Chapter 1
The Role of Plasma Igniters and Fuel Injectors in Hypersonic Technology

"If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations - then so much worse for Maxwell's equations. If it is found to be contradicted by observation - well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation."

- Arthur S. Eddington (British Astrophysicist, 1882-1933)

From the beginning of the first powered flight in 1903 by the Wright brothers, advances have been made in the propulsive devices used to propel vehicles, producing higher flight velocities and extended ranges. Evolution from propeller-driven vehicles, to turbojet, turbofan, ramjet, and scramjet-propelled vehicles has been fueled by the need for those vehicles to accomplish different mission types. Rotating engines, such as propeller, and turbojet designs, rely on thrust to be developed through fluid interaction with rotating blades. As early as the 1930s, engines requiring no rotating parts (ramjets and later scramjets) were envisioned as the next stage in aerospace propulsion evolution. Ramjets rely on the compression of intake air solely through the shape of the inlet into the engine. The air is then mixed with fuel, burned subsonically in the combustor, and forced out the nozzle in the back, generating thrust. These types of engines can propel vehicles up to a maximum velocity of about Mach 5. At this point, deceleration of the flow to subsonic velocities within the combustor causes a rise in temperature sufficient to melt most known materials. To overcome this, supersonic combustion ramjets (scramjets) utilize a different combustor design, one employing supersonic combustion, allowing higher flight velocities. However, this performance benefit does not come without a price. At supersonic speeds it is extremely difficult to burn an appreciable amount of fuel within the combustor due to the relatively low residence time the fuel spends within the engine. Furthermore, the maximum allowable flight speed is a function of the fuel type used. Hydrogen, which burns easily, permits higher flight speeds, but has less energy density than hydrocarbon fuels, which although they burn more slowly, allow for greater range. This concept is illustrated in Figure 1.1. In addition, the results of an extensive study investigating the use of subsonic versus supersonic combustion was published by Dugger (1960), who determined that the flight range to transition from subsonic to supersonic combustion lies between Mach 6 and Mach 8.

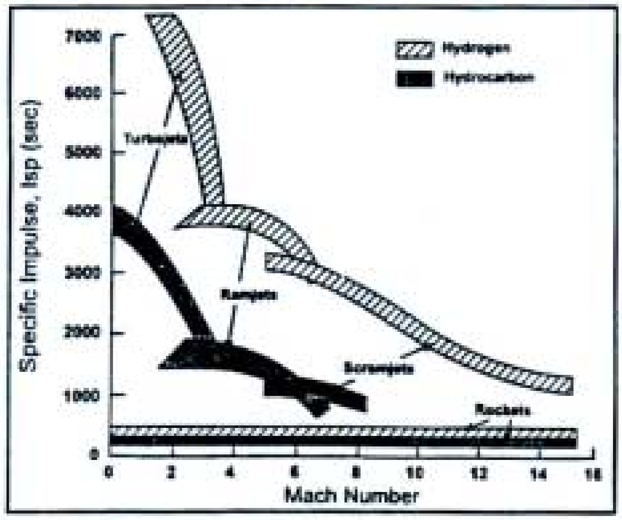


Figure 1.1: Approximate Performance Levels of Various Classes of Engines (Curran, 1999)

1.1: Development of Hypersonic Technology

Supersonic combustion ramjets (scramjets) were identified in the 1950s as having the potential for huge performance gains over all known means of air-breathing propulsion above Mach 5. A brief review in the developments of ramjet and scramjet technologies are discussed here. Readers interested in a more detailed description of topics presented here and other related propulsion topics can read Curran's discussion of the historical development aerospace engines (Curran, 1997 and 1999). The earliest practical ramjet was used for tank shell range extension in 1928. However, Weber and McKay (1958) identified a problem associated with the current ramjet technology in that, for speeds above Mach 6, the high temperatures caused by the flow deceleration were enough to melt most known structural materials and cause dissociation of the combustion constituents, resulting in a subsequent loss of a large portion of the available chemical energy combustion process. They envisioned that the application of supersonic combustion could overcome many of these challenges by reducing the high temperatures induced by flow deceleration. They based their supersonic combustion work on early 1950s experiments by Pinkel, Sarafini and Gregg (1952), who demonstrated supersonic combustion on a flat plate. Dugger and Billig (1959) paralleled Weber and McKay's work with theoretical and experimental studies and produced the first major milestone in supersonic combustion technology, the production of net positive thrust on a double wedge.

The 1960s saw a major push for supersonic combustion developments in the United States with the construction of four separate research engines built for the United States Air Force. These engines were designed to test various aspects of ducted scramjet engine design, such as staged fuel injection for combustor transition, variable geometry inlets for ramjet-scramjet transition and rearward facing steps for flameholding. Contributors were GASL, JHU/APL, NASA-Langley, and the Marquardt Company, with important individual contributions made by Ferri (1964 and 1968) and Swithenbank (1966). The result was an engine incorporating a rearward facing step, constant area combustor section, and the use of hydrocarbon fuels with pyrophoric ignition. Ground tests at Mach numbers between 5 and 7 produced the first demonstration of net positive thrust for a model scramjet engine. NASA also began development of scramjet engines in the 1960s for use on the X-planes. Although the flight demonstration of these engines was never realized, two engines were built and tested by Garrett. Subsequent developments provided insight that higher levels of thrust and efficiency could be produced by ducted scramjets. Numerical analyses showed that a ducted scramjet powered missile could achieve powered ranges of several hundred miles flying in the upper atmosphere at speeds up to Mach 8. The Navy began supporting efforts for development of these ducted scramjets in the early 1960s (Dugger, 1961; Billig, 1965). The project was to be known as the Supersonic Combustion Ramjet Missile, or "SCRAM," and is now the name by which the technology is identified. The SCRAM program successfully demonstrated that ducted supersonic combustion was feasible, but was cancelled in 1977 due to technical shortcomings.

The project directly succeeding the SCRAM project, and also the most developed concept design throughout the 1970s, was the Dual-Combustor Ramjet (DCR) designed by JUH/APL (Waltrup et al. 1979; Billig et al. 1979). The DCR contains all the features of a scramjet with the addition of a small subsonic combustor to act as a pilot flame and fuel cracker for the main engine. The concept of a DCR is illustrated in Figure 1.2. This subsonic combustor acts as fuel preconditioner, cracking the fuel and preparing it for the supersonic combustor. Essentially, a portion of the intake air is diverted into this secondary combustor where all of the hydrocarbon fuel is injected. In this region a pilot flame is easily maintained because the flow is subsonic, and the heat released through partial combustion of the fuel chemically cracks any unburned fuel as it passes out of the combustor into the supersonic air stream. Although theoretically feasible, a difficulty with this design is the nontrivial amount of space taken up by the subsonic combustor. Waltrup continued the development of the DCR concept well into the 1980s through several discussions on the drawbacks and proposed improvements associated with the technology (Waltrup, 1982 and 1987).

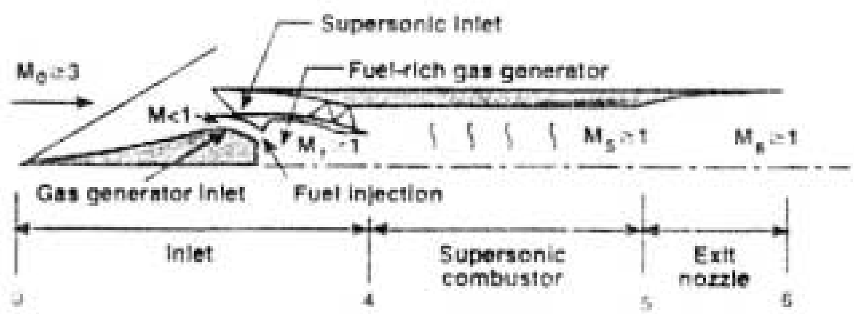


Figure 1.2: The Dual-Combustor Ramjet Concept (Waltrup et al., 1996)

The 1980s and early 1990s were host to the NASP project (X-30), the next major step in demonstrating the feasibility of hypersonic flight (Harsha and Waldman, 1989). A concept picture of the X-30 is shown in Figure 1.3. The goal of the NASP project was to provide a technology base for reaching orbit in a single manned stage with horizontal takeoff and landing capability. The broad-based NASP project involved development of scramjet testing requirements, understanding the high-speed flow physics, and spawned many fundamental investigations of supersonic combustion, such as those done at NASA-Langley (Northam and Anderson, 1986). Development of the X-30 research vehicle, continuing until 1993, comprised the second stage of the project, which was designed to demonstrate the capability of hypersonic cruise and ultimately, the possibility of achieving single-stage-to-orbit.

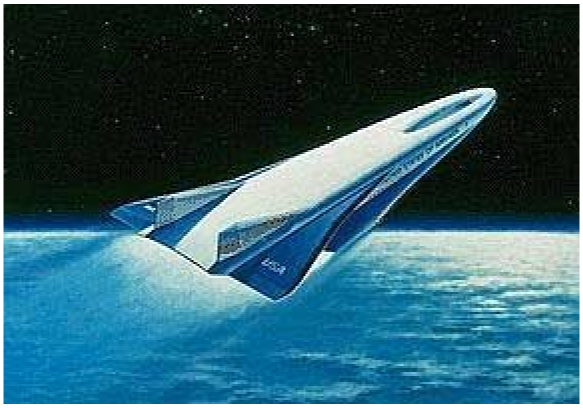


Figure 1.3: A Concept Picture of the X-30

Aside from the United States' NASP project, the early 1990s were a proving ground for Russian supersonic technology as well. Basing their designs on Billig and Waltrup's earlier DCR work, the Russians developed and flew a hydrogen-fueled scramjet engine utilizing a dump combustor as a pilot and fuel preconditioner (Vinogradev et al., 1990). The engine was mounted on the tip of a Russian SA-5 booster rocket and telemetry data were used to measure the amount of thrust generated by the engine. According to Covault et al. (1992) and Roudakov et al. (1991), the Russians succeeded in flying several short tests with this dual combustor ramjet and achieved powered flight under scramjet operation at a flight speed of Mach 7. Although reports of Russian advancements are not easily accessed, a report by the Air Force Scientific Advisory Board notes that the Russians are "pressing ahead most forcefully" (Covault, 1992).

More recently, Russian propulsion efforts have mainly been the result of research programs at the Central Institute of Aviation Motors (CAIM), the Central Aerohydrodynamic Institute (TsAGI), the Institute of Applied Mechanics (ITPM), and the Moscow Aviation Insitute (MAI). A partnership between MAI and Aerospatiale in France has formed to develop what is known as the Wide Range Ramjet (WRR) (Chavalier et al., 1996). The WRR concept incorporates moveable panels within the combustor to allow transition from subsonic to supersonic combustion. In addition, the design uses two fuels, kerosene for subsonic combustion and hydrogen for supersonic combustion. Another joint program includes that between Germany and Russia's TsAGI in the development of cooling technology for scramjet operation. A detailed report on this program is provided by Sabelnikov et al. (1995). Those interested in earlier Russian work can read a report by Kurziner, detailing research in the area of jet engines for supersonic flight velocities (Kurzinir, 1977).

The latest United States hypersonic program gaining national acclimation is the Hyper-X (X-43) project sponsored by NASA-Langley and NASA-Dryden. Building on the earlier gains made by the NASP (X-30) project, the Hyper-X project is expected to demonstrate flight operability under full scramjet power. Half-engine and flight model (HXEM and HXFM) ground testing was undertaken mainly by the Air Force Research Laboratory (AFRL) and, at present, is in the final stages of development (Huebner et al., 2000). Perhaps the most intriguing feature of the Hyper-X program is that the engine has the shortest combustor flow path of all dual mode scramjet engines tested to date. Barring setbacks, three unpiloted 12-ft research vehicles are scheduled for flight during 2001. Hopefully, these will demonstrate that supersonic combustion vehicles not only have the potential for huge gains in the aerospace industry, but are also practical and reliable devices. The Hyper-X vehicles, if successful, will be the first demonstration of a scramjet-powered vehicle capable of operating from Mach 4.5 to Mach 7. The Phase-2 vehicle of the Hyper-X program has been currently envisioned as a reusable 45 ft, Mach 7 vehicle using a revolutionary turbine based engine (RTBE) and a dual-mode scramjet (TRJ/SJ) engine (Rausch et al., 1999). If constructed, this vehicle would be the first ever air-breathing vehicle, capable of takeoff and powered flight up to hypersonic speeds, a milestone for the hypersonic industry.

1.2: Identified Difficulties with Supersonic Combustion

The use of supersonic combustors has the potential to greatly increase the upper flight-speed envelope of hypersonic vehicles. However, with the implementation of supersonic combustion, new difficulties arise with effective mixing, cooling requirements, and various losses due to shock waves and wall friction. The development of a practical design usually involves some tradeoff, one that balances the mixing and combustion characteristics with the necessary losses needed to achieve such conditions (Swithenbank et al., 1989). The ignition delay time for hydrocarbon, or hydrogen, fueled systems continues to be the driving force behind scramjet combustor designs for low hypersonic Mach number operation. As with all air-breathing engine combustors, a shorter ignition delay time translates into shorter combustor lengths, or higher flight speeds. Hydrogen is easy to burn and has a very low ignition delay time compared with liquid hydrocarbons, but lacks the necessary energy density to make long-range hydrogen-fueled scramjet vehicles. In addition, with supersonic combustion, the added difficulty of anchoring the flame within the engine poses its own problems. A flameholding region must be provided, traditionally created by means of physical obstructions, and produces the expected tradeoff of large pressure losses. Although practical, useable scramjet combustor designs have been built and tested, the designs are by no means exhaustive in the methods by which they balance the mixing and pressure loss tradeoff. An investigation of the elimination of these physical shapes, along with the integration and parallel development of the fuel injection and ignition systems, may prove most beneficial for overcoming some of the obstacles present in current supersonic combustion technologies.

A significant amount of work has been performed in the areas of fuel injection and ignition systems for supersonic combustion applications to overcome the previously identified obstacles; but unfortunately little consideration has been given to the integration of the systems, which is absolutely necessary to realize the full potential of an injection/ignition design. By far, the most abundant amount of research in the area of supersonic combustion has been on the fuel injector. One has only to look at the literature in the field to realize that the igniters have been given a relatively minor role, compared to the overwhelming amount of sources related to improving the mixing or penetration of various fuel injector arrangements. Admittedly, an even distribution of fuel within the scramjet combustor is key, but to say that the role of an igniter is merely to initiate combustion once the injector has done all the work is selling the potential of the igniter short. The role of an igniter can be much greater than the "place ignition source here" label undoubtedly written on many fuel injector designers' drawings.

The regrettable reality is that all too often the igniter is treated as merely a black box, with little thought given as to placement, orientation, or operation of the igniter. Admittedly, sustained flameholding systems for supersonic combustion are only necessary for flight speeds between Mach 5 and 7 where the total temperature of the flow is too low to cause auto-ignition of the fuel; but the role of a plasma torch can be made to be much more than a simple flameholder and igniter. The parallel development of a fuel injector and plasma torch, and then combined as an integrated design, can produce important advances in the area of supersonic combustion, showing that both the injector and igniter are key components in developing reliable and practical engines. However, to realize such effects, the integrated injector and igniter must be given an ample research effort, as the parametric studies involved in such a task are practically endless. Careful selection of important parameters affecting the combustion process, and the execution of experiments designed to study those parameters, will provide the necessary data and insights for the development of an integrated injector/igniter design capable of exceeding the performance of current injection/ignition strategies. The development of such a device is the focus of this dissertation.

1.3: Mixing and Flameholding Methods in Supersonic Flow

The goal of supersonic combustor designers is to produce a high efficiency combustor, while minimizing the total pressure losses induced by the fuel injection and flameholding devices. High efficiency does not always translate into higher engine thrust, as the thrust is a function of both the amount of fuel burned and the pressure losses induced within the combustor. To achieve high efficiencies, the injector must produce rapid mixing and combustion of the fuel and air, which also allows for a shorter combustor, and hence, weight and drag savings. Physical shapes for flameholding, such as struts (Masuya et al., 1995), ramps (Sands et al., 1997), and cavities (Baev et al. 1983, Mathur et al., 1999 and 2000), have often been used to enhance mixing and provide a subsonic region from which to anchor a flame, but at the cost of pressure losses induced by these types of systems. The following sections briefly discuss some of the various means by which researchers have sought to maximize the benefits of injection schemes while minimizing the pressure losses associated with them.

1.3.1: Flameholding by Means of Passive Mixing Devices

Passive mixing devices require no control for the device to produce fluidic phenomena for mixing enhancement. Configurations such as ramps, cavities, wedges, lobe mixers, vanes, and steps belong to this class of device. These devices aid in mixing fuel and air streams through various physical means, such as the production of streamwise vorticity (ramps), or acoustic excitation (cavities). Typically, fuel injector port geometry is also considered a passive mixing device, but discussion of this is deferred to a later section involving fuel injector developments.

1.3.1.1: Cavities

Recent supersonic combustion work in many countries has focused quite heavily on cavities and how the geometry of the cavity affects the combustor performance. The purpose of a cavity is to sustain a hot pool of combustion products to which a flame can be anchored. In addition, the cavity induces self-excited resonance within the free shear layer by means of acoustic excitation, producing flow oscillations and increasing the rate at which fuel and air mix. The design of a cavity will generally focus on either the ability of the cavity to flamehold, or to enhance mixing, both of which are a function of the depth and length of the cavity.

The most intense research on cavities in the United States is being conducted at AFRL (Mathur et al, 1999; Hsu 2000) and the Naval Air Warfare Center at China Lake (Yu et al. 1998). Yu et al. investigated the performance of cavities with various lengths and rear wall angles in a Mach 2 crossflow. They hypothesized that adjacent cavities could be used to maximize the effectiveness of the overall design; that is, with one cavity design used as a flameholder and another used for mixing and combustion enhancement. Figure 1.4 illustrates this concept. Preliminary results showed that the general shape of the cavity affected the flame length and intensity, as well as the ability of the cavity to flamehold. They found that the most efficient design used two cavities, with the downstream cavity employing an inclined wall. This design produced the highest combustor pressure and exit recovery temperature, suggesting higher combustor efficiency and supporting their hypothesis that a combination of cavities could be used to flamehold *and* enhance mixing.

Figure 1.4: Dual Cavities for Flameholding and Mixing (Yu et al., 1998)

Joint work on cavities between Russia and the United States has been performed at Russia's Central Institute of Aviation Motors and NASA-Dryden (McClinton et al., 1996; Roudakov et al., 1998). The work by McClinton et al. involved a flow path analysis of cavity-based designs for the purpose of mixing enhancement and flameholding. Their work demonstrated that cavities were excellent sources for mixing and providing a subsonic region in which to anchor a flame. The work was in support of then-future flight tests of the "Kholod" flight vehicle (Roudakov et al., 1998). A history of this program is provided by Roudakov, A. et al. (1996). Baev gives a good account of earlier Russian cavity work for those interested (Baev, 1977).

Recently, the most useful analytical work in the area of cavity design was performed by Baurle et al. (1998, 2000), building upon a stirred reactor analysis by Davis et al. (1997) for cavity flameholders. Baurle and his associates showed that various basic geometric parameters of the cavity affected the flow conditions within the cavity, namely that the depth determined the cavity residence time and the length determined the mass entrainment characteristics. They further concluded that short, deep cavities were more suited for supersonic combustion applications because of their lower drag characteristics and longer residence times.

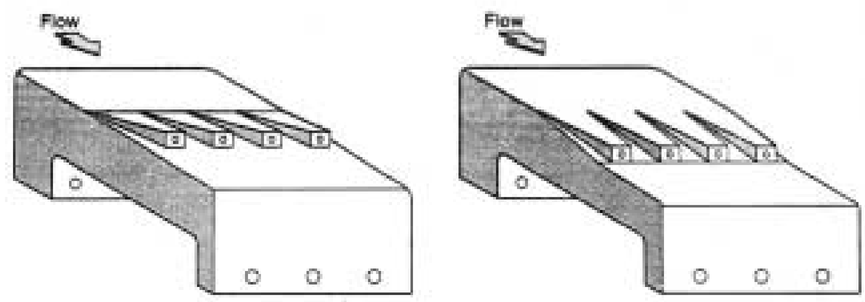
1.3.1.2: Rearward-Facing Steps

Although really a simplified cavity, or rather one with no back wall, rearward-facing steps produce a subsonic recirculation zone just downstream of the step that can be used to anchor a flame. Traditionally, an igniter is placed within this recirculation zone to initiate combustion. Important work with this type of configuration was performed in the late 80s at NASA-Langley, incorporating a plasma torch in the recirculation region as an igniter and flameholder (Wagner et al., 1986). Although the study was more focused on the characteristics of the plasma torch than the step, the work demonstrated that rearward-facing steps could be used to produce ignitable fuel-air mixtures in the subsonic recirculation zones just downstream of the step. More recent work by Fernando and Menon (1991) focused on a two-tiered step, designed to produce acoustic resonance behavior between the two flow regions. Their experiments demonstrated a two-fold increase in the mixing rate of the shear layer along the lower wall, but failed to increase the mixing performance of the outer shear layer. This suggests that the acoustic resonance that was hoped for was not realized; nevertheless these experiments are a unique investigation worthy of mention.

1.3.1.3: Ramp Injectors

Ramp injectors are passive mixing devices that produce counter-rotating streamwise vortices to enhance the mixing of fuel and air. Supersonic flow over a ramp generates shock and expansion waves which lead to the production of baroclinic torque, a result of the geometry of the ramp. This torque, in turn, induces the vortical motions that enhance fuel-air mixing. Important ramp dimensions include the angle of sweep and the ramp angle. Another important consideration is whether the ramp is an expansion or compression style design. Ramp designs have been quite popular with the supersonic combustion community and the important dimensions associated with ramps have been widely studied, both experimentally and analytically.

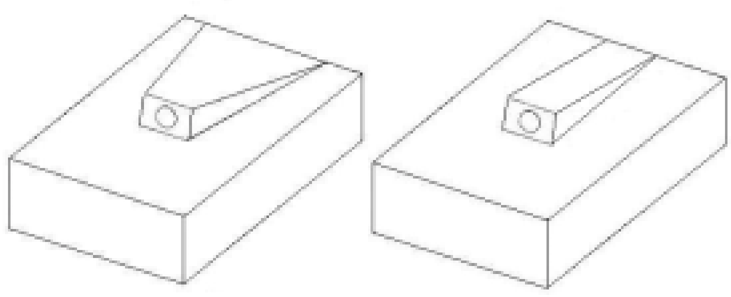
An example of an investigation of the phenomena by which ramps are effective mixers involved the study of compression and expansion style ramps (Stouffer et al., 1993). An illustration from Stouffer's work illustrating the differences between these two designs is shown in Figure 1.5. Compression ramps induce shocks at the base of the ramp, whereas the shocks are located in the trough for expansion ramps. The location of the shock was found to affect the mixing performance of the design. Stouffer discovered that expansion ramps produced higher combustion efficiencies despite having lower overall mixing performance. This was attributed to the improved local, small-scale mixing near the fuel injection port for the expansion ramp.



(a) Compression Ramps (b) Expansion Ramps

Figure 1.5: Compression and Expansion Ramps (Stouffer et al., 1993)

Another major geometric feature of ramps is the angle of sweep, as shown in Figure 1.6. Tests at NASA-Langley demonstrated that swept ramps produced higher combustion efficiencies than ramps without sweep, which was attributed to the lowering of the shock angle for ramps with sweep (Stouffer et al., 1994). Numerical investigations by Drummond et al. (1989) and Donohue et al. (1994), and a later study by Ekland et al. (1997) confirm the importance of this geometric feature. In addition, more recent numerical work by Abdel-Salam et al. (2000) studied the performance of the combination of swept compression and expansion ramps and their unswept counterparts. The authors conclude that swept ramps performed better than unswept ramps for both compression and expansion configurations and that the swept expansion ramp has the highest performance of all the designs investigated.



(a) Swept Ramp Injector (b) Unswept Ramp Injector

Figure 1.6: Illustration of Swept and Unswept Ramp Injectors

1.3.1.4: Lobe Mixers

Lobe mixers are similar to ramp injectors, except that the ramps are hollow and are referred to as lobes, as shown in Figure 1.7. Fuel is injected within the lobes at a small angle relative to the combustor floor. Air is entrained between the lobes and goes through an expansion wave as it enters the lobe. At the exhaust lip, streamwise vorticity is induced along the entire cross section of the lobe mixer where the fuel and air interface. Although the lobe mixers generally exhibit excellent mixing characteristics, they suffer from large aerodynamic losses due to the squared-off geometry at the lobe exit. Recent studies of lobe mixers have been performed by Marble et al. (1990) and Tew et al. (1995). Marble and his associates studied the mixing performance of squared-off lobe mixers and found that the design mixed quite well, but also incurred huge pressure losses as a result of the sharp geometry. Tew et al. focused on lowering those losses by rounding the lobe exits, but discovered that the mixing performance was also decreased. In addition to their large pressure losses, another drawback of lobe mixers is that they have no provision for the creation of a flameholding region and therefore could be quite susceptible to changes within the combustor flowfield induced by outside phenomena such as water vapor ingestion.

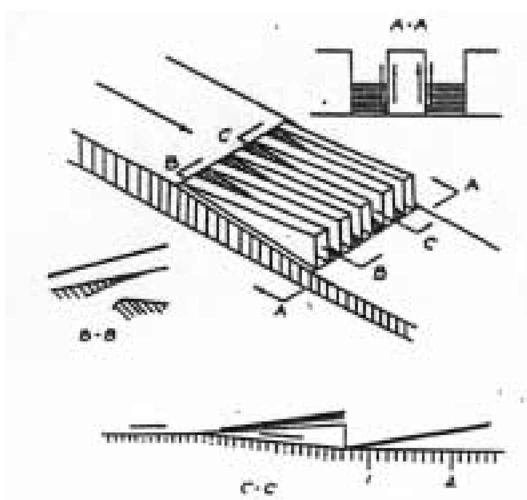


Figure 1.7: Squared-off Lobe Mixer (Marble et al., 1990)

1.3.1.5: Wedges

Although wedges are currently being used as passive flameholding devices in some afterburner applications, they incur large pressure losses and are generally regarded as impractical for hypersonic propulsion systems. However, recent work on wedges has been performed despite the apparent drawbacks. Fujimori et al. (1997) conducted extensive work on a wedge in supersonic crossflow and studied the location of the reaction zone as a function of the fuel flowrate fed through upstream injectors. They found that with low fuel flowrates, the reaction zone was located almost entirely within the recirculation zone provided by the wedge and higher fuel flowrates caused the reaction zone to move downstream out of the recirculation zone, thus extinguishing the flame. Although wedges can be used to produce a flameholding region within supersonic flow, it is generally considered that the massive obstruction caused by the wedge is unacceptable and better means are available for mixing and flameholding.

1.3.2: Flameholding by Means of Active Mixing Devices

Unlike passive devices, active mixing devices are those whose dynamic involvement in the mixing process can be controlled. Although active devices are not a focus of the work presented here, one active mixing device, the pulsed jet, deserves mention. The pulsed jet produces a columnar instability and hence, produces eddies that are swept downstream and enhance mixing. Recent work by Bogdanoff (1994) showed that the combination of a small cavity and an annular Hartmann-Sprenger tube could be used to develop large pressure oscillations similar to those produced by much larger cavities. However, of particular interest to this dissertation is the idea that a pulsating jet can be used to induce resonance with other combustor devices. The direct application to the present work is the ability to actively control the pulsation of a plasma jet, expanding the role of a plasma torch beyond that of an igniter to include mixing enhancement as well. Unlike in Bogdanoff's work, pulsation of the plasma jet is not controlled by means of the feedstock flowrate, but rather by the arc voltage frequency. This pulsation could be used to enhance mixing by the production of eddies, but more importantly, could be tuned to match the acoustic frequencies of various flameholding devices such as cavities, producing a synergistic effect. This concept is discussed in more detail in section 1.4.

1.3.3: Recent Fuel Injector Developments

Although physical bodies such as ramps and cavities have proven to be effective mixing devices, thought must also be given to the method of fuel injection itself. The simplest fuel injection device, dating back to the 1950s, used a circular, normal injection port. Traditionally, circular orifices have been used to inject fuel, with an example of recent work in this area by Lee et al. (1991). However, normal injection produces large separation regions both upstream and downstream of the injection orifice, translating into significant pressure losses. Normal injection has since fallen out of favor, not because the methods do not work, although they do experience larger pressure losses, but because the fuel imparts no axial momentum (thrust) to the engine. This deficiency can be quite significant at supersonic speeds.

Two recent improvements on the conventional circular orifice are the elliptical (Gruber et al., 1995) and diamond-shaped orifices (Tomioka et al., 2000). Noteworthy for the elliptical injectors is that, compared to a similar circular injector, they produced a smaller separation region upstream of the injector orifice and also induced faster spreading of the fuel in the spanwise direction. Similarly, diamond-shaped injectors experienced greater spanwise spreading due to the production of streamwise vortices and greater penetration. In addition to the mixing benefits associated with the diamond-shaped injector, Tomioka and his associates also noticed that the Mach disk was located closer to the injector orifice, reducing the total pressure losses through the disk.

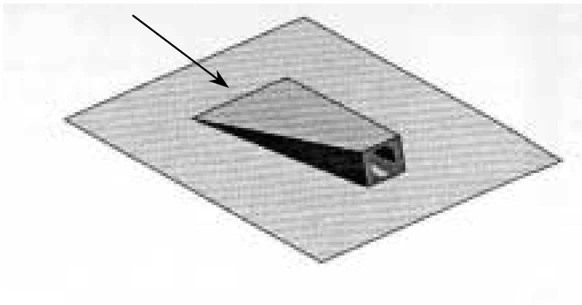
In addition to studies of the port geometry, Jacobsen et al. (1999) studied mixing improvements associated with the addition of swirl to a circular, normally oriented fuel port, which was part of a three-holed injector design. The swirl was induced by means of a flow swirler embedded within the fuel injection cavity. They discovered that the angular component not only improved the mixing efficiency, as measured with helium sampling, but also produced lower total pressure losses than a similar design without swirl.

Building upon the advances made with single-holed injectors, a natural step would be to assume that injector jets could be arranged in such a way as to produce a synergistic effect between the jets, resulting in improved mixing over a single jet of the same effective diameter. Hollo et al. (1994) demonstrated that significant improvements in the initial mixing rate could be achieved over that of a single-hole injector, by using an array of jets. Cox (1994) supported these conclusions, and demonstrated that an injector array could be designed to generate vortical motions, similar to those produced by a physical ramp. This gave birth to the “aeroramp,” a concept generally credited to Schetz (1998).

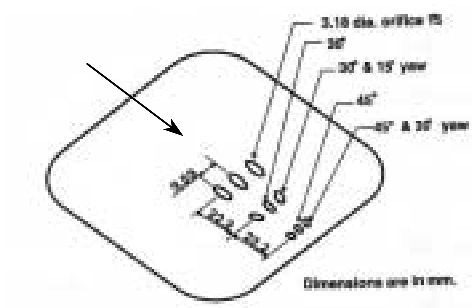
1.3.4: Development of Aeroramps

Aeroramps, short for “aerodynamic ramps”, consist of an array of flush-walled fuel injectors arranged in such a way as to produce fuel-vortex interactions beneficial for mixing. In essence, the fuel injected by the aeroramp creates a zone, which appears to behave as a physical ramp to the supersonic crossflow, but with fewer total pressure losses, as there is no actual physical obstruction. The injected fuel causes the crossflow to rise and spill over the sides of the interface formed by the fuel and crossflow. This in turn causes vortical motions useful for mixing, similar to those produced by physical ramps, but with no physical obstruction, as the jets are flush-wall. Schetz et al. (1998) report on the unusual design process by which the aeroramp came to exist. Their original aeroramp design is shown in Figure 1.7.

Fuller et al. (1996) experimentally investigated the concept of an aeroramp versus a physical ramp by comparing a physical ramp (Northam et al., 1992) with a nine-holed aeroramp (Schetz et al., 1998), as shown in Figure 1.8. Results for a Mach 2.0 crossflow showed that for increasing momentum flux ratios the aeroramp experienced increased penetration, while the physical ramp experienced no discernable change. In addition, the aeroramp experienced superior near-field mixing for lower momentum flux ratios and comparable far-field mixing for higher momentum flux ratios. Perhaps the most significant result reported by Fuller and his associates was that, “in all cases, the total pressure losses suffered with the aeroramp were less than those incurred with the physical ramp.” (Fuller et al., 1996) They further concluded that, regardless of the ability of the aeroramp to outperform the physical ramp under certain operational conditions, the comparable performance of the aeroramp alone merits further investigation, particularly because of the lower pressure losses induced by the aeroramp.



(a) Physical Ramp Model



(b) Aeroramp Injector Model

Figure 1.8: Comparison of a Physical Ramp and Aeroramp Injector (Fuller et al., 1996)

The experiments conducted by Fuller et al. (1996) prompted an investigation of the fundamental phenomena behind the success of the aeroramp. At the time of the their experiments, it was thought the vortical motions produced by the aeroramp were the driving mechanism behind the observed mixing performance, but the importance of various features of the aeroramp were not well understood. Fundamental studies on simpler three-holed injector arrays conducted by Jacobsen et al. (1998 and 1999), investigated the toe-in angle of, and the addition of swirl to, the aeroramp jets. Experiments with a three-holed aeroramp showed that the toe-in angle has a significant effect on the penetration height of the plume core, on mixing performance, and on the total pressure losses induced by the injector. Comparing toe-in angles of 0°, 15° and 30°, they reported that both the plume core penetration height and the mixing potential of the injector were improved for increasing momentum flux ratios and toe-in angle of the injector array. They further concluded that the total pressure losses were minimized for a toe-in angle of 15°. In subsequent swirl studies, they placed flow swirlers within the outer holes of the injector array to ascertain how the addition of swirl affected the mixing characteristics and total pressure losses of the array. They discovered that the addition of swirl not only increased the mixing characteristics of the array, but also reduced the total pressure losses as compared to an array without swirl. This was observed both through the reduction in bow shock angle and total pressure measurements.

Further experimental and computational studies of the original nine-holed aeroramp yielded further insight into the effect that various design choices have on aeroramp performance (Schetz et al., 1998). First, evaluation of the results showed that the pitch and toe-in angle of the first row of injectors should be minimized to reduce flow blockage and subsequently reduce the size and strength of the resulting shocks. In addition, the spacing of the holes is critical in that the interaction of the oblique shocks formed by each jet is significant to the mixing process. However, the front-row jets should not be so closely spaced as to prevent air from being allowed to pass between them, as the air entrained through the aeroramp is important for mixing. The toe-in angles of the second and third rows were found to strongly influence the blockage and shock strength experienced beyond the first row of jets. Schetz et al. observed that the toe-in angles on those rows might not be necessary for the formation or the preservation of the aerodynamic structures induced by the first row. Therefore, they concluded that the toe-in angles could be reduced until a degradation of performance occurs. Perhaps the most important realization, at least for the present work, is the observation of subsonic wakes and regions where the flow is reversed within the aeroramp structure. These regions are areas of low static and total pressure, and likely increase the drag of the design, but could be quite useful for flameholding. The presence of an igniter within one of those regions would undoubtedly ignite the subsonic fuel-air streams, producing a fuel injection/flameholding design without the need for physical obstructions or cavities.

Based upon his own recommendations regarding the design of aeroramps, Jacobsen (2001) designed a four-holed aeroramp array, believing that by reducing the number of holes, he could reduce the total pressure losses induced by the aeroramp, while still maintaining the desired mixing and penetration characteristics of the original design. Jacobsen et al. (2001) report on the comparison of this four-holed aeroramp to a single-holed injector used by AFRL. These experiments were similar to the earlier comparison made by Gruber and his associates (Gruber et al., 2000), but without a downstream cavity and with a four-holed instead of a nine-holed aeroramp. Analysis of the results showed that the four-holed aeroramp had slightly higher total pressure losses and lower penetration characteristics than the single-holed injector. The authors attribute this to the injectant being forced out of four holes rather than one. However, the aeroramp also demonstrated much better mixing characteristics than the single-holed injector with the same effective diameter. Refinement of the aeroramp concept could produce a design with significantly superior performance in all areas over that of a single-holed injector. Furthermore, the earlier experiments by Gruber et al., which showed the single-holed injector superior to a nine-holed aeroramp, may have suffered from a lack of optimization, as that aeroramp design was selected solely from a CFD analysis. Payne discusses this type of design process and notes that although experimental evaluation of a number of designs can be quite expensive, relying solely on CFD analysis could produce inconclusive or misleading results (Payne et al., 1999). In addition, a cavity may not be necessary with an aeroramp configuration, as aeroramps produce their own subsonic flow regions, and the addition of a cavity might actually serve to increase the total system losses without much added benefit. Nevertheless, a well-designed aeroramp can demonstrate significant performance benefits over other injection and mixing methods in some areas and furthermore, can produce subsonic flameholding regions that are ideally suited for the placement of an igniter such as a plasma torch.

1.4: Development of Plasma Torches for Supersonic Combustion

Although the thought of adding electrical energy to flames by means of arc discharges to promote flame stabilization was proposed as early as 1924 by Southgate (1924), Felix Weinberg and his associates were responsible for the first fundamental discussions of the concepts and mechanisms behind the theory in the late 1960s (Weinberg, 1968; Lawton et al., 1969). The theory was that by introducing a very small portion of electrical energy, perhaps only 2% of the total chemical energy flux found in the reactants, to a small volume of gas, higher flame throughputs could be achieved by artificially increasing the combustion reaction rates. These reaction rates were increased by the rise in concentration of combustion enhancing species. However, it was not until the early 1970s that the first concrete experiments were performed, using magnetically rotated plasma jets to stabilize methane flames in high-speed flows (Harrison and Weinberg, 1971). One of Weinberg's plasma torch designs, illustrating many of the aspects of general torches, is shown in Figure 1.9.

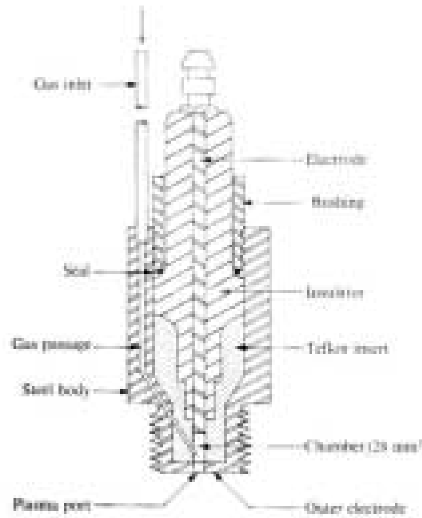


Figure 1.9: A Plasma Torch Design for Combustion Enhancement of Internal Combustion Engines (Weinberg, 1978)

In the above referenced work, Harrison and Weinberg studied the effect of radical addition to methane-air streams by means of various carrier gases (mostly nitrogen) and electrical power input. The most important applicable result of the work was the discovery that the addition of 10% electrical energy, as compared to the chemical energy available in the fuel, increased the combustor volumetric flowrate by an amazing 700%. Consequently, the increase in flame temperature was only 116 K, which corresponds to only a doubling of the theoretical flame speed for the conditions tested. Furthermore, augmented flames were observed to have reaction zones similar in volume to unaugmented flames, despite a much larger throughput. Weinberg identified this as a direct result of the early attack on the fuel by the plasma jet and higher concentrations of combustion species. Tests with argon as the feedstock gas showed little evidence of augmentation, further demonstrating that the combustion enhancement process observed with the nitrogen-methane experiments was not a result of the addition of mere electrical or thermal energy, but rather due to the presence of combustion enhancing radicals produced by the electric arc. Extending the nitrogen experiments into other feedstocks known to contain hydrogen and oxygen atoms produced similar results. They concluded that an oxygen feedstock was as effective as nitrogen at flame stabilization, and that methane and methane-air feedstocks had an effectiveness somewhere in between that of nitrogen and argon. Harrison and Weinberg's experiments convincingly demonstrated that a small amount of electrical power supplied to a small volume of gas could be used to generate combustion-enhancing radicals and enhance a flame.

Later experiments by Weinberg focused on applying plasma torch technology to IC engines and his attempts to operate them with leaner mixtures to control NO_x production (Weinberg et al. 1978; Orrin et al., 1981). Although seemingly unrelated to hypersonic technology, the results are fundamental and hold value for a wide range of combustion applications. He observed that the choice of plasma feedstock is quite crucial to the performance of the design, noting that the diffusion coefficient of some lighter radicals, such as hydrogen, may be an advantage in systems that are not well mixed and may compensate for their lower apparent combustion enhancement capability as compared to the nitrogen atom. The most important result with his hydrogen work resulted in the observation that the flammability limits of the system were increased through plasma torch ignition as opposed to traditional spark ignition. He reports that even under extremely fuel-rich conditions, enough to make the mixture conventionally inflammable, the mixture was not only ignited by the plasma torch, but the flame speed was comparable to that of a stoichiometric mixture. Weinberg attributes this to the production of hydrogen atoms through pyrolysis of the fuel, and states that, "the effectiveness of [the plasmas tested] is, in fact, in the sequence of the amount of hydrogen atoms produced."

1.4.1: Chemical Processes Governing the Effectiveness of Plasma Torches

At this point, it is necessary to understand the chemical processes that make plasma torches so effective for combustion enhancement applications, now that a discussion of the effect of various radicals on combustion enhancement has been addressed. Numerous studies on combustion enhancement by plasma torch have been performed, with perhaps the first most fundamentally important being those conducted by Kimura et al. (1981). Traditionally, authors have disagreed on exactly which radical for use in combustion-enhancement is most effective for supersonic combustion applications, with nitrogen or oxygen atoms being the most popular candidates. However, Weinberg wisely noted in the 70s that the effectiveness of a particular plasma feedstock is almost definitely dependent upon the application for which it is intended. It is with this in mind that the general chemistry and history by which plasma torches affect the reaction rates shall be presented.

As stated earlier, Kimura et al. (1981) performed the first fundamental experimental studies of radical addition to supersonic flows, focusing on the addition of nitrogen and oxygen radicals by means of a plasma torch to a Mach 2 hydrogen-air stream. Kimura and his associates reported a clear difference in performance, noting that oxygen plasma ignited a wider range of fuel-air mixtures and reduced the ignition delay time more than nitrogen did. Despite their observations, other investigators came to mixed conclusions. Through both experimental and numerical work, results emerged stating that in some cases using a nitrogen feedstock is just as effective as an oxygen feedstock (Takita et al., 1999), and in other cases, even more effective (Masuya et al., 1993). Traditionally it has been accepted that hydrogen atoms are the least effective at combustion enhancement when compared to oxygen or nitrogen, except for work by Kimura et al. (1981) where they report hydrogen atoms as being the most effective. However, recent experimental and analytical work performed by Takita et al. (1999, 2000) seems to be the final and most convincing work on the subject. Both experimentally and analytically, they observed that nitrogen and oxygen radicals are equivalent for combustion enhancement due to the extremely rapid reaction of nitrogen atoms with diatomic oxygen to produce NO and oxygen atoms. They also noted that hydrogen atoms have a somewhat lower potential.

Despite the apparent lack of agreement on which radical is most effective, from a chemical viewpoint all radicals are valuable for combustion enhancement as they all contain available energy. However, logically some are more valuable than others; and N, O, and H atoms have been identified as the most important. As stated by Weinberg, the role of a plasma torch is to artificially increase the radical pool available for combustion reactions and ultimately to increase the reaction rates. According to the fundamental Arrhenius kinetic equation,

$$-\frac{d[A]}{dt} = pN_{AV}\sigma_{AB}^{2}\left[\frac{8\pi k_B T}{\mu}\right]^{1/2}\exp\left[\frac{-E_A}{R_u T}\right][A][B], \tag{1.1}$$

the rate of reaction is a function of the collision geometry, temperature, various constants, and the concentration of the reactants involved. Therefore, artificially increasing the concentration of a reactant will serve to increase the reaction rate and ultimately, the entire combustion mechanism, particularly if the reactant supplied is part of a chain-branching reaction such as

$$H + O_2 \leftrightarrow OH + O \tag{1.2}$$

for hydrogen, in which the consumption of one hydrogen radical produces two other important radicals, OH and O. Consequently, O, H, and OH all aggressively attack fuel molecules as well as participating in early chain branching reactions.

Nitrogen atoms are also important combustion enhancing radicals because they quickly react with surrounding oxygen molecules to form nitric oxide and oxygen atoms, as illustrated by the famous Zeldovich mechanism,

$$N + O_2 \leftrightarrow NO + O\,. \tag{1.3}$$

According to this, it seems improbable that nitrogen atoms produced by a plasma torch would ever be as effective as oxygen atoms, since they are merely the means by which the combustion-enhancing oxygen atoms are produced. However, it cannot be overemphasized that nitrogen has proven to be quite an effective plasma feedstock for supersonic combustion applications and is usually preferred to air or oxygen feedstocks as they are both quite erosive to plasma torch electrodes.

1.4.2: Demonstrations of Plasma Torch Enhancement for High-speed Flows

It has been well documented that plasma torches hold great potential for flame stabilization and the promotion of combustion reaction mechanisms for high-speed flows. Kimura et al. (1981) performed the earliest experimental work demonstrating such potential in supersonic flow and reported that the burning velocity of hydrogen-air mixtures was increased in a Mach 2.1 flow by addition of nitrogen and hydrogen atoms. Similar to Harrison and Weinberg's experiments, Kimura and his associates demonstrated that a small amount of electrical energy supplied to a plasma torch could be used to anchor a flame, but now within a supersonic crossflow. By supplying electrical energy on the order of 2% of the total chemical energy throughput, they reported a 68% increase in the area occupied by the flame at a set distance downstream of the plasma jet. Furthermore, they observed that the position of the plasma jet is critical. Placement of the plasma torch upstream of the fuel ports showed limited combustion due to the radicals recombining before interacting with fuel molecules. With close downstream placement, the plasma energy was spent on heating fuel molecules before sufficiently mixing with air. Only when the plasma torch was placed in a location downstream of the fuel injectors where the fuel and air were well mixed was the potential of the plasma torch realized.

Later experiments by Warris and Weinberg (1984) also showed that plasma torches could be used to extend the limits of flammability for high-speed flow combustors, similar to the IC engine work performed by Weinberg in the 1970s. Most significant was their observation that, "no matter how little hydrocarbon fuel is present in the mixture, there is always some flame luminosity." This is in direct contrast to conventional spark igniters, which are quite dependent on the condition that the fuel-air mixture is within traditional ignitable limits. The increased range of ignitability and flame stabilization is bought at a very small electrical cost. Furthermore, Warris and Weinberg note that plasma torches with choked orifices cannot be blown out, as combustor conditions cannot propagate into the arc chamber.

With the potential of plasma torches well addressed, the question then becomes, "Do plasma torches require a flameholding region, such as one produced by a step or cavity, to be effective?" From earlier work with argon-hydrogen torches, the answer appears to be "no" (Northam et al., 1984, and Kato and Kimura, 1996). Work in the mid 1980s by Wagner et al. (1987) demonstrated that an argon-hydrogen torch could be quite effective behind a step, igniting mixtures of hydrogen and air within the recirculation zone provided by the step. The work was a demonstration that previous methods of using pyrophoric silane injection could be replaced by much safer methods, rather than a study of the ability of a plasma torch to flamehold without the need for a step. However, subsequent tests by Northam et al. (1984) showed that a flame could be anchored by a plasma torch without the need for a step and established the concept of a free-radical flameholder. Extinguishing the torch consequently caused the extinguishing of the flame, demonstrating that the plasma torch served not only as the ignition source, but also as the flameholder. More recent numerical simulations seem to contradict the argument that plasma torches must be operated in conjunction with a step (Kato and Kimura, 1996). Kato and Kimura state that, "although the combination of a rearward-facing step and a plasma torch is a promising method for scramjet combustors… the present numerical simulation suggests that flame stabilization can be made without the step." They observed that the plasma jet, with adequate power, establishes a high-temperature recirculation zone that acts as a flame stabilizer similar to the step and also acts to promote the combustion of the fuel jet, so the addition of the step appears redundant.

At this point, it is necessary to address the misuse of plasma torches in the past, perhaps altering the view that some have of the potential of such a device. In one unpublished study, a plasma torch was used to replace a spark plug within a cavity. Not only did the plasma torch not exceed the performance of the spark plug, it also required a lot more power. In this configuration it is clear that the potential of the plasma torch was misused. The work performed by Sato et al. (1992) is another example of misuse. Oddly, despite the earlier work by Northam and Kato demonstrating that a step is not necessary for flameholding when a plasma torch is present, and the work by Kimura et al. showing the need for the plasma torch placement well downstream of the fuel injectors, Sato and his associates performed experiments in a Mach 2.5 stream with a torch placed *upstream* of a step and the fuel injectors *downstream* of the step. Although their goal was to exhibit the ability of the torch to operate on a variety of feedstocks, their results showed that all the feedstocks performed nearly the same, which is not surprising given the configuration. It cannot be overemphasized that the poor application of a device such as a plasma torch has caused many setbacks in the history of hypersonic research, and only lends further urgency to the need for an integrated design where the injection and ignition systems are developed with the express goal of incorporating the two systems together.

1.4.3: Other Methods of Ignition in High-Speed Flows

As discussed in the previous section, plasma torches are not suited for every type of combustion application. Furthermore, work with spark igniters (Gruber, 2000) and pyrophoric compounds (Diskin et al., 1986; Perkins et al., 1997; Thomas et al., 1997) has yielded good results the past for various supersonic flow applications. Spark igniters traditionally perform well in environments not requiring large amounts of ignition energy, like those found in stoichiometric cavities. However, they are not well suited for high-speed crossflow as they do not have the ability to impart the required energy necessary to overcome the activation energy of the fuel for such a short residence time. Pyrophoric compounds, such as silane, were widely used through the 1960s and into the 1980s to ignite hydrogen and hydrocarbon fuel in a supersonic crossflow (Beach, 1980). However, pyrophoric compounds are not only dangerous, but also require their own storage and injection systems onboard the flight vehicle. Work by Diskin et al. (1986) investigated the use of fluorine as a substitute for silane, since the sulfur hexaflouride by which the fluorine is produced is non-toxic and non-explosive in air. Flourine atoms are highly reactive to hydrogen and hydrocarbon molecules, thereby accelerating the chemical breakdown of the fuel. Results showed that the flouring addition was competitive to similar experiments run with silane, but the design was not optimized for mixing and so produced inconclusive results regarding application into an actual supersonic combustor. The point to be made here is that other ignition sources exist, besides plasma torches, and careful consideration and selection of an ignition source must be made in light of the combustor system for which it is intended.

1.4.4: Recent Advances in Plasma-Torch-Aided Supersonic Combustion

Two striking advances in plasma torch technology have been made during the last three years. Interestingly, while the two projects were focused on studying dissimilar phenomena, they both uncovered hidden potential within basic plasma torch designs. One project enhanced the chemical aspects of the torch as a radical supplier (Shuzenji et al., 2000), while the other demonstrated the ability of the torch to act as an actively controllable eddy source (Gallimore, 1998.)

The work by Shuzenji et al. (2000) focused on creating an arc wholly outside of the plasma torch body, so that a much larger portion of the energy contained within the arc could be used to ignite the cross-flowing fuel-air stream. Their design is shown in Figure 1.10 and is referred to as DAIM (Direct Arc Injection Method). Compared to a traditional torch, a much smaller amount of feedstock gas was fed through the torch body. The feedstock gas fed through the torch was used to prevent the arc from discharging within the torch body. The premise behind the work is that not only is a larger portion of energy in the arc used for ignition, but also that the total pressure losses induced by the plasma jet are reduced since the volumetric flowrate of the jet is much smaller than for a conventional torch. To aid arc stability in the high-speed crossflow they designed Teflon sublimated electrodes, which also allowed for a larger arc in the freestream. This helped to more effectively transfer the heat from the arc to the main airflow. Comparison to a conventional plasma torch at 3000 W showed an increase in the maximum downstream temperature of about 400 K by using the DAIM method.

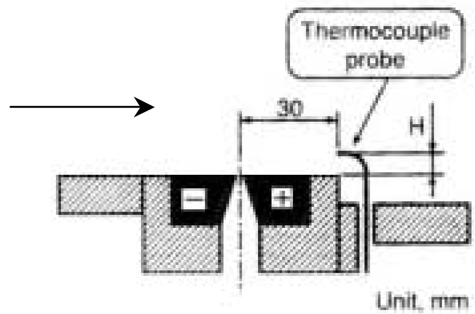


Figure 1.10: Direct Arc Injection Method (DAIM)

On the fluid dynamic side of torch advancements, work by Gallimore demonstrated that adding a small amount of voltage ripple to a DC supply could induce plasma jet oscillation (Gallimore, 1998). Using high-speed digital photography, he discovered that the rate of plasma jet oscillation matched the frequency of the voltage ripple and that the plasma jet length was a function of the actual time-varying voltage. Clearly, this could expand the potential of plasma torches beyond that of a mere flameholder. They could be used as actively controlled flameholding devices, producing eddies at a set frequency in order to instill fluidic resonance with other devices inside the combustor, such as an aeroramp. The ability of a plasma torch to be "tuned" to match the dynamic characteristics of other devices in the combustor is significant and signals an inherent need for the integration of the plasma torch into the combustor system.

1.5: Attempts at Injector/Igniter Integration

The need for an igniter and fuel injection system to be integrated seems obvious; but, surprisingly, the work done in this area has been sparse. Quite often, the flow fields of various combustor configurations are studied intensively, both with experimental flow visualization techniques and CFD analysis; but little regard is given to the type or placement of the ignition system. This is not to say that the systems designed by such methods are poor, but instead, that they have an undiscovered potential that could produce huge benefits, namely the synergistic effect between the fuel injection and ignition systems.

One prime example of this type of design process was the development and testing of a model scramjet by National Aerospace Laboratory's Kakuda Research Center (Tomioka, S., 1996; Mitani, 1996; Masuya, 1997). The model was designed based on various component studies, such as the exhaust nozzle (Nickerson, 1988), the inlet (Trexler and Saunders, 1977), the combustor (Waltrup, 1976 and McClinton, 1978), and the ignition system (Yatsuyanagi and Chinzaei, 1996). Early experiments suffered from the failure of the ignition system to produce intensive combustion for flight Mach numbers above 6. The additions of struts, recesses, and auxiliary oxygen injectors were studied to enhance performance. Subsequent experiments demonstrated the improvements made by these changes (Sato, 1997), but did not concentrate on the ignition system. Admittedly, the design choices made by these authors were successful; but perhaps even a minor change of the torch feedstock, power, or location could have saved much time and effort.

Recent advances in supersonic combustion in America have been made primarily at Air Force Research Laboratory (AFRL) (Gruber, 2000) and the Naval Air Warfare Center at China Lake (Burnes, 2000) and appear to follow the same design process as the researchers mentioned above. A review of the literature from these two facilities shows that a vast majority of the work concentrates on the mixing characteristics of various combustor configurations; but little mention is made of the ignition system, which for these configurations is a spark plug. The lack of concentration on the ignition system may compromise what would otherwise be a well-integrated design. Admittedly, not all the experiments at these facilities were focused on creating an integrated design; but studying only one aspect of a combustor system at the expense of another may create a final design with unmet potential.

In contrast to the recent research at AFRL and China Lake, earlier experiments at NASA-Langley focused on both the ignition and injection aspects of the combustor

(Wagner, 1986 and 1987). The experiments by Wagner and his associates dealt with the ignition of hydrogen by means of a plasma torch located downstream of a step. Their results were based on variations of the freestream conditions, torch power, feedstock type, and fuel flowrate to determine if a plasma torch could be used to replace dangerous pyrophoric compounds, and if so, how best to minimize the amount of igniter energy required to achieve ignition. Although the design process of Wagner and his associates considered variations of both the injector and ignition systems, the work did not investigate the effect of plasma torch location.

Perhaps the best-integrated study to date has been performed at Tohuku University by Masuya et al. (1999) and Takita et al. (1999). The experiments were a study of the ignition of hydrogen by means of a downstream plasma torch in both low and high-speed flow. They studied not only the effect of changing the angle and location of hydrogen injection but also the torch feedstock and power. In addition, the authors realized that a step or cavity is not needed to act as a flameholder when a plasma torch is used as the igniter, and so did not include one. Regardless of the results, their experiments are exactly the type of engineering process that is needed to create a well-integrated, well-performing design. As a result, the experiments were quite useful for identifying a range of ignitable configurations of injector locations, angles and flowrate, and also of effects of these configurations on the required plasma torch feedstock and power. Despite the high quality of the experiments, the one aspect missing was the inclusion of geometric studies of the torch, such as nozzle geometry and injection angle.

1.6: Key Issues Related to Current Ignition/Injection Systems

Several key points need to be made regarding the present design processes by which combustors for scramjet engines are designed. The main points that have been presented within this chapter are that:

- Injectors and igniters are often designed without regard to the final system in which they will be integrated.
- The injection system is often given more thought than the ignition system when a combustor is designed.

- The final design may suffer from unmet potential without a well-defined integration process.
- An integrated design will realize the synergistic effect present between the fuel injection and ignition systems.

Focusing on these key aspects could prove not only beneficial as far as creating well-performing combustor configurations, but also save time and money in overcoming problems associated with the initial designs.

1.7: Proposed Advances

Successful ignition and flameholding by the use of a plasma torch in a supersonic cross flow has been well documented. In addition, the enhanced mixing effects for various fuel injector arrangements into a supersonic stream through single and multiple wall injectors have been studied in depth. However, a majority of past studies involving the design and development of an injection/ignition system for supersonic combustion applications have been heavily weighted towards the injection system, with little regard given to the ignition system. The parallel development of an injection system and ignition system, and then a subsequent study for the integration of the two, is absolutely necessary to achieve a well-integrated design, fully realizing the potential and synergistic effects available when such a combination is made. It is proposed that the development of the fuel injection system should be made with thought given to the later introduction of a plasma torch as an ignition source. Consequently, the development of the plasma torch should allow for future integration into the fuel injection system. Questions such as, "What fuels are to be used?", "What is the maximum amount of power available to the plasma torch?", "Where should the injector and torch be located relative to one another?", among a host of others, must be answered in order to produce a design that maximizes the potential of both the fuel injector and the plasma torch. Such is the focus of this dissertation.