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The Performance of a Liquid-Fueled High Pressure Igniter for Scramjets

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THE PERFORMANCE OF A LIQUID-FUELED HIGH PRESSURE IGNITER FOR SCRAMJETS

by

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B.S. Aerospace Engineering, University of Central Florida, 2022

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ABSTRACT

Ignition systems within scramjet combustors remain a trending topic of research because of the essential role they play in the engine's operation. An alternative to currently researched ignition systems is investigated in this study with the main goal of utilizing the same liquid fuel as the main combustion chamber for the ignition system itself. In this case, JetA fuel was injected in a liquid jet in crossflow configuration with air to atomize the fuel. To characterize this ignition system, metrics such as combustion chamber pressure rise, pulse frequency, and jet penetration were used to validate possible utilization within a scramjet combustor. Tests were completed at different air temperatures ranging from 150°C to 275°C, varying spark plug frequencies, and at two unique combustion chamber exit diameters. Schlieren imaging was also used to compare effects of temperature and exit nozzle diameter on jet quality. Results obtained demonstrate a high pressure rise, reliable ignition, and a fine jet exhaust from the combustion chamber. To increase pulse frequency a more optimized combustion chamber is required along with a fuel injection system that would atomize the liquid fuel better than the current system. Following studies include further testing within a supersonic flow regime to simulate the flow effects experienced within a scramjet combustion chamber. If results continue to prove useful, the current technology studied has the ability to innovate supersonic combustion engines by reducing mass from the flight vehicle and increasing reliability, both critical parameters.

ACKNOWLEGMENTS

A well-deserved thank you to Dr. Robert Burke for his excellent mentorship and guidance every step of the way. Much gratitude is also due to Dr. Ahmed and the rest of PERL for their support and welcoming nature. A final big thanks to committee members Dr. Mazumdar and Dr. Ozbay for taking time to be a part of my thesis defense and your instruction in a multitude of courses.

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NOMENCLATURE

AFRL – Air Force Research Laboratory

DBD – Dielectric Barrier Device

LJIC – Liquid Jet in Crossflow

LIP – Laser-induced Plasma

PJ – Plasma Jets

PR – Pressure Ratio

Scramjet – Supersonic Combustion Ramjet

CHAPTER ONE : INTRODUCTION

Achieving steady state combustion in supersonic and hypersonic engines is much easier said than done. A key component to reliable combustion and operation for these engines is the ignition system used to combust the incoming air and fuel mixture. Throughout this study, the focus is on creating an ignition system that utilizes the same fuel and air as the main combustion chamber it is being held in. This is especially important because it would increase the efficiency of hypersonic scramjet vehicles and remove the need for such vehicles to carry separate fuel and oxidizer solely for the ignition system. Before describing the complexities, difficulties, and achievements of creating a liquid-air scramjet ignition system, it is necessary to understand the different ignition systems implemented in the subsonic ramjet combustor and more significantly the ignition systems withing supersonic combustor ramjets (scramjets).

Ramjets are air-breathing engines without any moving parts. Unlike turbojets that use a compressor to suction-in atmospheric air to produce thrust, ramjets take in supersonic atmospheric air and utilize shock effects to have subsonic air inside the combustion chamber. Ramjets operate from speeds of about Mach 2 to 6, depending on varying conditions, and use either some sort of rocket or turbojet engine to initially reach those supersonic speeds. Once those speeds are reached the ramjet engine takes over and provides additional thrust to the system, by compressing incoming air, and using oblique and normal shocks, the air flowing into the system reaches subsonic speeds in the combustor [1-2]. Here the fuel is injected, and the subsonic fuel-air mixture is ignited, initiating the combustion process. There are four distinct types of ignition systems used in ramjets, these include spark ignition, continuous ignition, plasma ignition, and laser ignition. Spark ignition is the most common ignition system used in ramjets but becomes limited at exceedingly high pressures and temperatures. Continuous ignition systems use a pilot flame to continuously ignite the fuel-air mixture in the combustion chamber, but this type of ignition system usually leads to incomplete combustion and lower thrust efficiency, this occurs because of the need for a fuel-rich mixture to keep the pilot flame ignited. Plasma ignition typically either uses an electrode placed at the front of the combustor, or a plasma torch to initiate the combustion. This form of ignition is very dependable and efficient but is limited due to the difficulties of sustaining a plasma-torch under the high speeds and temperatures inside the ramjet. Finally, laser ignition is a novel ignition method for ramjets and works by directing a high-energy laser using fiber optic cable positioned inside the combustor, to ignite the fuel-air mixture, but is limited by the severe operating conditions of the ramjet engine [3-7]. The ignition systems in ramjets are overall a lot less complicated compared to that of scramjets, and it is particularly important to investigate the current ignition systems in scramjets and scramjet research.

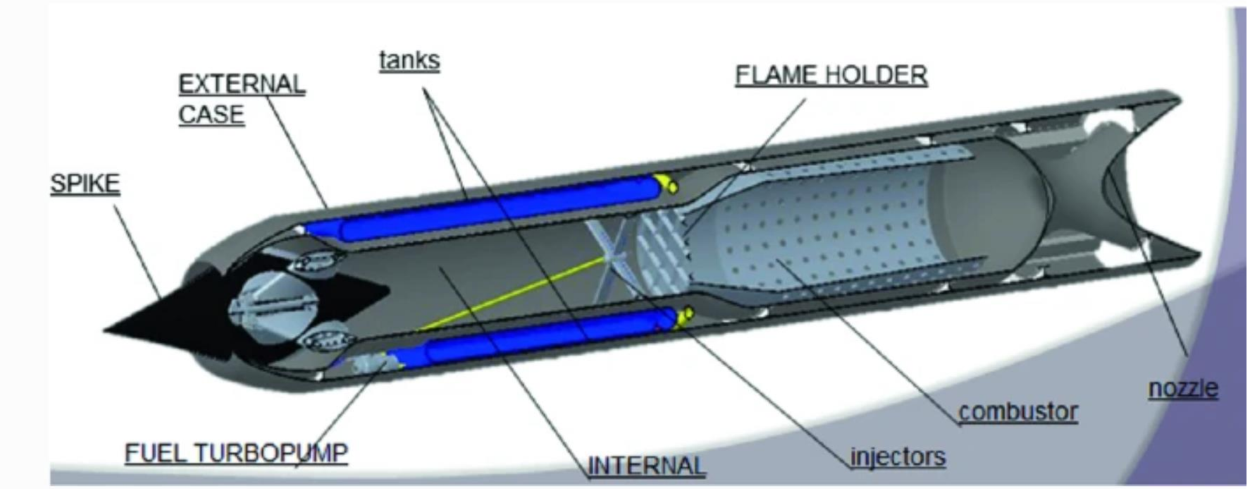


Figure 1 : Ramjet Engine [1]

Scramjet engines follow the very same basic principle that turbojet and ramjet engines follow, having three general areas : compression, combustion, and expansion (from inlet to outlet). Yet, scramjets have specifically designed geometries to allow for supersonic airflow throughout the entire combustion process, unlike the ramjet that has incoming air reach subsonic levels when entering the combustion chamber. The ability to maintain supersonic speeds within the engine allows for scramjets to operate efficiently at higher Mach numbers than ramjets.

To properly understand the differences between the varying ignition systems within scramjet engines, it is necessary to know how each of them work and the benefits and drawbacks of each. With this knowledge in mind, the outstanding benefits of a working liquid-fueled ignition system, utilizing the same fuel as the main combustor, become very evident. Some of the different forms of ignition systems being used and researched within scramjet engines include plasma assisted ignition, microwave discharge, precombustion aerodynamic blockage, and using separate fuel for engine initiation to name a few [27-29].

Plasma-assisted is a broad term used to define initiation methods sparked by plasma, this can result from a plasma torch, laser, or even low energy release tools such as a spark plug. Using plasma torches in scramjet combustors have been investigated by researchers at Tohoku University in Japan [8-12]. In this study, the researchers used a configuration of two plasma torches with different feedstocks, upstream a H_2/N_2 plasma jet (PJ) and a downstream PJ with O_2 as feedstock. They ran these tests for three different fuels including H_2, CH_4, and C_2H_4 with the PJs in a straight line in the direction of the supersonic flow, with the fuel injecting normal to the flow region. In another study conducted by the same group at Tohoku University [13-15], they combine the plasma torches used in the previous study with a Dielectric Barrier Device (DBD) used to enhance combustion in the system. The goal of the DBD was to create nonequilibrium plasma to enhance the combustion, so instead of using two plasma torches like in the previous study, they could use two Al_2O_3 electrodes and a sinusoidal voltage input to operate the DBD. DBD plasma creates several oxygen radicals including O_3 radicals which enhance combustion by decreasing ignition delay times for the H_2/Air mixture that was being tested. Enhancement was also only noted for relatively weak and unstable flames with strong combustion not experiencing any benefits from DBD addition. The plasma torches described in these studies are depicted below in figures 2 and 3, although they ignite efficiently, require extensive power consumption to operate. This causes these systems to not be very efficient if adapted to actual flight functionalities. A sufficiently large battery would be required to power both the plasma torch and DBD within a scramjet combustor. Not only that, but if the fuel in the main combustor is not H_2 the scramjet engine would need to have separate reservoirs of fuel to operate the plasma torches, both increasing the weight and size needed to implement this ignition system.

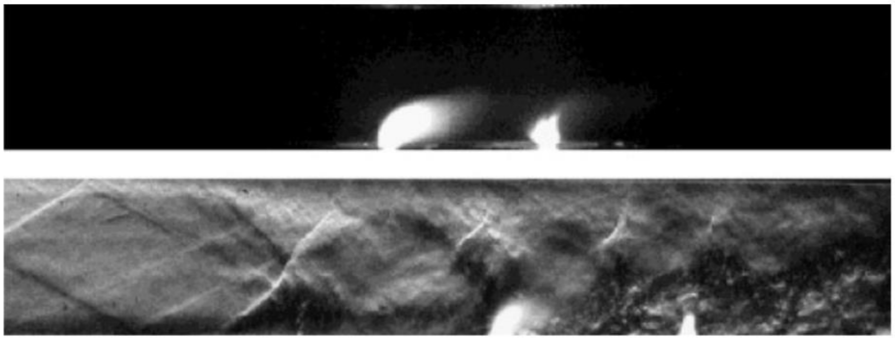


Figure 2 : Picture and Schlieren of twin PJs [8]

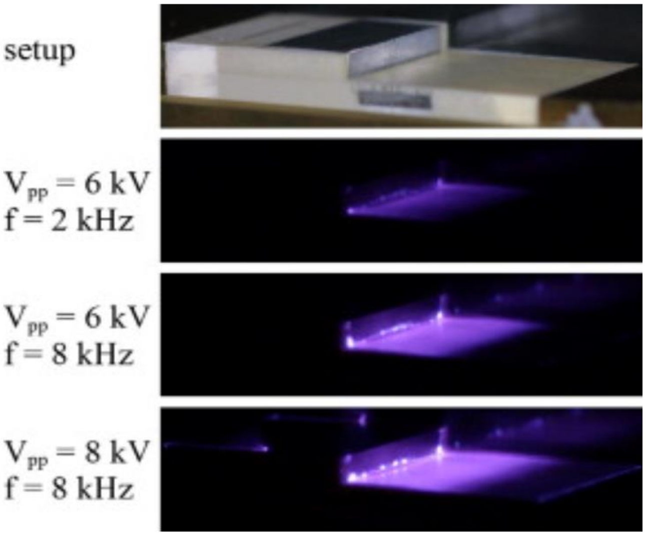


Figure 3 : DBD used in Mach 2 flow [13]

Some other scramjet ignition systems currently being researched include the nanosecond pulsed electrode ignition system studied by Hyungrok Do, et al at the Stanford University [16-20] and similarly a Quasi DC multi-electrode discharge method of ignition for gaseous fuel studied by Russian Academy of Science along with the U.S. Air Force Research Laboratory [21-26]. In the Stanford studies, they use a jet in crossflow (JIC) configuration for fuel injection of H_2 and C_2H_4 and like the DBD producing nonequilibrium plasma, the electrodes in this study achieve the same thing by pulses at 15kV and a 50kHz pulse frequency with a 20ns width. The group at Stanford can achieve reduced ignition delays and reliable ignition and cavity flame holding within their facility. They also ran pure oxygen as oxidizer and were using hydrogen fuel, although this is very ideal, it is not indicative of actual in-flight conditions. Instead of pure O_2, air is used as oxidizer, and Hydrogen would not be feasibly used as a scramjet's main fuel. Unlike the previous study where only one pair of electrodes are used to create a nonequilibrium plasma, in the research conducted by the Russian Academy of Science and the U.S. AFRL, varying electrodes were used ranging from three, five, and seven with an input voltage of 5kV. Successful ignition and flame holding were realized for both hydrogen and ethylene fuels and the effects of the electrical discharge on the Mach 2 flow were that it heated up the gas and possibly induced separation.

Alternative and less researched, but potentially viable, methods of scramjet ignition include using under critical microwave discharge and laser-induced plasma for ignition. Igor E., et al at the Moscow Radiotechnical Institute [30], have studied the possibility of using an electromagnetic vibrator to discharge a deeply under critical discharge immersed in supersonic flow. The fuel-air mixture used in this study is propane and air and has a flow velocity of 200 m/s in the combustion chamber. The microwave discharge leads to a combustion efficiency of

60% and has a heat release of approximately 1 kW. The microwave discharge initiation method has a relatively high efficiency and because of this, it proves to be a viable method, the fundamental issues with this system lie in its complexity and the lack of testing in harsher conditions that a scramjet engine would experience in-flight. The research completed by Stefan Brieschenk, et al at the University of Queensland and the University of New South Wales [31-39], dealing with laser-induced plasma (LIP), was effective in its production of OH radicals. In their research, they were able to accurately replicate the harsh conditions experienced within a scramjet engine, and were able to capture combustion products, where they would not be otherwise. Below in figure 4, the flow field on the compression ramp is shown with a Schlieren image and overlayed with flow features. The LIP ignition method was able to show that combustion is possible at the hypersonic in-flight conditions when the laser is pulsed at frequency of about 100 kHz.

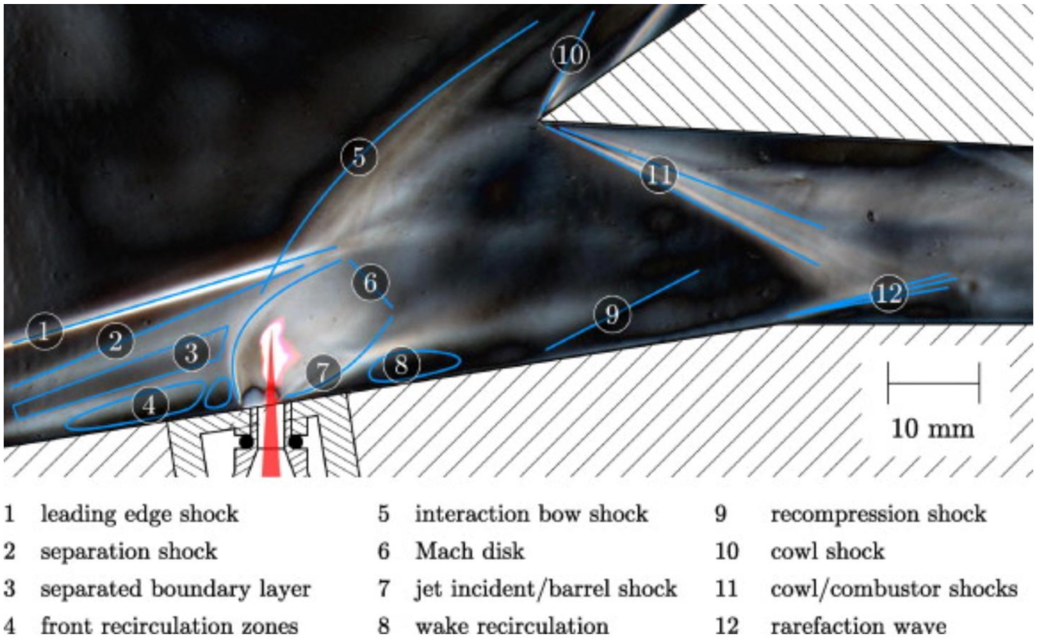


Figure 4 : Schlieren image displaying LIP location and flow field [31]

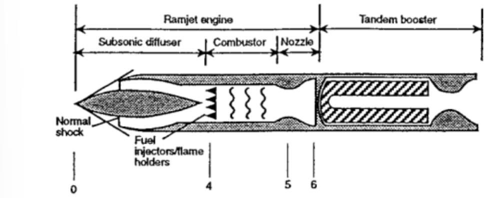
The last two alternative ignition methods reviewed during the completed literature study are more direct comparisons to the completed research. The first of the two is a study which uses two plasma torches with H_2/N_2 feedstock, as conducted by Lance Jacobsen, et al at the Air Force Research Laboratory [40-45]. This study discusses the use of a secondary gas to block the exit and increase back pressure. This is a difficult balancing act because too much blockage will increase the back pressure to a point where the engine un-starts, and too little blockage and the self-sustaining combustion shock train condition will not be attained. To counteract this, the group at AFRL decided to use two plasma torches along with flame holding cavities to ignite the fuel which is injected directly upstream of the torches. The other is one completed by Ming Bo Sun, et al at the Science and Technology on Scramjet Lab in China [46-48], where they used direct injection of hydrogen fuel in a cavity, right next to a spark plug to initiate the scramjet main combustor. The main combustor was being operated at Mach 4 flight conditions and it was noted that once the initial flame spreads along the cavity shear layer, the fuel downstream is quickly ignited and distributed throughout the combustion chamber. The facility has two separate cavities where they were uniquely tested with direct injection of hydrogen and sparked, this was completed to draw accurate conclusions regarding initial flame kernel location and flame spread.

Ignition and steady combustion within the scramjet engine have proven to be very difficult for several reasons including, the supersonic flow through the main combustion chamber and its turbulent effects can cause the flame to destabilize and extinguish easily. The best way to counter this effect is to have both a remarkably high energy source to ignite the mixed fuel-air mixture and some sort of flame-holding cavity or step geometry to help stabilize the flame. More traditional methods utilized within ramjet engines such as, using a continuous pilot flame for ignition becomes much more challenging to implement in supersonic combustors. Subsonic combustor flow speed within ramjet engines allows for lower energy ignition methods as observed by Bin An, et al at the Science and Technology on Scramjet Laboratory in China [49-53], where they were able to reach successful ignition by operating a spark plug at 50hz frequency.

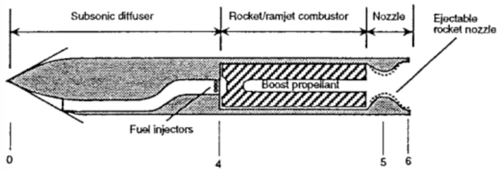
Steady, reliable, and feasible ignition within scramjet combustors is hampered for several reasons including extremely low residence time, due to supersonic flow speed, the ignition delay of the hydrocarbon fuels used as the main fuel in scramjet engines, and the lack of appropriate fuel/air mixing. As noted by several studies, mixing can be made more efficient with the implementation of cavities and stepped geometries, creating recirculation zones for the flow. These recirculation zones work by slowing down some of the highspeed flow and sending it back through the combustion chamber. Mixing is improved by both increasing the residence time of the flow within the chamber and introducing turbulence and vortices which further aid the fuel/air mixing. Recirculation zones are also helpful in flame stability by working as a buffer between fuel injection sites and supersonic flow, preventing blowout and instability [54-59]. To fully understand the current and future advancements with scramjet engines, it is important to look back through its history and development.

The history of the scramjet is one that, like most advancements, took an iterative approach towards its evolution. The supersonic combustion ramjet came into existence as a variant of the traditional subsonic ramjet engine as the need for hypersonic flight vehicles became relevant. In Figures 5 and 6 below the different ramjet and scramjet geometries, including designs for hybrid engines utilizing both subsonic and supersonic combusting ramjets. Waltrup, et al from Johns Hopkins University provides an extensive overview of the U.S. Navy’s involvement in development and advancements in scramjet engines from its beginning in the

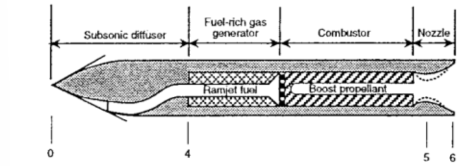
1950s to the early 2000s [56]. The Navy’s application for ramjet engines is mostly adapted as the propulsion system for supersonic, long-range missiles.



a) Conventional can combustor ramjet (CRJ)

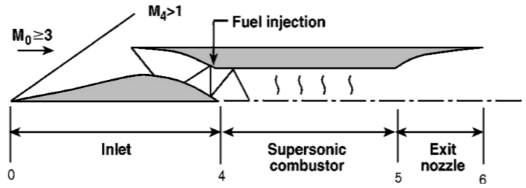


b) Integral rocket/dump combustor ramjet (LFIRR)

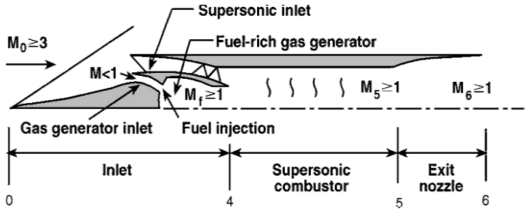


c) Solid-fueled ramjet (SFIRR)

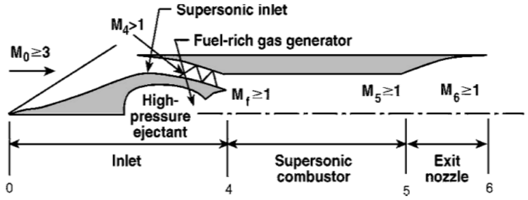
Figure 5 : Ramjet Variations [56]



a) Supersonic combustion ramjet



b) Dual combustor ramjet (DCR)



c) Ejector scramjet (EJS)

Figure 6 : Scramjet Variations [56]

The Navy was involved in several scramjet projects including SCRAM, NASP, and the more recent counterforce. NASP, was a highly theoretical design which stands for National Aerospace Plane and was designed to go from takeoff to orbital velocities of Mach 25. Although the development of this technology was not realistically able to be created, the national investment into the project led to major advancements in aerospace and high-speed flight CFD technology. Nonconventional, solid-fueled scramjets have been a topic major research interest in the last ten years, with that progress being detailed by Zhao, et al at the Department of Aerospace Science and Engineering at the National University of Defense Technology in Changsha, China [57]. This review explains the importance of the monumental Mach 7 and 10 flight tests of the NASA liquid-hydrogen fueled X43 scramjet, which sparked widespread interest in scramjets. Liquid-fueled scramjets typically have a very complex system pipes and tanks which lead to mechanical complexity and reduces mass ratio of the vehicle, in turn decreasing efficiency. Solid-fueled ramjets offer improved storage efficiency and simplifications for the entire system. These solid-fueled scramjets still require much more research in heat-resistant metals, as ramps and struts used to stabilize flames and create turbulence are being morphed leading to inefficient mixing due to surface regression. Another key scientific issue deals with the studying of ignition and combustion of condensed phase particles, as most research deals with solid-gas phase ignition and combustion.

The work presented in this study has undertaken a unique approach to scramjet engine ignition that has not been previously studied, using the same liquid fuel and air as the main combustion chamber for ignition. Liquid fuels present challenges to ignition that are not present with gaseous fuels such as hydrogen, methane, and ethylene. Some of these challenges include the need for atomization and evaporation, to increase the surface area of the fuel and make it ignitable, ignition delays present in hydrocarbon fuels, and possible combustion instability due to uneven mixing and incomplete atomization. To better understand how the system presented works, it is imperative to go through the steps required in liquid fuel ignition. These include the liquid fuel breakup process, fuel-air mixing, and finally ignition.

There are four main categories of breakup mechanisms as seen below in Figure 7, each characterized by their own range of Weber numbers. Weber number is a nondimensional value that represents deforming forces to stabilizing cohesive forces. The four different categories are capillary, bag, multi-mode, and shear breakup, each with increasing ranges of Weber numbers [63,65]. For a liquid jet in crossflow (LJIC) representative of what was conducted in this study, the breakup regime lies in the shear breakup mechanism. The shear breakup mechanism allows for the greatest atomization of the liquid fuel and provides the best fuel-air mixing outcome out of the four mechanisms. In a review conducted by Broumand and Birouk [66], they discuss the process of multi-phase flow with transverse liquid jet in a gaseous crossflow. LJIC is a complex process to characterize due to the many different parameters impacting the breakup regime, trajectory, and penetration. These parameters can be broken down into three groups, the liquid, gas, and surrounding parameters. To define a certain feature of the LJIC, it can be described as a function of momentum flux ratio and both jet Reynolds number and crossflow Reynolds number. Other dimensionless parameters such as density ratio, viscosity ratio, Ohnesorge number, and Bond number each play a role in characterizing the liquid jet. All these parameters play an important role in understanding the inner working of liquid fuel breakup and mixing process.

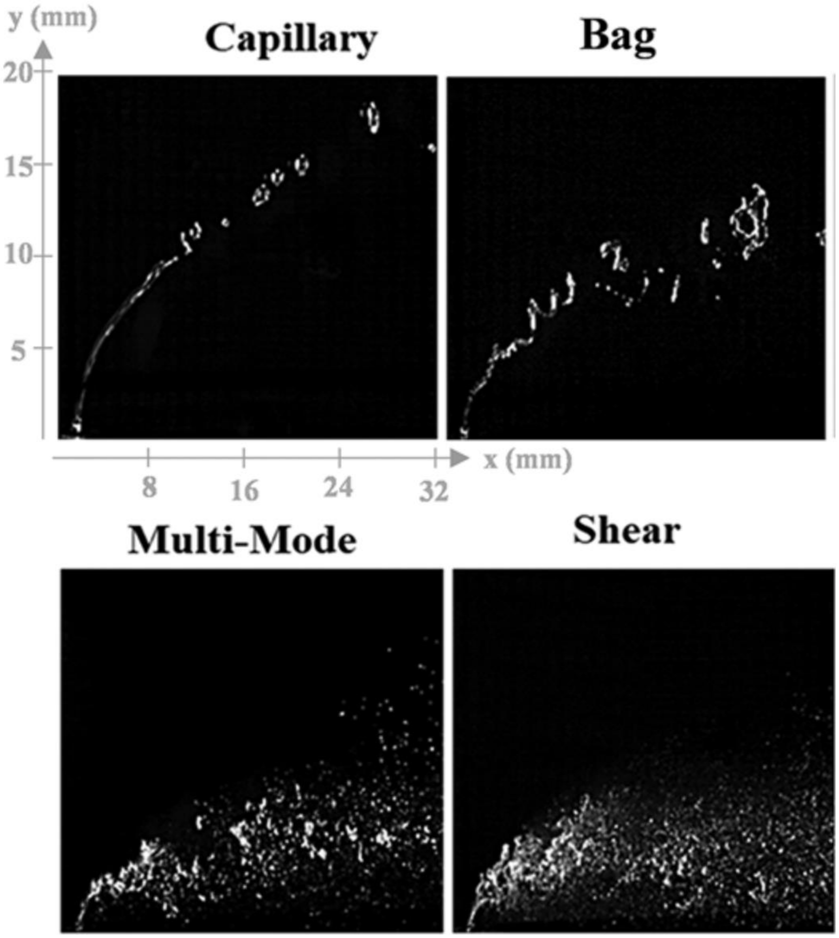


Figure 7 : Primary Breakup Regimes [63]

The viability of liquid fuel ignition systems also relies on the lowest possible ignition delay. Ignition delay consists of two parts, the first being the physical delay, which includes the entire atomization and mixing time scale, and the second being the chemical time scale, which varies with different fuels [64]. For scramjet applications, ignition delay is a critical parameter that must be accounted for due to the extremely low residence time of air flowing through the engine typically in the order of milliseconds [60-62]. The physical aspect of ignition delay accounts for most of that time scale making the atomization and mixing process of utmost importance. Gaseous fuels such as hydrogen have optimal combustion characteristics compared to liquid fuels but are typically hindered by their storage requirements because of their extremely low density. Utilizing the same liquid jet fuel used in the main combustion chamber of scramjet engines would significantly increase the efficiency of the entire system by excluding the need for auxiliary fuel reservoirs for gaseous fuels as are used in many of the current ignition systems.

In a literature survey, there has been little to no research conducted developing an ignition system for supersonic combustion utilizing the same liquid jet fuel for both main combustion and ignition. Thus, a system was developed with reliable and consistent ignition, with a high chamber pressure rise, and a strong exhaust jet; especially so, in hypersonic scramjet applications where weight reduction is a critical factor in reducing drag and increasing fuel efficiency.

CHAPTER TWO : METHODOLOGY

The scramjet igniter studied is comprised of four major components that make up the entire system, these include : the fuel tank, the air and fuel feed lines, the air heater, and the combustion chamber. Along with the facility components, a variety of electronics were used for diagnostic and control purposes. A comprehensive description of the entire methodology will be detailed in the following section.

2.1 Scramjet Igniter System Design and Setup

A pressurized six-gallon fuel tank reservoir containing JetA liquid fuel was used and directly injected into mixing chamber where it acted as a transverse jet within a LJIC configuration. The fuel tank was pressurized to 150 psi with a 0.011 inch diameter orifice connected upstream of the mixing chamber. This provided the primary breakup mechanism for the fuel with secondary breakup coming from air in crossflow. The air feed line was supplied by a high volume air compressor set at 120 psi going through an air heater directly upstream of air injection into the mixing chamber. Downstream of the mixing chamber is a narrow 0.25 inch NPT pipe that acts as a mixing region with a 0.039 inch orifice as the inlet into the combustion chamber. Directly upstream of the 0.039 inch orifice, a bypass valve was included to reduce total flow rate and ensure properly mixed fuel and air were entering the combustion chamber. The combustion chamber is a tee-shaped stainless steel pipe fitting with a volume of 71.13 inch^3, modified with a quarter inch hole on its face to fit an automotive spark plug. The top side outlet of the combustion chamber was fitted with a pressure transducer used to measure the pressure-rise from ignition. The ignition flame exhausted out of the bottom of the combustion chamber, where varying outlet orifice sizes were fitted. Figures 8 and 9 below display the system configuration and combustion chamber where ignition occurred.

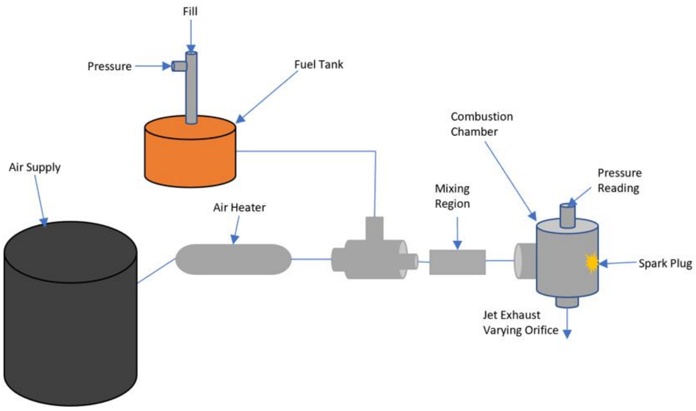


Figure 8 : Diagram of Entire System

Figure 9 : Pictures of Combustion Chamber

The electronics of the facility can be broken down into two groups the controls electronics and the data acquisition (DAQ) hardware. The controls electronics includes the relay and controller for the air heater, which is shown below in Figure 10 as part of the air feed line, and the system used for sending signal to spark plug. Spark plug operation also required two of its own devices, one being the timing box which is a BNC model 575 pulse/delay generator, and the other being a lab made relay box that connected to the spark plug directly via an ignition coil and grounding wire. Parameters such as spark plug pulse frequency and width of each individual spark were set using the timing box.

The DAQ electronics consisted of a pressure transducer with a 275khz sampling rate, connected to a PCB PIEZOTRONICS model 482C series sensor signal conditioner, which was connected to a NI USB-6356 multifunction DAQ. The multifunction DAQ then is directly connected via USB to a laptop computer running NI LabVIEW, which was calibrated to convert the voltage readings from the pressure transducer into usable pressure readings inside the combustion chamber. To capture schlieren imaging, a high-speed Photron SA-Z camera was used capturing video at 10,000 frames per second pointed at an illuminated mirror configuration and combustion chamber outlet nozzle.

Figure 10 : Picture of Air heater with Thermocouple, DAQ system

2.2 Theoretical Calculations/Combustion Efficiency

Before initial testing, stoichiometric equilibrium, mass flow rate, and equivalence ratio calculations were completed to identify the different parameters needed to properly operate the facility. By using the choked mass flow rate equation, it was possible to both set a theoretical mass flow rate and desired equivalence ratio to output the required pressure settings for the facility. These calculations proved fruitful in initial testing to get an approximation of what pressures to set both the air and fuel to, but to reach ignition, alterations were made to these pressures, respectively. Once reliable ignition pressures were attained during testing, an inverse of the mass flow equations allowed for a refined understanding of the actual mass flow and equivalence ratio of propellants realized in the system. From these results, approximately 7.06 g/s of total mass flow was experienced in the chamber and with the addition of the bypass valve, the combustion chamber had about 5.29 g/s of total mass flowing in.

From the pressure rise readings, and using online numerical simulations from NASA CEA, combustion efficiency for the system was also completed. Using an assigned enthalpy and pressure problem solver in NASA CEA, chemical equilibrium calculations were completed using all the known input parameters of the propellants. From these results, combustion efficiency was calculated using both output temperature-rise from combustion, and combustion product composition. Because the facility did not have the physical tools to acquire these output parameters NASA CEA was used to bridge the gap and provide somewhat of an understanding of combustion efficiency for the ignition process. Equation 1 below was used to solve for combustion efficiency by using the temperature rise from NASA CEA, this equation was obtained from research completed by Sadat Akhavi et al, at the Department of Aerospace Engineering in Amir Kabir University of Technology [67-68,70]. Equation 2 shows an alternative way of calculating combustion efficiency by taking the reaction product composition by mass and proves to be in relative agreement with the values obtained from equation 1 [69].

$$\eta_{combustion} = \frac{C_p(T_{exit} - T_3)\dot{m}_{air}}{\dot{m}_{fuel} LHV_{fuel}} \tag{1}$$

$$\eta_{combustion} = \frac{mass\ CO_2}{mass\ CO_2 + mass\ CO} \tag{2}$$

2.3 Experimentation and Diagnostics

Several parameters in the facility were varied throughout the testing campaign to help determine which configuration led to the highest reliability, pressure rise, and penetrating jet. The parameters varied include fuel/air mixture temperature, sparking frequency, and combustion chamber outlet orifice diameter. Initial testing was completed with a 0.113 inch diameter orifice as the nozzle of the combustion chamber with varying temperatures from 150°C to 275°C. From there, the temperature that resulted with the best combination of pressure-rise and reliability was chosen to be the set temperature for the following set of tests that varied sparking frequency from 0.5hz to a maximum of 20hz. Schlieren and mobile video capture were also used at varying temperatures, to analyze the effects on jet exhaust quality. The following tests were then completed in the same manner for different combustion chamber outlet orifice sizes. The next section delves into the results obtained, selection reasoning, and discussion of results relevant to the research goals.

CHAPTER THREE : RESULTS AND DISCUSSION

3.1 Preliminary Results at Varying Temperature and Constant Spark Plug Frequency

Initial testing of the facility was conducted at varying mixture temperatures ranging from 150°C-275°C at 1hz spark plug frequency. This set of tests were conducted separately for each outlet diameter. Two main parameters were considered when selecting a set temperature for the following set of tests, pressure ratio (PR) and reliability. Reliability was given priority over PR especially if two temperatures were close together. Figures 11 and 13 display the PR and reliability graph that explains the reasoning behind temperature selection for varying frequencies. For the 0.113 inch case, 150°C had the highest reliability and a similar PR to the other cases. At the 0.096 inch outlet, the reliability was the same at two different temperatures meaning the differentiating parameter was which temperature had the higher PR. This led to the selection of the 225°C temperature. For reference, an example pressure trace of the 150°C, 1hz, 0.113 inch outlet test case is also seen below in Figure 12.

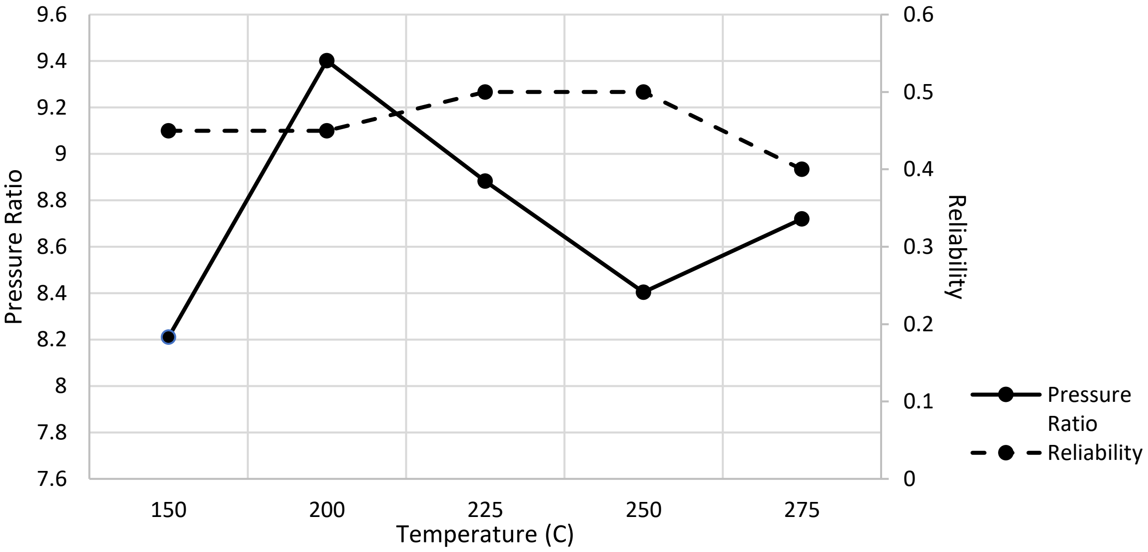


Figure 11 : 0.113 inch PR and Reliability

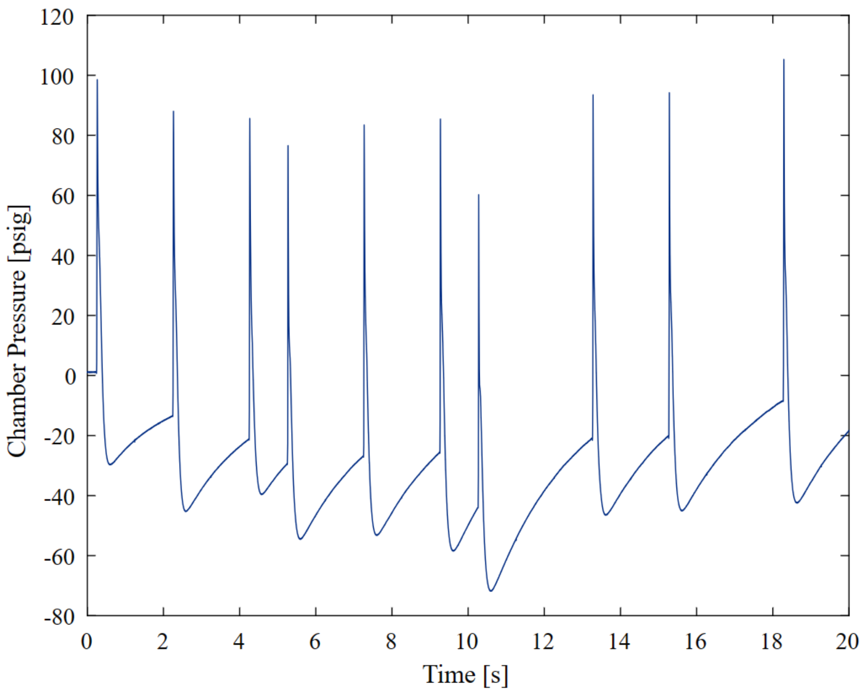


Figure 12 : Pressure Trace at 150℃, 1hz spark, and 0.113in. outlet

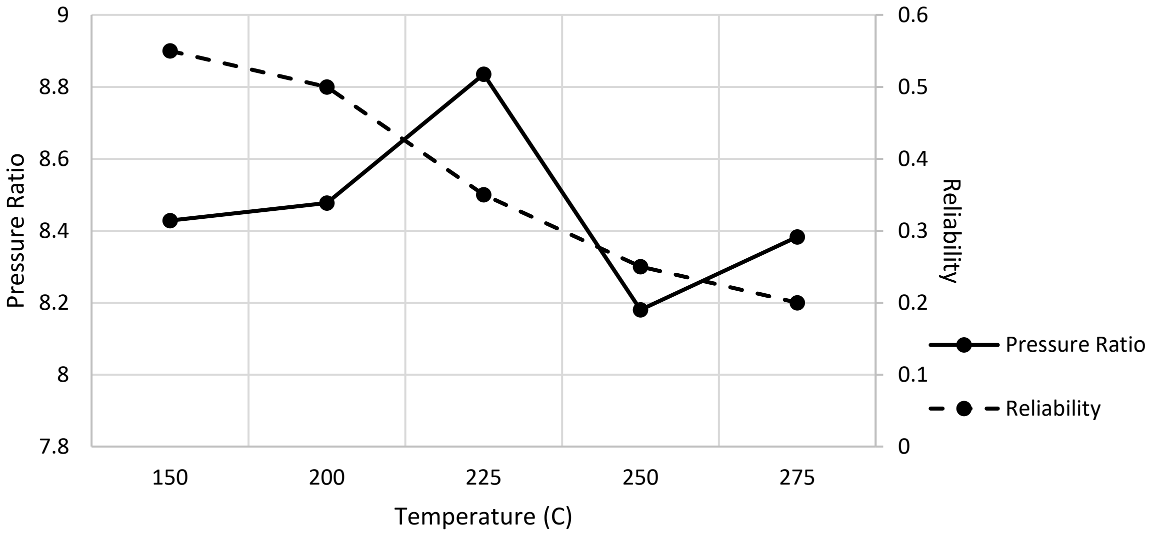


Figure 13 : 0.096 inch PR and Reliability

3.2 Repeated Testing at Selected Temperature and Varying Spark Plug Frequency

Once exact temperatures were selected, the following set of testing included fixing said temperature and changing the spark plug frequency from 0.5hz up to a maximum of 20hz. A strong relation with increasing the spark plug's frequency and increasing ignition pulse frequency is evident in Figure 14 below. There also appears to be a limit near one hertz frequency no matter how high the spark plug frequency is set.

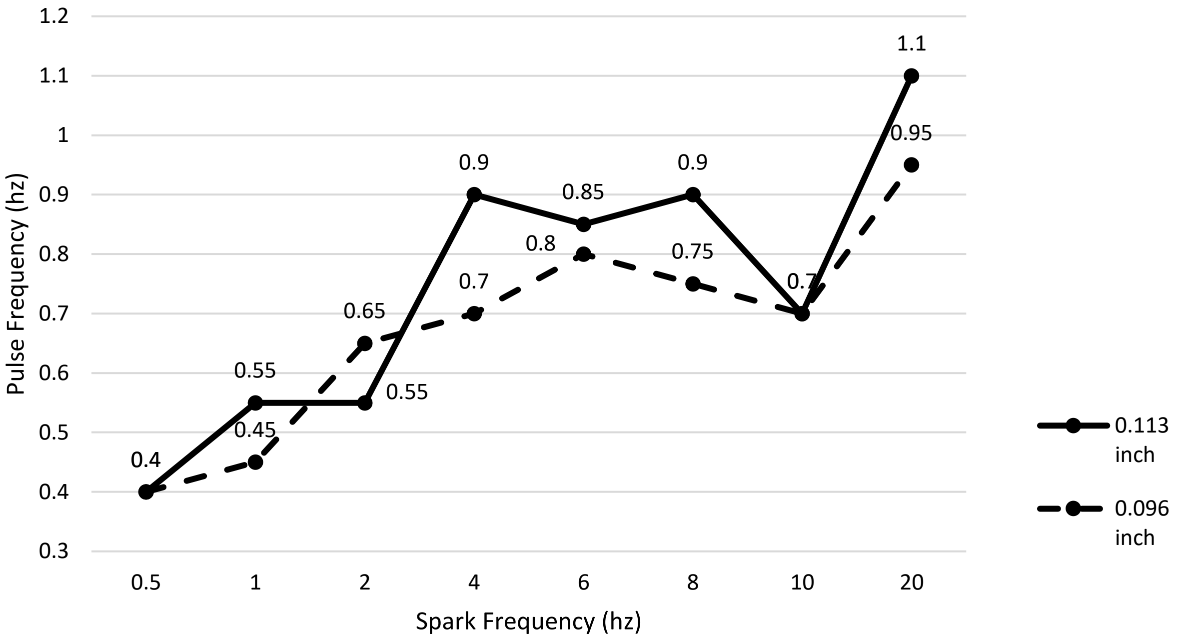


Figure 14 : Comparison of Ignition Frequency at Varying Spark Plug Frequencies

Varying the outlet nozzle to a smaller diameter of 0.096 inches results in an expected pressure rise. At a sparking frequency of 20hz this pressure rise difference between combustion chamber outlets becomes evident as seen below in Figure 15. Pressure was higher on average for the 0.096 inch orifice but both orifices displayed similar trends throughout the ignition period. Values for the peak pressure are different from the ones displayed below, this is because as ignitions occur the starting pressure decreases. The values displayed below are calculated by taking the difference between the peak pressure and the starting pressure at each ignition to give an absolute pressure rise per ignition. It is important to note that the reason for starting pressure being negative for the high frequency sparking cases is because as ignitions occur the combustion chamber needs a certain amount of time to refill to reach a baseline pressure. The relatively long fill time for the combustion chamber acts as a detremint to the facilty as it reduces the maximum possible ignition pulse frequency, and plays a part in reducing ignition reliability at lower sparking frequencies. With a properly optimized combustion chamber geometry, higher ignition pulse frequency would be possible, because of reduced fill times.

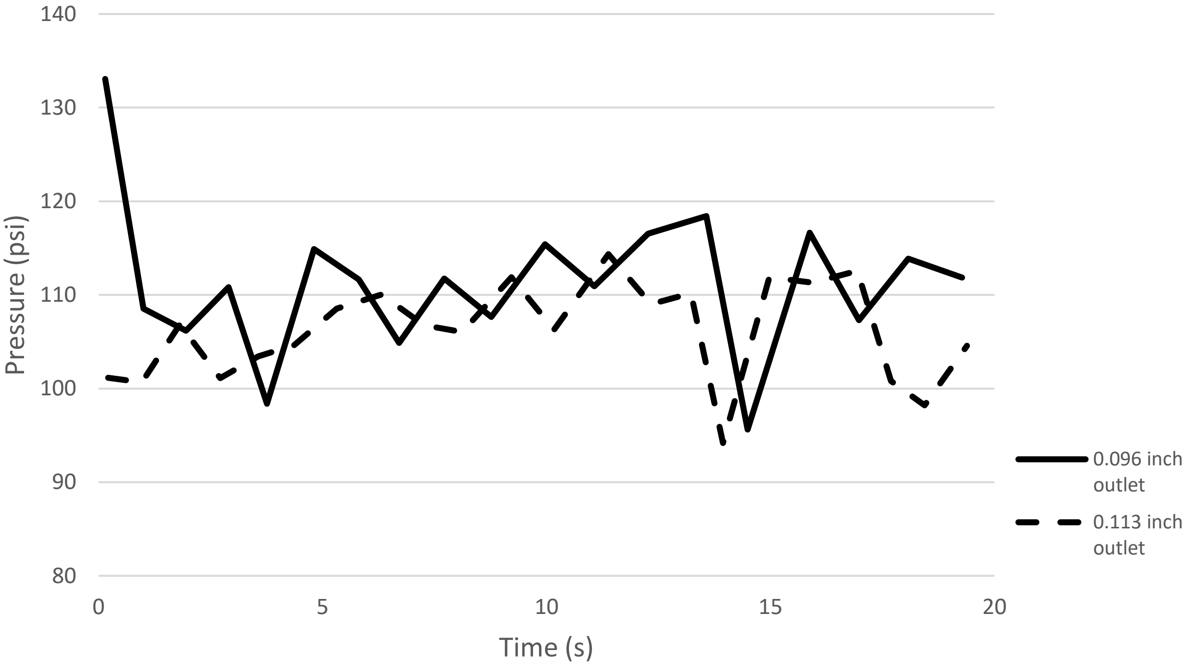


Figure 15 : Absolute Pressure Rise vs Time at Different Outlet Sizes

The facility reaches a maximum of 1hz when pushing the sparking frequency to its maximum tested value of 20hz and maintains a pressure ratio average above 8, and maintains a penetrating jet expressing high energy release. One final metric that is important to take note of is the combustion efficiency of the entire system. Below in Table 1, the combustion efficiency is calculated in two ways that both yield similar results of about 50% combustion efficency. Considering the lack of opitimization, and the increased equivalence ratio of 1.544 used throughout testing, a 50% combustion efficiency is not that far from the values obtained in literature of 75-90% with liquid jet fuel.

Table 1 : Data Used to Calculate Combustion Efficiency

T_3(K)	T_{exit} (K)	C_p(kJ/kg*K)	Initial Pressure (psia)	CO_2%	CO%	η(ΔT)	η(products)	U_{flame} (m/s)
423	2029.5	1.5332	15.732	8.690	13.636	54.2235	50.0361	900.8
473	2068.29	1.5439	17.126	8.599	13.694	54.221	49.667	908.7
498	2087.35	1.5558	14.2286	8.556	13.721	54.4354	49.4928	912.4
523	2107.44	1.5591	16.782	8.511	13.750	54.3824	49.3077	916.6
548	2127.54	1.5647	18.395	8.468	13.777	54.4089	49.1321	920.7

3.3 Imaging of Exhaust Jet

The final method of diagnostics taken to evaluate the ignition system created was to get imaging of the jet exhaust from the combustion chamber. This was achieved by using both a conventional phone camera and a highspeed camera operating at 10,000 frames per second. Figure 16 below shows the phone cameras capture of the exhaust jet for 150°C, 225°C, and 275°C at 0.113 inch outlet. It can be noted in all three images that there is a penetrating jet with barely visible Mach diamonds, indicating a supersonic exhaust plume, which is expected from the high PR obtained from ignition. The Schlieren imaging taken not only provides a valid depiction of the ignition process, but also allows for another perspective on the time scale that are represented in the pressure trace readings. The ignition process is shown in Figure 17 beginning with filling of the combustion chamber with propellent, followed by ignition resulting in combustion chamber jet exhaust, and finally the expelling of flue gas and refilling of the combustion chamber with propellant. When comparing the pressure trace, from the point after ignition to flame exhaust represents the peaks in the pressure trace, followed by the flue gas expelling and refill of air into the chamber represents the fill time portion of ignition cycle.

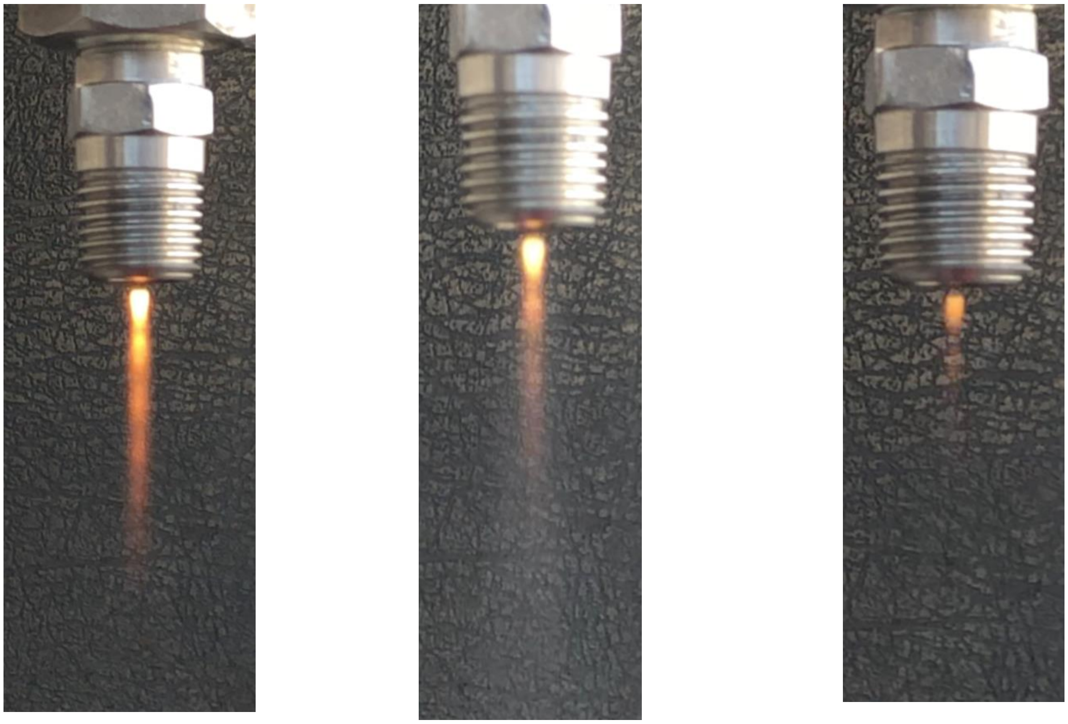


Figure 16 : Jet Exhaust at 150℃, 225℃, and 275℃

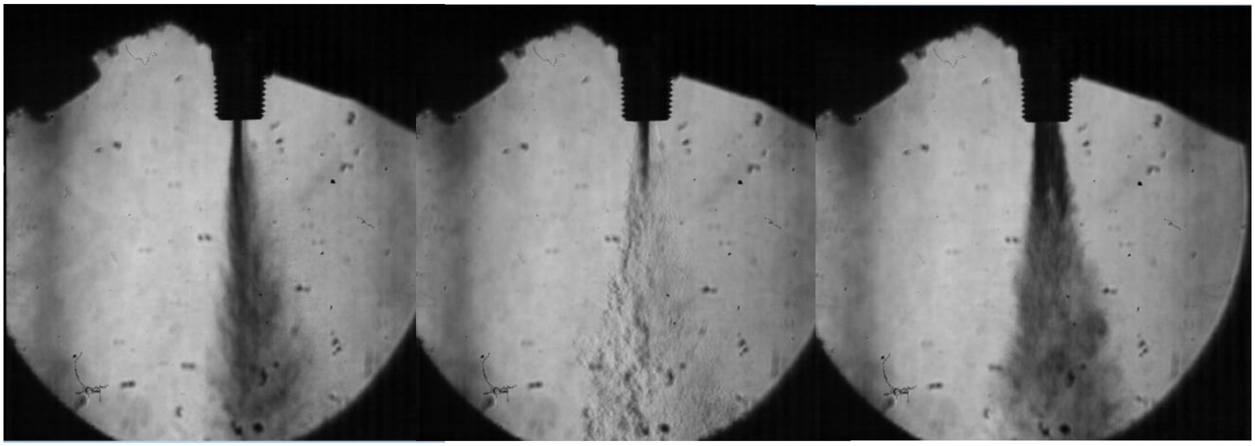


Figure 17 : Schlieren Imaging of Ignition Jet Process at 150℃

CHAPTER FOUR : CONCLUSIONS

With scramjet engines being a trending topic of hypersonic flight research, any innovations that would reduce complexity and weight, while increasing system efficiency would be a fruitful venture to tackle. In this study, a preliminary proof of concept for a unique ignition system with the purpose of utilizing the same liquid fuel and air as the main combustion chamber of a scramjet engine has been developed. By overcoming the many difficulties present in multi-phase liquid fuel and air combustion, and obtaining reliable ignition with high pressure ratios, the ignition system created is ready to take on the next phase of development including, design and manufacturing of an optimized combustion chamber followed by initial testing within a supersonic flow tunnel. In this study, liquid JetA fuel was injected in a LJIC configuration with an equivalence ratio of about 1.5 and total mass flow rate of about 5.2 g/s. Reliable ignition was successfully attained at a max pulse frequency of about 1hz and pressure ratios averaging greater than eight throughout most test cases. Both methods of calculating combustion efficiency by using propellant parameters and combustion products by mass led to efficiency of around 50% with negligible changes at varying temperatures. This has also proven to be very adequate considering the fuel rich equivalence ratio and unoptimized combustion chamber geometry. Schlieren imaging and traditional recording methods were used to further understand the characteristics of the ignition cycle while also identifying jet quality for penetration purposes. Successful testing of the facility proves the viability of its application within scramjet combustors and leading innovation for a critical system within scramjet engines.

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