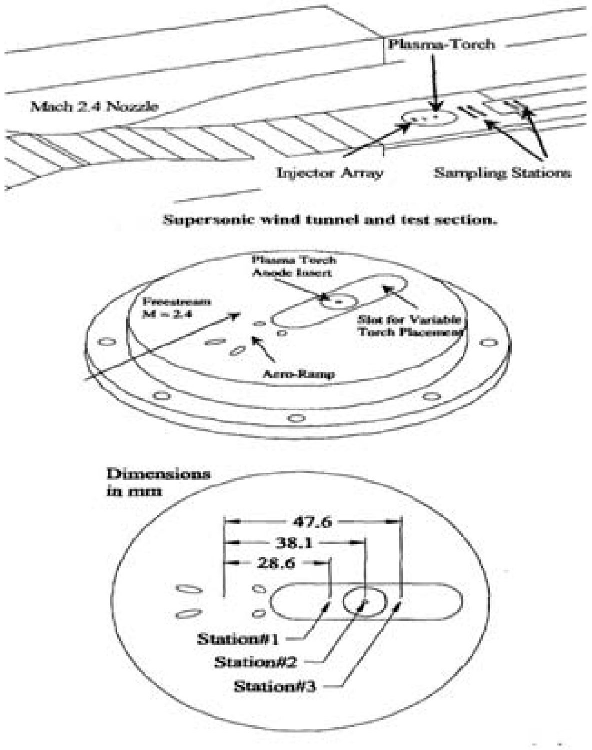

Figure 8: Plasma torch ignition arrangement with injection ports

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.

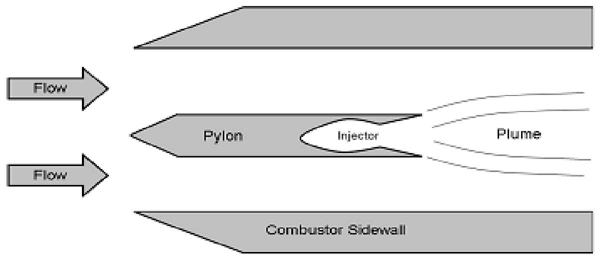

Figure 9: Central Pylon Fuel Injection

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.

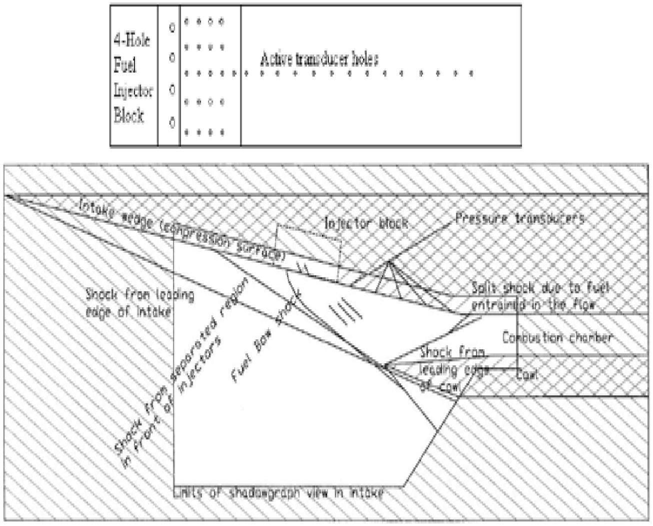

Figure 10: Upstream injection

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.

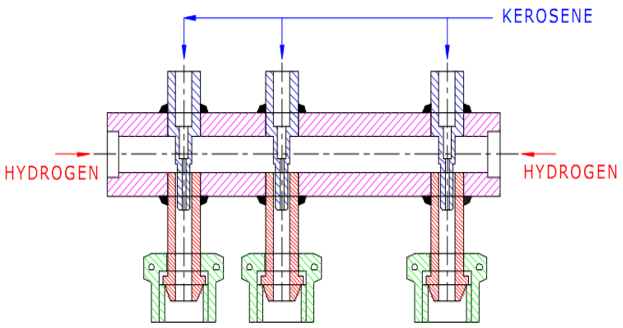

Figure 11: Barbotage system

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.

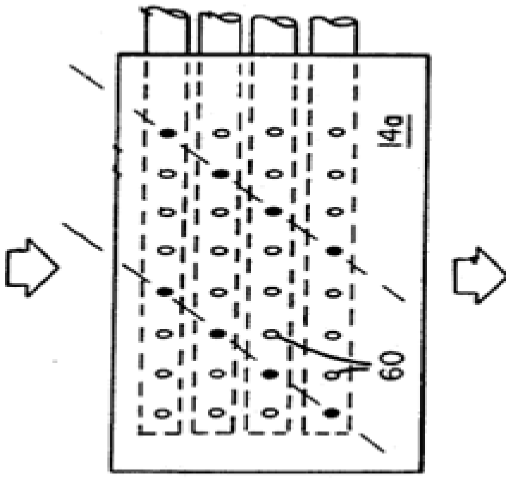

Figure 12: Pulsed fuel injection

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.

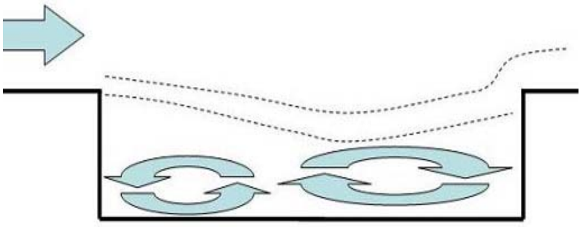

Figure 13: Rectangular cavity flame holder

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.

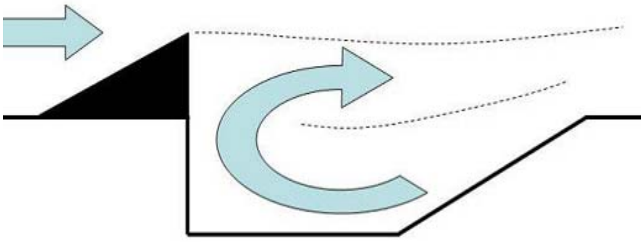

Figure 13. Cavity flame holder with inclined downstream ramp and leading edge pylon (on centerline)

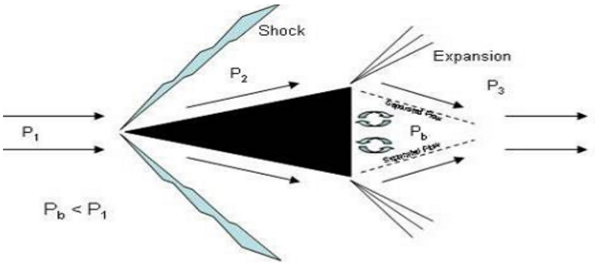

Figure14: Two-dimensional pylon shock/expansion system

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.

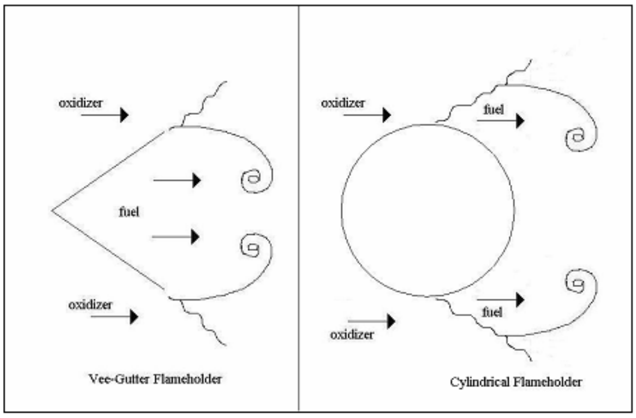

Figure 15: bluff-body flame holders

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.

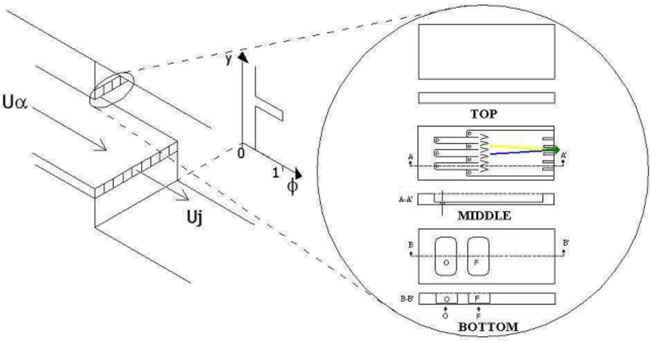

Figure 16: Schematic of scramjet micro-flame holder

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.

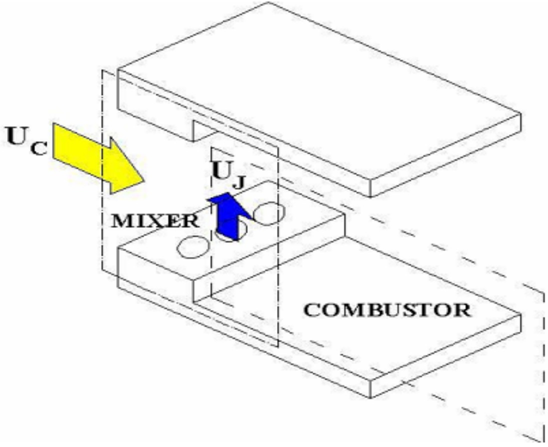

Figure.17 Schematic of micro-power system micro-flame holder

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.

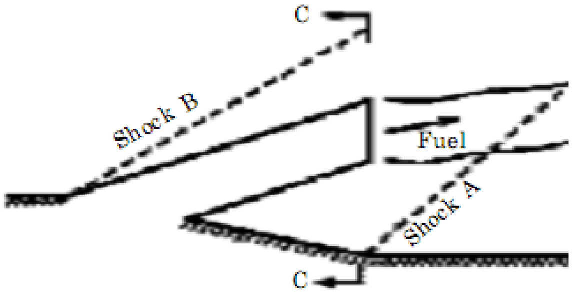

Figure 18: Geometry of Cantilever Fuel Injectors

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 high mixing rate increases the efficiency of a scramjet, as it reduces the combustor length, and hence the skin frictions drag.

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