2015-01-01

Design and Testing of an OX/CH4 Swirl Torch Ignition System

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Dedication

I dedicate this thesis to my family who has always supported me.

DESIGN AND TESTING OF AN OX/CH4 SWIRL TORCH IGNITION SYSTEM

by

GABRIEL RICARDO TRUJILLO, B.S. Mechanical Engineering

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Mechanical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

August 2014

Acknowledgements

There are some people who I would like to acknowledge for helping me throughout my time at UTEP. I would like to acknowledge my past and present team mates: Jesus Flores, Vanessa Dorado, Robert Ellis, Luis Sanchez, Javier Chaparro, Samuel Guzman, and Daniel Vargas. I would like to acknowledge Dr. Choudhuri for giving me the opportunity to work in the cSETR. And last I would like to acknowledge several people form the center that helped me throughout my stay, Abraham Trujillo, Manuel Galvan, Juan Barragan, Jose Mena, and Arturo Acosta.

Abstract

NASA has renewed its interest in oxygen and methane as propellants for propulsion. Some of the reasons that drive this interest are the ease of storage of liquid methane when compared to hydrogen, the handling safety when compared to hypergols, in-situ resource utilization and its relative clean burning process. This project is part of the larger goal of the Center for Space Exploration Technology Research (cSETR) to better understand the aspects of using this propellants to create future hardware that are specifically optimized for their use. This paper discusses the testing of a previous iteration of the swirl torch igniter with liquid oxygen and liquid methane. The data and conclusions that led to the design of a new iteration of the swirl torch igniter will be discussed. The purpose of the new design is to replace the previous methane manifold used in the two previous iterations, add a new sparking system, and test the Characteristic Chamber Length (L*). The L* was to be analyzed by comparing the performance of two igniters, each with a different chamber length. The data obtained and design changes needed for testing will be discussed in this document.

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Chapter 1

There are three main purposes to this document. The first is to detail the testing of a previous swirl torch ignition system. The purpose was to determine the flammability map for this torch igniter while using oxygen and methane both in liquid state and add to the previous collected data. The discussing of the failure of the test with the propellant combination will be done. The second purpose is to show the calculations, design and testing of a 3^{rd} generation swirl torch igniter. The change of the methane manifold, the change of the sparking system, and the testing of the characteristic length will be discussed as well. The third and final purpose is to be a guide for further reference to continuing generations of students from the cSETR.

1.1 INTRODUCTION

The torch ignition system was designed as the ignition source of a series of experiments involving shear coaxial injectors which purpose is characterize methane's properties and performance as a rocket fuel[1]. This makes it necessary to create a flammability map of Oxygen and Methane in their gaseous and liquid states. These maps will aid future designs by showing the range of ignition of these propellants. This ignition system will be then be used in the Multipurpose Optically Accessible Combustor (MOAC) to test three different shear-coaxial injectors [2][3].

One of the requirements of the torch ignition system is that it should ignite the propellants at all inlet conditions; at any combination of the propellants of being in a gaseous state, cold gas state or in a liquid state. This comes from an idea that the torch ignition system should be feed from the boil-off of the main propulsion engines feed system, which should be in a liquid state. This document will show the experimental approach in testing the propellants at different inlet conditions, previous and new data obtained, and the evaluation of the new data obtained using the previous swirl torch igniter.

This document will as well show the design and testing of two new swirl torch igniters. The purpose of these tests will be to evaluate the characteristic chamber length using oxygen and methane in their gaseous state. The tests will be conducted in the multi-purpose altitude simulation system (MAA), which is located inside the bunker of the Goddard Laboratory at The University of Texas at El Paso. Instrumentation to gather pressure, temperature and volume flow rate will be used in the tests to gathered data used for the analysis.

1.2 LITERATURE REVIEW

1.2.1 Methane as a Propellant

Reasons like high energy density, high specific impulse, and a similar cryogenic storage temperature to oxygen, and possible in situ utilization, make Methane an excellent candidate for a propellant [4]. The problem is that most engines that currently use LOX/CH4 are engines that were designed for hydrogen and had been modified to be used with Methane [5]. The process of modifying the hydrogen engines by trial and error has a very high cost with minimal results. This is due to the lack of knowledge in how LOX/CH4 propellant combination works, this reduces the efficiency of the engines and makes them undesirable when compared to the other more understood propellant combinations which have optimized hardware.

Organizations such as the National Aeronautics and Space Administration (NASA) have renewed their interest in Methane. The organization has taken part in researching the many aspects to fully understand methane. The cSETR has taken part in this process by doing research in methane heat transfer characteristics, injector design, spray atomization and flammability maps.

The current method that has been used to design methane engines is by creating models with Computational Fluid Dynamics (CFD). The problem is that these models do not have any experimental data to validate the results. The cSETR has created some visually accessible combustors so that imaging software can be used, such as Schlieren, Particle Image Velocimetry

(PIC), and Phase Doppler Particle Analyzer (PDPA). This will help understand how the injector design will affect the propellant break up length, and the particle velocities.

1.2.2 LOX/Methane Engines

Aerojet USA and NASA's project Morpheus have created and used LOX/CH4 engines. The largest engine made by Aerojet was an adapted LOX/Ethanol, which was originally used in the Kistler Program. The systems igniter still used ethanol as fuel. The test showed that methane was not as efficient as ethanol in cooling; the engine was designed with film cooling. The reasons might be that the engine was optimized for ethane or maybe the propellants heat transfer characteristics were not adequate. The overall test was a success with an approximate efficiency of 97%.

A Reaction Control System (RCS) engine made by Aerojet was tested at both atmosphere and at altitude simulation. The Isp values given were of 320 seconds and 305 seconds respectively. The tests showed that colder propellants gave more efficiency while that warmer propellant gave a higher performance. Methane does not meet the same Isp values as hydrogen (~430s) and Nitrogen Tetroxide/Hydrazine (~344s) but is still a very practical propellant.

The most recent work comes from NASA's project Morpheus. The project seeks to create a lunar lander which propellant combination is LOX/CH4. One of the reasons that the project was created is the revitalized interest in moon colonization and mars exploration where it may be possible to produce methane from local sources. This would cut down fuel costs since there would be no necessity in taking as much propellant into space. Project Morpheus is testing the capabilities of methane in both the main engine and RCS thrusters. The Isp for this vehicle is similar to that for Aerojet at 321s. Project Morpheus has only had one major setback which was that of the destruction of the first vehicle during an untethered test [6]. A second vehicle has been built and tested.

1.2.3 Literature on igniters

NASA Glenn Research Center designed, fabricated and tested a LOX/LCH4 RCS Igniter, which they named GRC Workhorse Igniter. For this igniter they used a spark plug as the ignitions source which exciter delivered 200 sparks per second at 20 kilovolts. They conducted over a total 1402 individual ignition pulses over the range of overall mixture ratios from 1.08 to 1.88. They had a corresponding chamber pressure range of from approximately 1040 to 1720 kPa, and they used a 5mm diameter throat. To set up their mass flow rates they used cavitating venturis in each of their propellant feed lines [8]. The testing was halted when the ceramic from the spark plug failed.

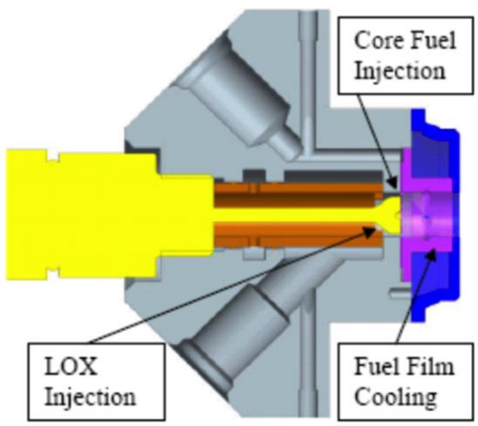

Figure 1 GRC Workhorse Igniter Sketch

Figure 2 GRC Workhorse Igniter Spark Plug with failed ceramic

NASA Glenn Research Center as well tested a LOX/Methane main engine igniter. They conducted an overall of approximately 750 ignitions test on the in-house designed spark torch igniter. They tested the test article in a simulated space vacuum environment. The purpose of their test was to evaluate the effects of methane purity, igniter body temperature, spark energy level and frequency, mixture ratio, flow rate, and their igniter body geometry on the ability to obtain successful ignitions. Figure 3 shows the cross section of the igniter assembly.

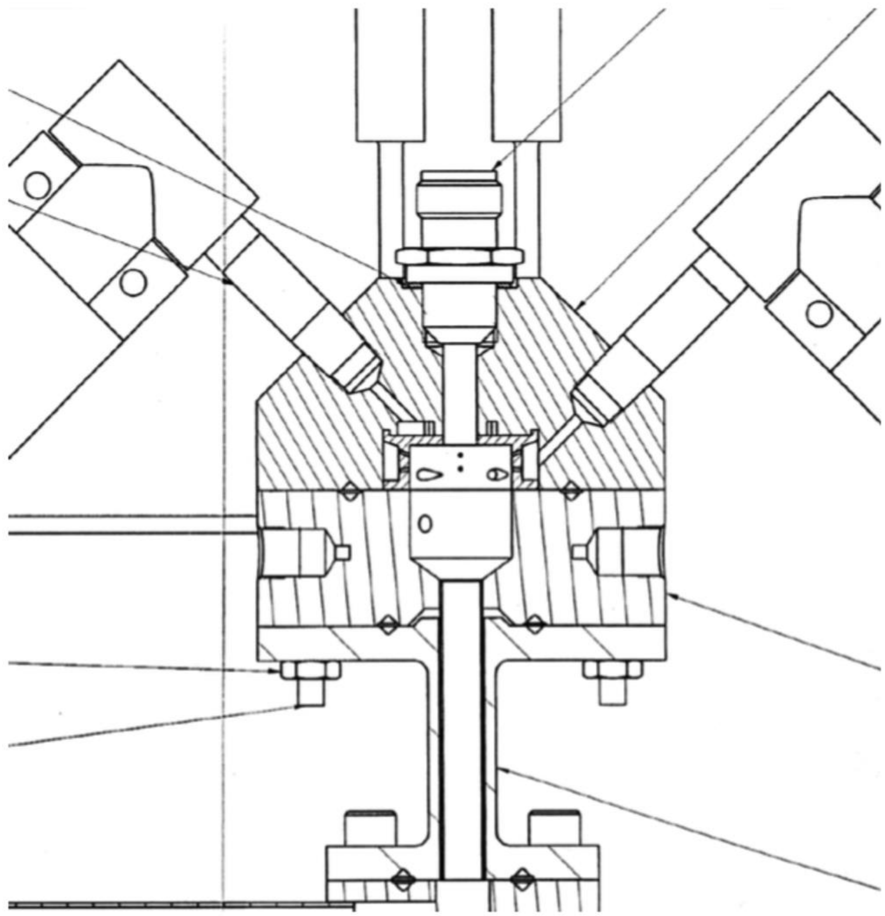

Figure 3 Cross-section of Igniter Assembly

1.3 STATEMENT OF PROBLEM

Some of the current methods of igniting the main engine either require too much power or consume too much propellant, which decreases the overall efficiency of the system. There are many problems associated with most widely used propellants that are hypergolic and hydrogen. Hypergolic propellants are difficult to handle because of their extreme toxicity and corrosiveness, and as well have an impact on the environment while running tests with them. Liquid hydrogen is difficult to be maintained at such low temperatures, even with the special thermally insulated containers used for cryogens. Hydrogen will leak away faster than other cryogens. This has led to the interest in green propellants, which are safer to the atmosphere when test, safer to handle and store. The problems that arise are that not much research has been done on methane for its process of burning, atomization, and many other characteristics that determine its functionality as a propellant.

The purpose of this paper is to show the data obtained from a continuation of tests done with previous iteration of the swirl torch igniter using LOX/LCH4. A description of the facilities used and test procedure will be shown as well as the analysis of the data obtained. The design and testing of two torch igniter with different chamber lengths will as well be discussed in the paper, which purpose is to analysis the effect of the characteristic length. The facilities, equipment and test procedure will be discussed as well as the data obtained.

1.4 PREVIOUS WORK

Two iterations of a swirl torch ignitions system have been tested at the cSETR, which will be discussed with further detail in a further chapter. The first iteration contained two separate manifolds, one for each propellant, that where connected together with Swagelok tubing. The second iteration contained both manifolds in a single body, and a throat section was added.

There have been four propellant combinations tested with the previous iterations of the igniters, which are a combination of both propellants at their gaseous state, liquid oxygen with

cold gas methane, gas oxygen with cold gas methane, and liquid oxygen and liquid methane. The last propellant combination has not been tested has vastly has the other combinations since there has been some difficulties, which will be discussed further in the next chapters.

1.5 PROJECT PURPOSE AND OBJECTIVES

The purpose of this thesis is to discuss the testing of a previous iteration of a torch igniter with Liquid Oxygen and Liquid Methane, and the design and evaluation of a new swirl torch igniter. The data obtained from the tests with liquid propellants will be discussed and future test will be discussed. The design of a new swirl torch igniter with a different methane manifold and the evaluation of the characteristic length will be discussed.

The objective of the swirl torch igniter is to provide a reliable ignition source inside an optical accessible chamber. Two different shear coaxial injectors will be tested with the aid of the swirl torch igniter. The torch igniter design is based on a previous-tested micro thruster that has been proven stable [10].

Chapter 2

2.1 TECHNICAL APPROACH

This chapter will be used to describe the testing facilities, hardware, data acquisition, and instrumentation. This will include the description of the cryogenic delivery lines, bunker and control room, and ambient test stand, Mobile Methane Condensing Unit, Data Acquisition and Remote Control System.

2.1.1 Bunker and Control Room

All combustion experiments are conducted inside the ballistic proof bunker facility. This room is lined with ¼ inch Kevlar walls and has two bulletproof windows, which makes it optimal for combustion and propulsion experiments. The cryogenic delivery lines, mobile methane-condensing unit, and the ambient test stand are located inside the bunker. Figure 4 is a picture of the layout of the cryogenic delivery lines, MASS and the two-stage ejector system. Figure 5 shows and overall layout of the bunker facility.

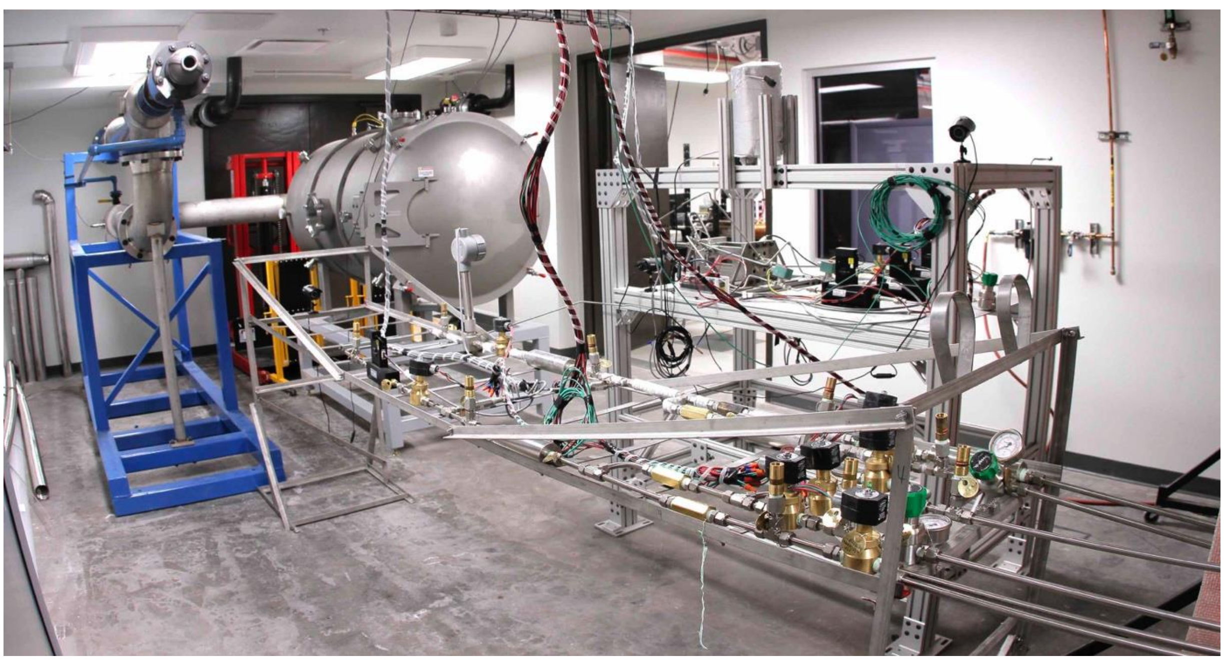

Figure 4 Integration of Cryogenic Delivery System and Ambient Test Stand

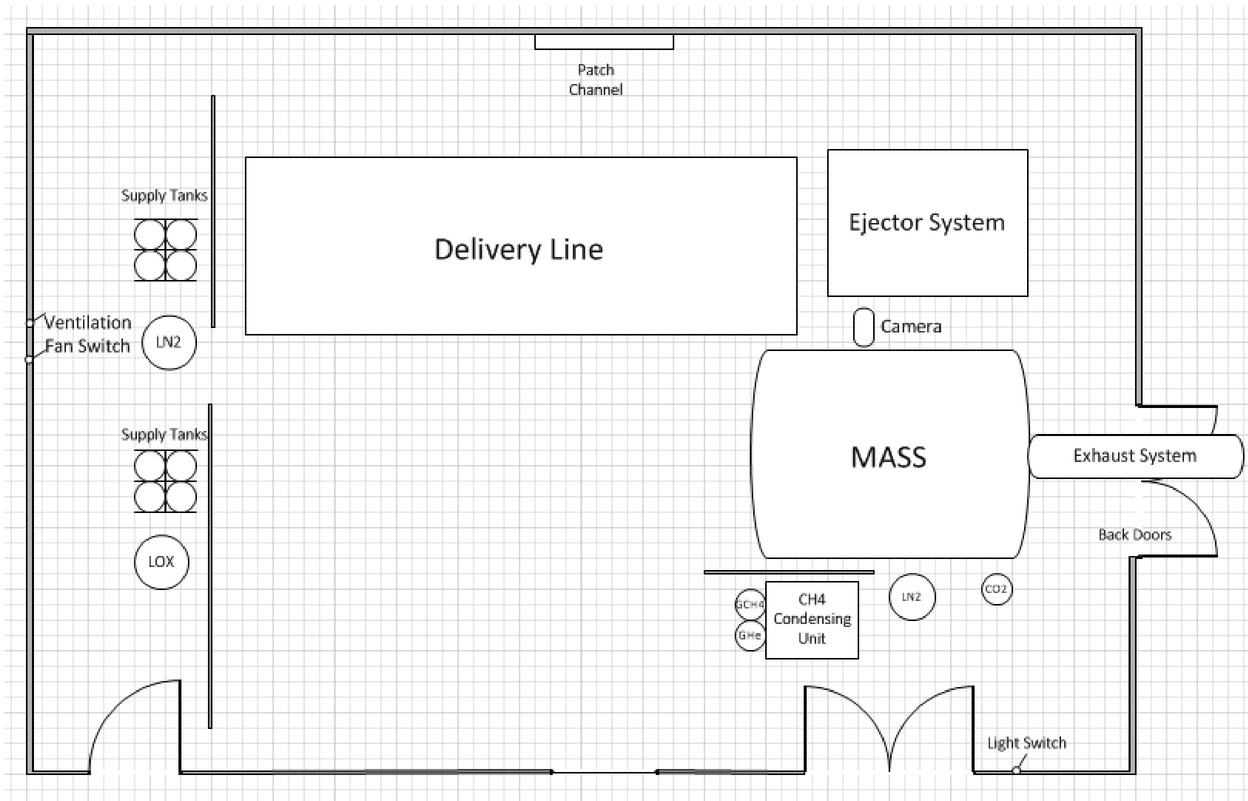

Figure 5 Bunker Facility Layout

The control is located directly next to the bunker. This room is used to control and run the experiments remotely for safety issues. To control the experiments LabVIEW software is used through a computer, which was order specifically for the laboratory needs. There are several cameras installed inside the ambient test stand to monitor the test article during the test, which video can be seen in a LG monitor in the control room. The power supplies are located as well inside the control room which task is to supply power to any necessary equipment. There is a patch channel inside the control room that connects to the bunker, where the instrumentation is plugged in to connect to the data acquisition (DAQ) systems.

2.1.2 Cryogenic Delivery Lines

The cryogenic delivery lines consist of two main lines, the oxygen and methane delivery lines, which have 2 adjacent lines connected. One of the lines is used for purging with gas nitrogen, and the second one is for the chilling of the lines with liquid nitrogen. Liquid nitrogen is used to chill the lines for the liquid testing instead of using liquid oxygen, which is most costly. Figure 6 shows the schematic of the delivery lines. The cryogenic delivery lines were designed to flow liquid oxygen and liquid methane, but this was not possible to use liquid methane due to the purchase quantity. Liquid oxygen as well as liquid nitrogen can be both in cryogenic tanks that contain 180 Liters. Liquid methane is only sold at much higher quantities and the laboratory that does not have the storage capacity.

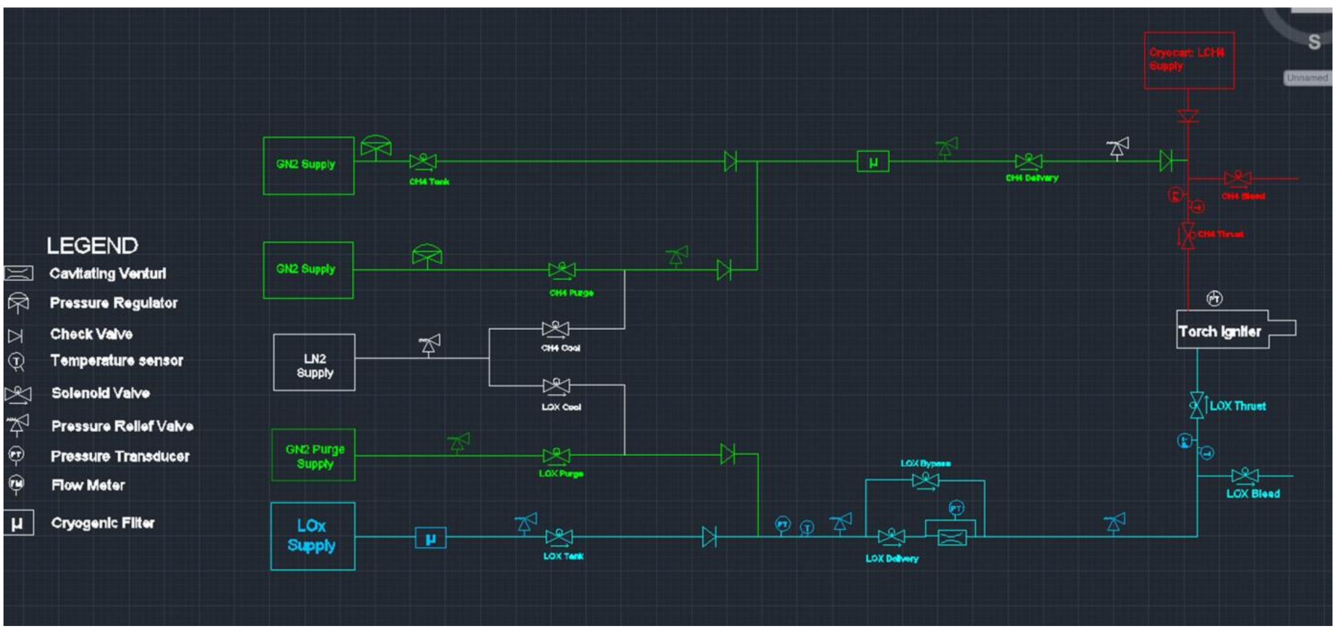

Figure 6 Cryogenic Delivery Lines Schematic

2.1.3 Ambient test stand

The ambient test stand consists of a chamber that contains three visual ports, 16 feed trough ports, a stainless steel plate, and an exhaust system. The dimensions of the chamber are 48in (1.22 meters) in diameter and 5 feet (1.52 meters) long. The feed through ports are used to

grant access to any electrical instrumentation wiring and as well to any propellant delivery hardware. The visual ports are there to provide access for any optical diagnostics, as well as to have cameras recording experiments. The stainless steel plate is ¼ inch thick and contains a grid of screw holes in the fashion of an optical table to allow any type on instruments or test articles to be secured. The exhaust system consists of two 8 inches in diameter galvanized steel ducts that are attached to a duct reducer. This duct reducer is welded to a flange, which is screwed to one end of the ambient test stand. Figure 7 shows the outside of the ambient test stand, and figure 8 shows the exhaust system.

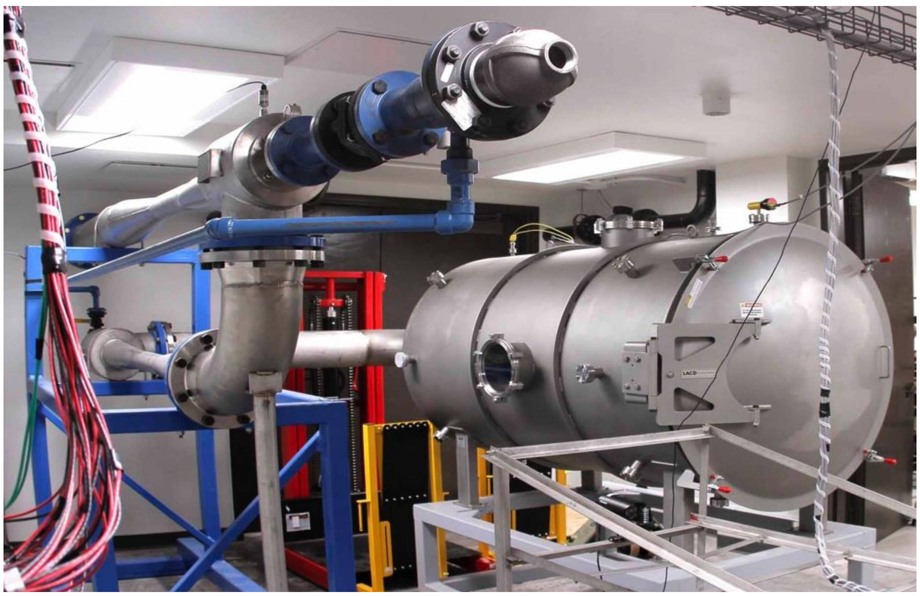

Figure 7 Ambient Test Stand

Figure 8 Exhaust System Attached to
Ambient Test Stand

2.1.4 Mobile Methane-Condensing Unit (MMCU)

The Mobile Methane-Condensing Unit was designed by previous students from the cSETR in order to accommodate testing that required liquid methane. The reason to design and create the condensing unit was due that the quantities that liquid methane can be bought are too big for the laboratory needs. The unit can produce about 15 liters of liquid methane. The unit contains two copper coils, one inside the tank and another one around the tank. The condensing unit is as well wrapped with a cryogenic insulating material to help maintain the low temperature. The way that the unit condenses methane is that the gas introduced at a desired pressure into the tank, and liquid nitrogen is flown through the coil. The liquid nitrogen lowers the temperature of the gas until its condensates inside the tank. The liquid methane is then pressurized to a

Figure 9 Mobile Methane-Condensing Unit

desired value with helium gas. Figure 9 shows a picture of the MMCU.

2.1.5 DARCS – Data Acquisition and Remote Control System

Previous graduate students in the cSETR designed the DARCS system. The intention was to be able to be able to control combustion and propulsion tests remotely for safety issues. The software used for testing is National Instruments LabVIEW, which controls several PCI cards and as well stores the data received from the instrumentation in the main control room computer. Several of the PCI cards control relays which allow current and voltage to flow to the solenoid valves giving the user the power to control the opening/closing of the valves remotely. Other PCI cards read the voltage output giving by the instrumentation which is interpreted in the software by a calibration curve given by the manufacturer to indicate either temperature, Pressure, Volume Flow Rate, etc. All the instrumentations is connected through some Patch Panels, which allow the communication of the instrumentation with the DARCS, figure 10 shows the Patch Panel located inside the bunker.

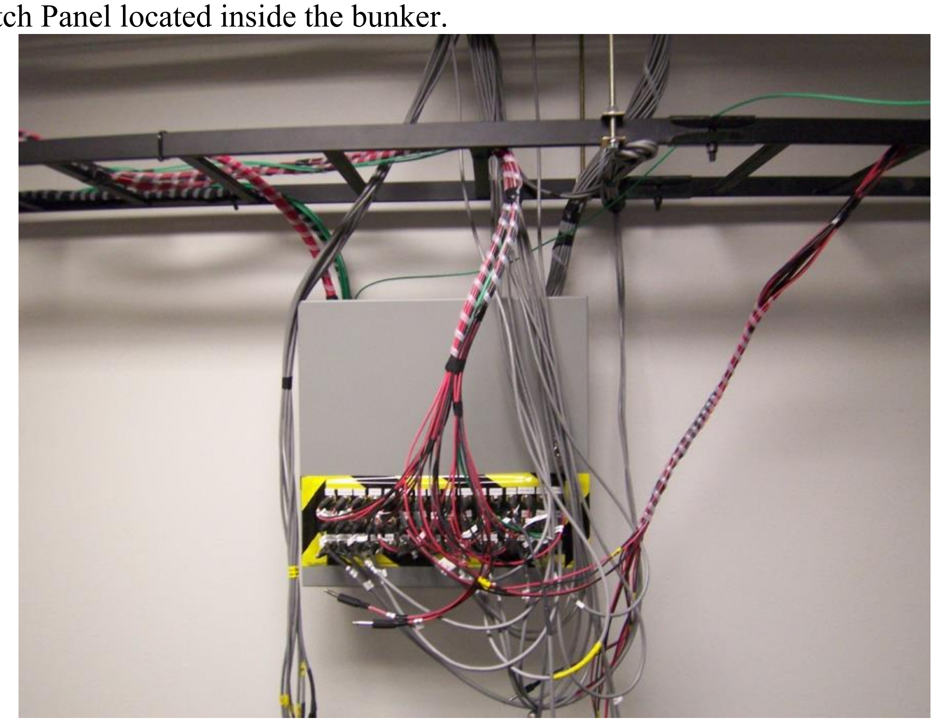

Figure 10 Bunker Patch Panel

Chapter 3

This chapter will provide information of the first two iterations of the swirl torch igniter. The overall purpose of the swirl torch igniter is to be an ignitions source for an optical accessible combustor. This chapter will contain information of the design, testing and data obtained. The following requirements were followed while designing the swirl torch igniter:

- Contain a swirl coaxial injection design, similar to a mN class Thruster previously developed and investigated in the cSETR
- Be able to interface to an optical combustor which contains a port with a female ¼ NPT thread
- Oxygen and Methane as propellants
- Compatible with Liquid Oxygen

3.1 First Swirl Torch Igniter Iteration

The size of the injection ports was based on a swirl number of 0.04 by assuming a mixture ratio of 4. The swirl number is an indicator of the swirl intensity, which is defined as the ratio of the axial flux of the tangential momentum to the product of the axial momentum flux and a characteristic radius [11]. The equation used to calculate the swirl number is the following:

$$S_g = \frac{r_o \pi r_e}{A_t}[\frac{\dot{m_{Tan}}}{\dot{m_{Toral}}}]^2$$

In this equation r_o stands for the distance of the center of the tangential inlets to the center of the axial flow, r_e is the radius of the exit of the tangential flow, $\dot{m_{Tan}}$ is the mass flow rate of the tangential flow (methane flow) and $\dot{m_{Toral}}$ is the total mass flow rate of both the tangential flow and the axial flow.

3.1.1 Hardware

The first iteration of the swirl torch igniter was designed with two separate manifolds, one for oxygen and the other for methane. The manifolds were made out of a stainless steel 304 blocks and were united through some NPT to Swagelok fittings and Swagelok tubing. The

Oxygen injection diameter was selected to be of 0.185 inches while the methane injection point's diameter was of 0.0625 inches. Figure 11 and Figure 12 show the CAD models, and Figure 13 shows a picture of the complete hardware.

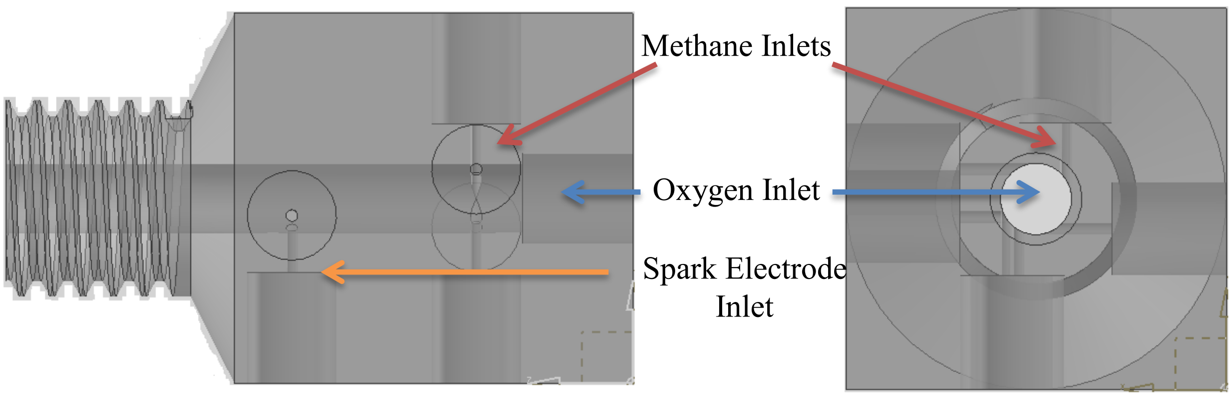

Figure 11 Oxygen Manifold

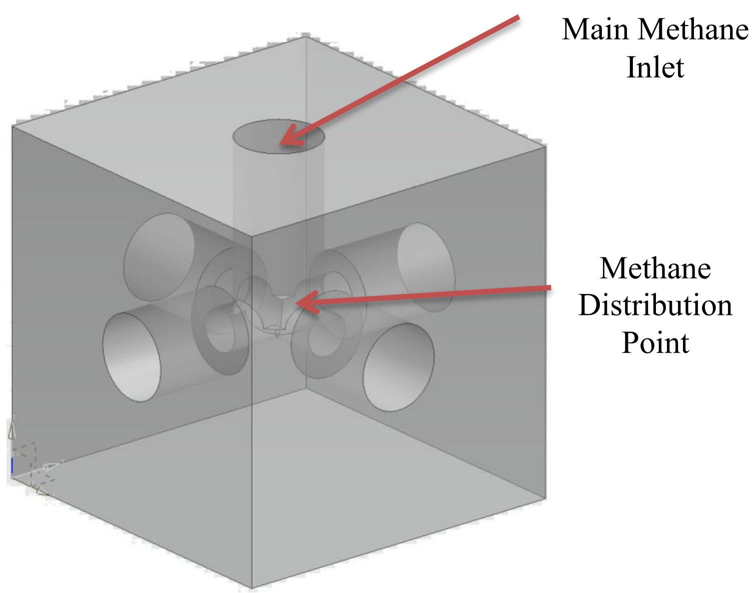

Figure 12 Methane Manifold

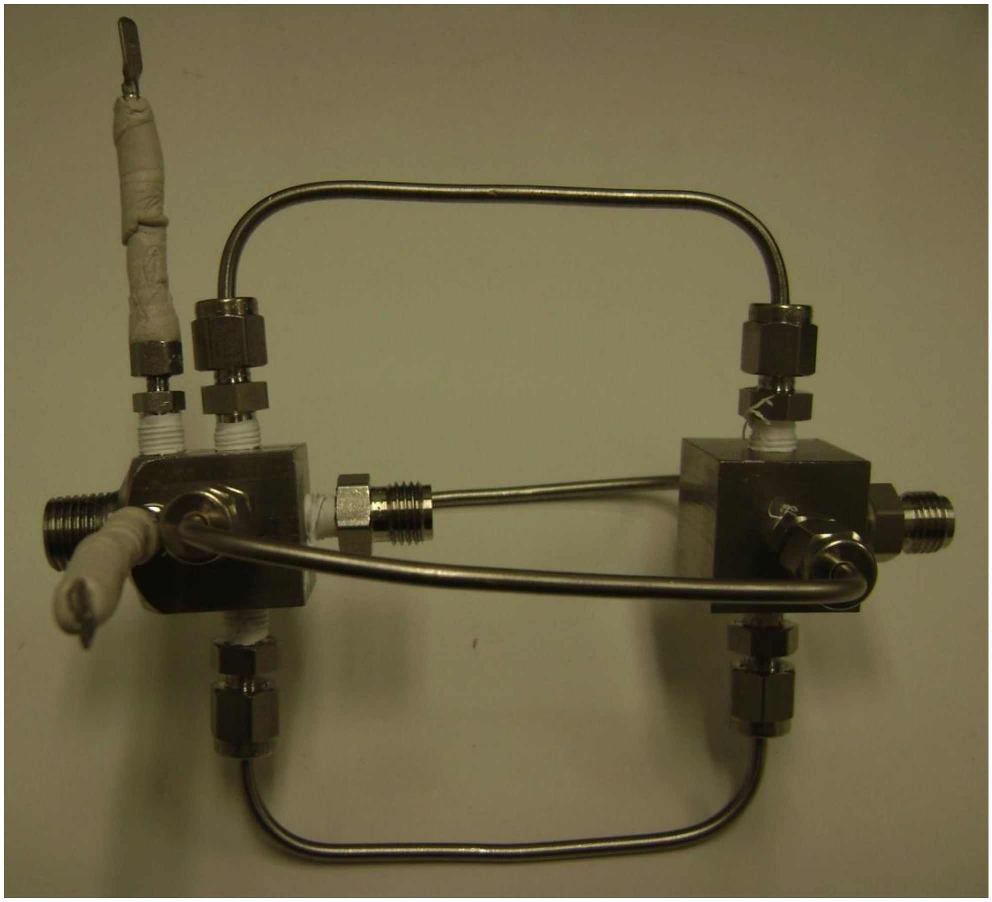

Figure 13 First Iteration of Swirl Torch Igniter

3.1.2 Sparking System

The sparking system has gone through several iterations due to problems undergone while testing. The original sparking system contained two 90%platinum and 10% rhodium wire that were placed inside a fitting that went from a 1/16 Swagelok tube fitting to a 1/16 NPT male fitting. These were placed to tangentially and to a certain distance as seen in Figure 13, the gap between the wires created a spark when voltage was given to each lead. The problem with this iteration was that after several tests done the wires integrity was compromised and it would stop sparking. Figure 14 shows the layout of the original sparing system.

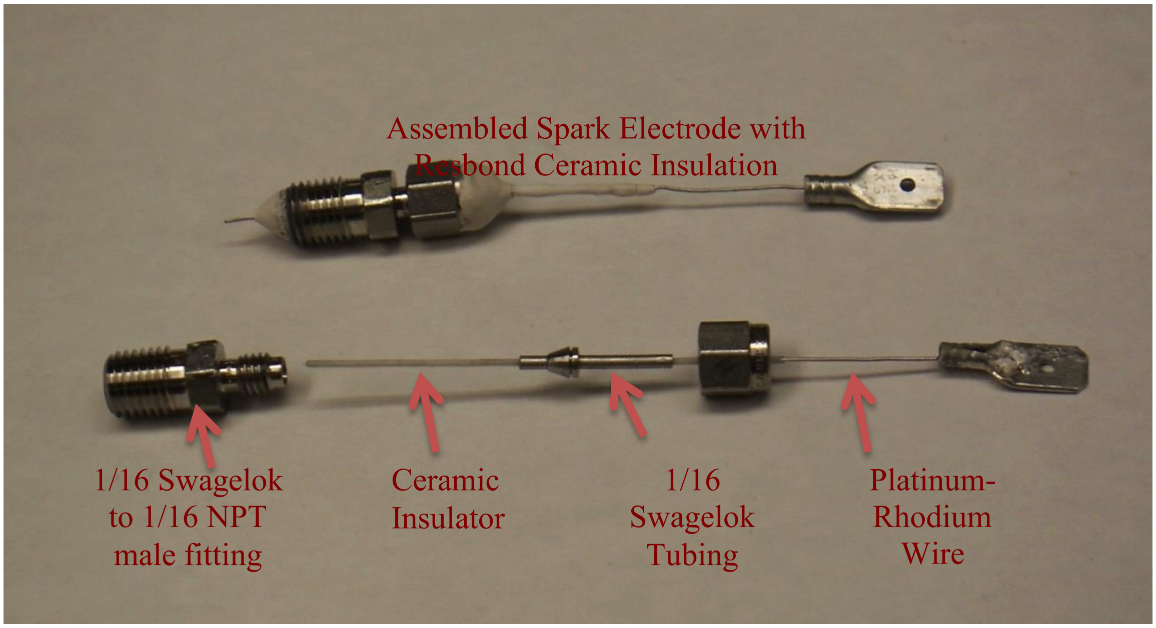

Figure 14 Original Sparker System

The following iterations used a tungsten lead instead of the Platinum-Rhodium wires. These iterations witch to use only one fitting, and ceramics insulators from Omega Engineering. The first iterations used a ceramic a 1/8 thick Alumina ceramic with two holes. The problem with iteration was that the ceramic would break after a few tests. So a thicker ceramic of 3/16 was bought, which indeed sustained more tests without failing. The following picture shows some of the iterations of the sparker system.

3.2 Data Obtained From First Iteration Of Swirl Torch Igniter

The following data was obtained from and discussed in previous thesis and a dissertation done by students and previous students of the cSETR. The graphs and schematics were taken from mentioned papers [12] [13]. For propellant combinations were tested with this first iteration, which were Gas Oxygen/Gas Methane, Gas Oxygen/ Cold Gas Methane, Liquid Oxygen/Cold Gas Methane, and Liquid Oxygen/Liquid Methane. This last propellant combination could not be tested with this igniter iteration since no ignition could be obtained.

3.2.1 Gas Oxygen/Gas Methane

This was the first propellant combination tested in an atmospheric aluminum test stand. All of the volume flow rate were measure with Omega flow meters which a give an output of volume flow rate which then were converted to mass flow rates. Mixture ratios (MR) between 1 and 8 were tested, which an MR of 4 is stoichiometric. Each point in the following graphs was tested a total of 5 times, in which they called reliable if ignition was obtained 4 out of 5 times. Figure 15 shows a schematic of the hardware used in the testing of the gas/gas propellant combination.

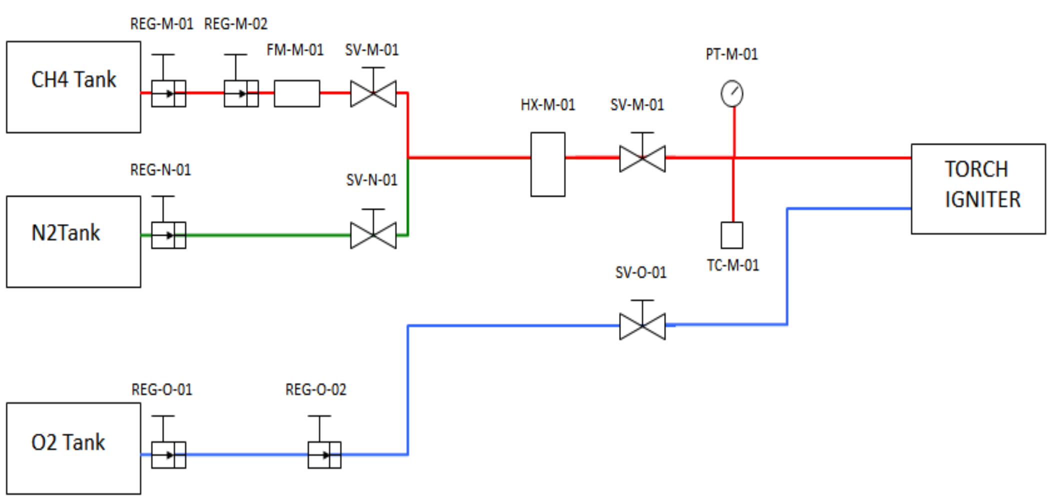

Figure 15 Instrumentation and Line Schematic for Gas/Gas and Gas/Cold Gas

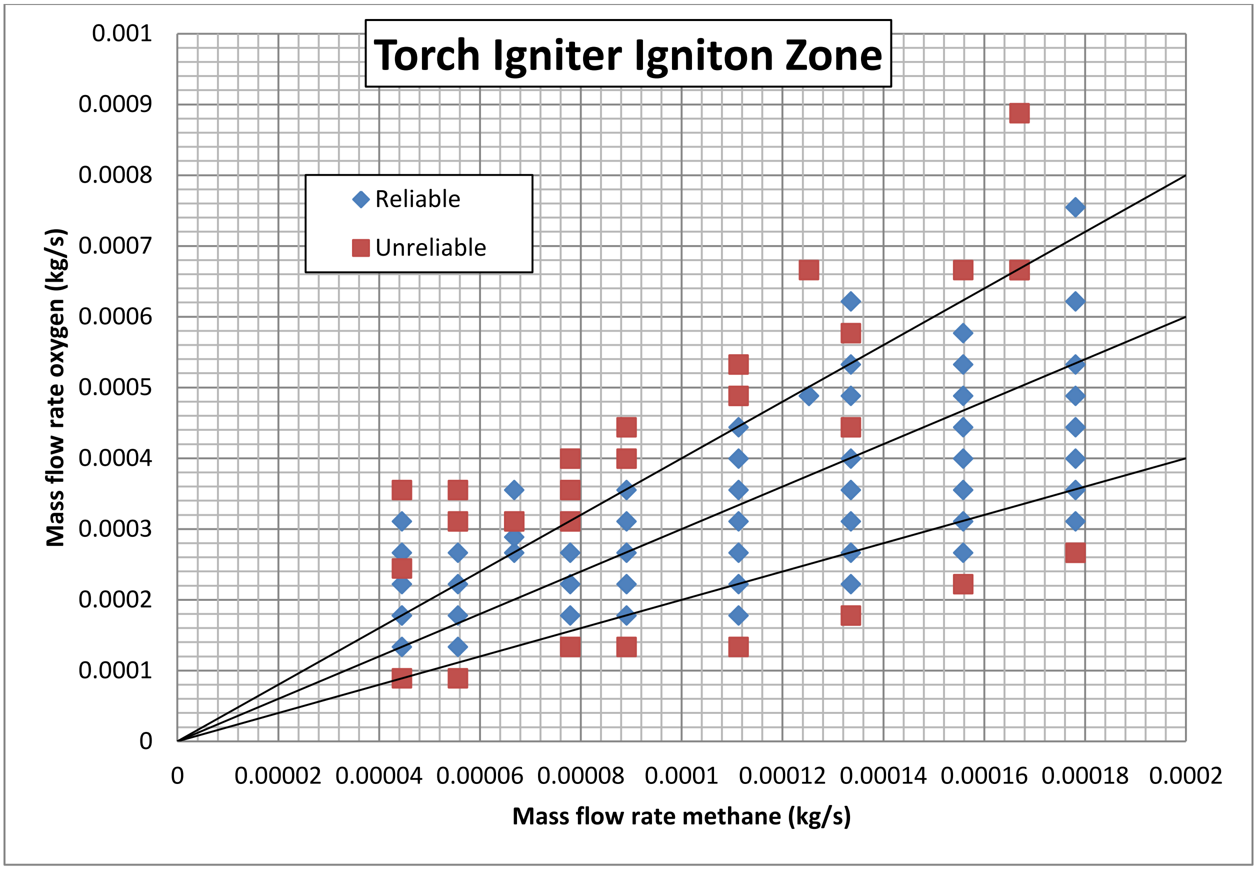

Figure 16 Flammability Map of Gas/Gas

Figure 16 shows the graph of the obtained data of the gas/gas tests. The graph shows the plotting of the mixture ratios and the reliability. The mass flow rate of the methane is plotted in the x-axis and the mass flow rate of the oxygen is plotted in the y-axis, it shows what it was called reliable and unreliable ignition. What is called reliable ignition is that obtained at least 4 ignitions out 5, if it did not achieve this it was called unreliable. The graph shows that most reliable ignitions were obtained in the range of the mixture ratios of 2 and 3. In the range between 2 and 3 most of the pints tested were in a reliable ignition, with only one point been unreliable.

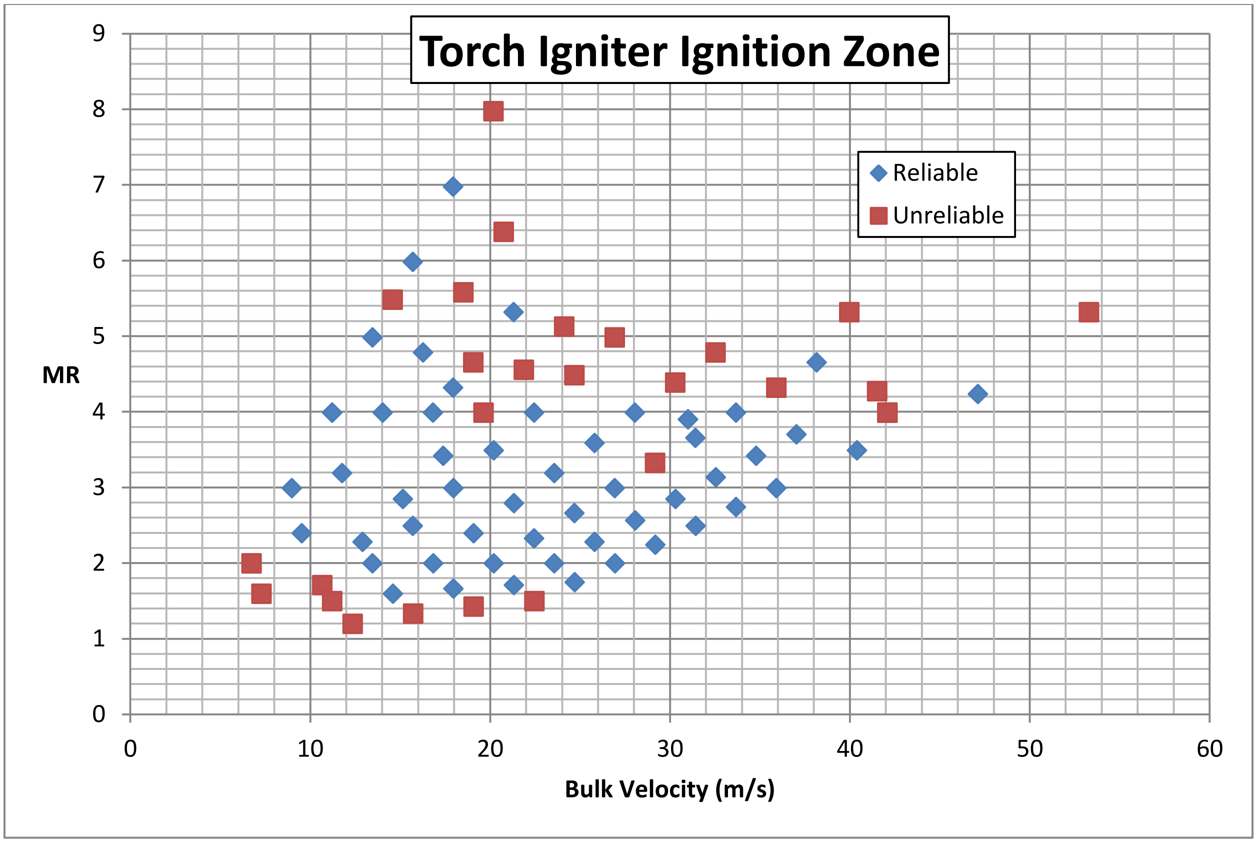

Figure 17 Bulk Velocity vs. MR

Figure 17 shows the graph of the bulk velocity obtained for each obtained compared to their respective MR. This graphs shows that between the MR's of 2 and 3 with reliable ignitions the velocity limit was about 40 m/s. And at higher MR the bulk velocity decreased at which reliable ignitions were achieved.

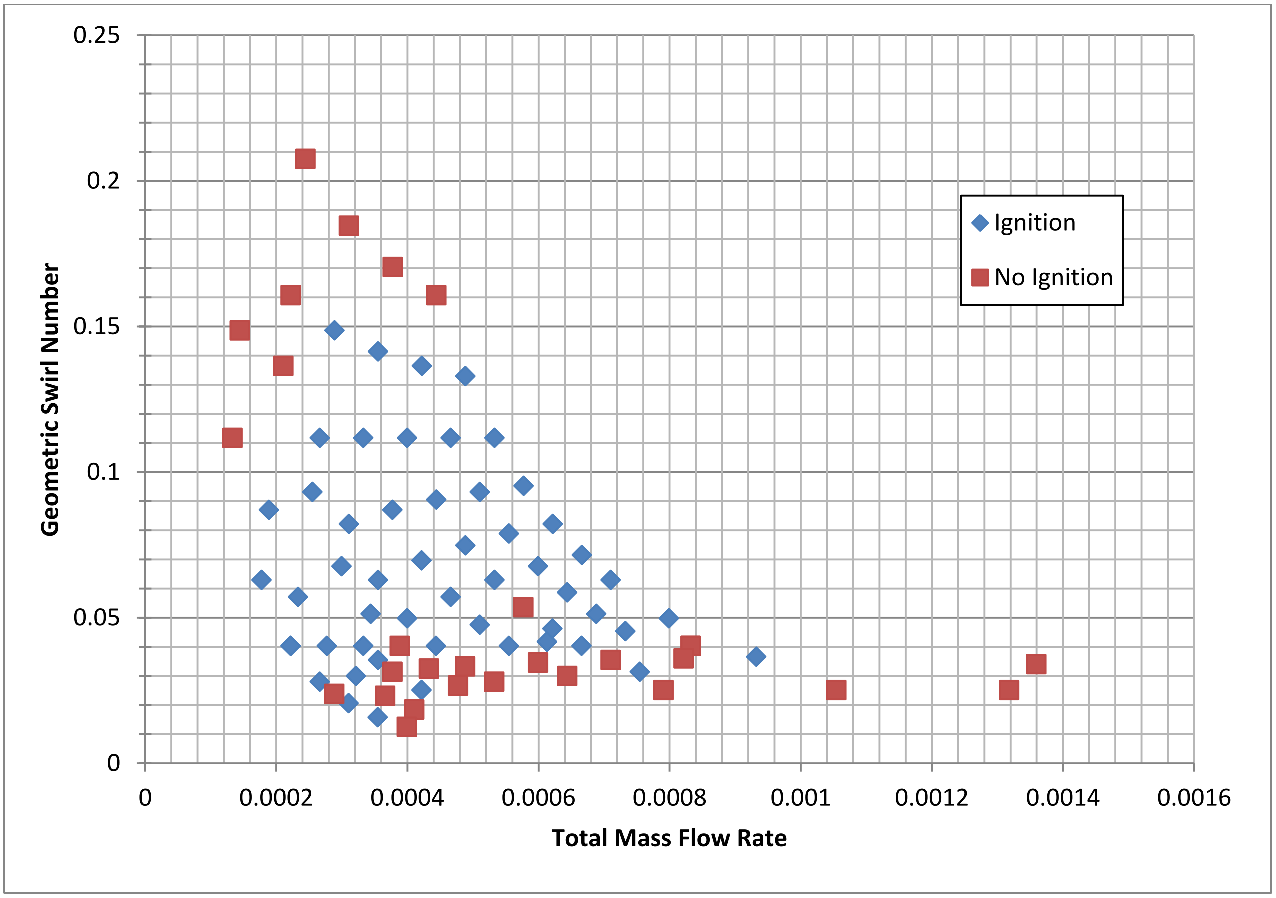

Figure 18 Swirl Number vs. Total Mass Flow

Figure 18 shows the graph that correlates the total mass flow to the geometric swirl number. This graph shows the lower limit of the swirl number being about 0.04. This can be attributed to the propellants not mixing efficiently and producing an ignitable mixture. The upper limit of the geometric swirl number is about 0.15, this can be attributed to the increase in the mass flow as well as the velocities, and the flame speed is much lower that the speed of the propellants and the flame blows out.

3.2.2 Gas Oxygen/Cold Gas Methane

These set of tests were produce in a similar manner to the gas/gas test, even using the same test set up seeing in Figure 15. The only difference in the set up was the addition of a heat exchanger, made of stainless steel ¼ inch tubing submerged in a bath of liquid nitrogen that van

be seen in Figure 19. This method produced temperatures in the range of 190 to 275 Kelvin. Using this method the temperatures were hard to predict and kept constant, but was a good method to predict how temperature affects ignition.

Figure 19 Coil Heat Exchanger

Figure 20 shows the flammability map obtained from these set of tests. The trend in this graph is similar seen in the gas/gas test but instead in this test the most reliable ignitions were obtained in leaner range of mixture ratios. These graph shows as in previous graphs for the different mixture ratios, as in the previous graphs. The reason for this more chaotic graph comes from the difficulty in control the flow rates in the methane side. In the gas methane flow rates the pressure was controlled by just setting a pressure in the tank regulator, while in the cold gas methane each time a different temperature was obtained. This difference in temperature gave different densities and therefore a different mass flow rate, make it harder to predict and control.

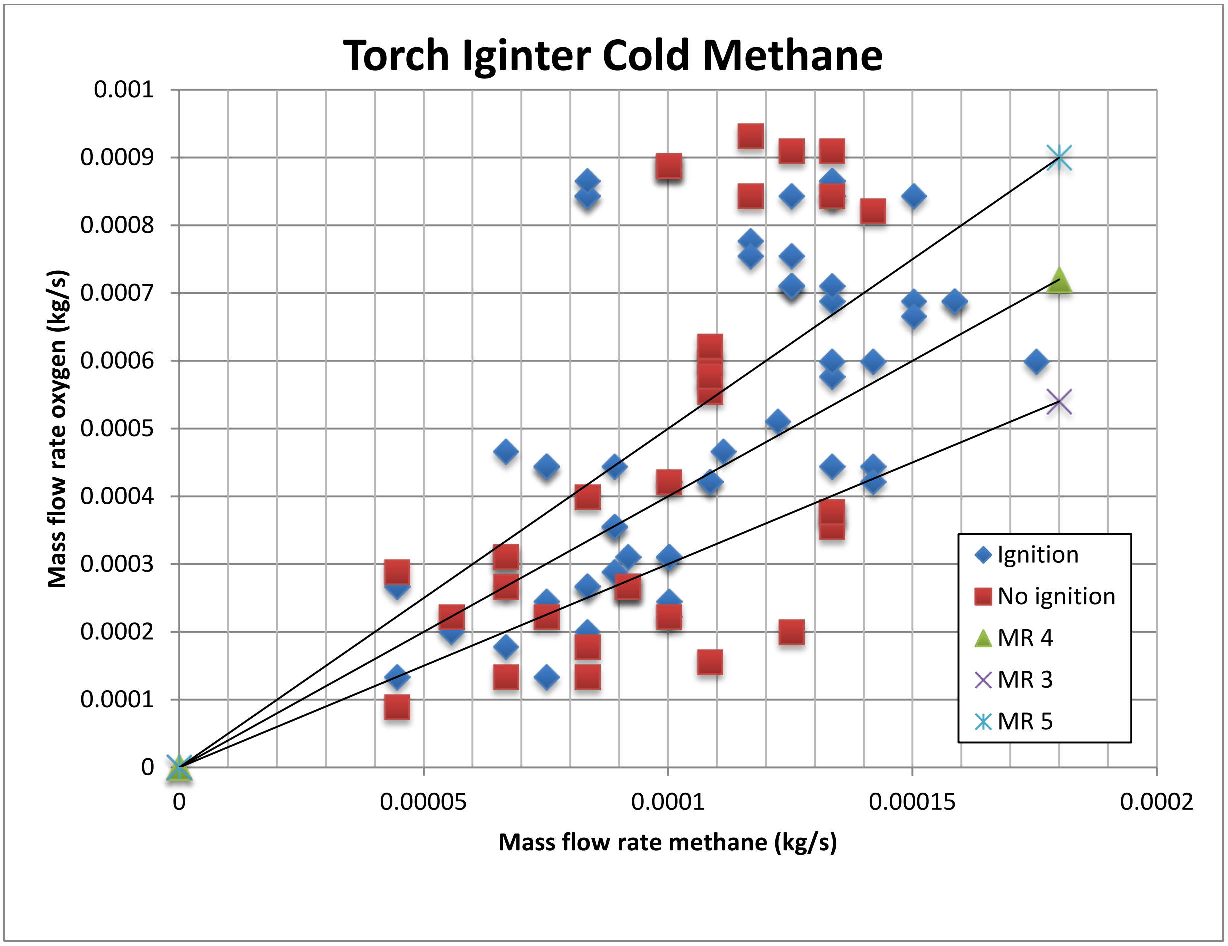

Figure 20 Flammability Map gas/cold gas

Figure 21 shows another graph of the flammability map of the gas/ cold gas testing. The graphs shows the mass flow rate of the methane that were set prior to ignition, and are not the actual mass flows obtained during testing. As before what was called reliable ignition from these tests is 4 out of 5 ignitions, the data points called unreliable seen between the mixture ratios of 2 of 4 did ignite but not meet the requirements.

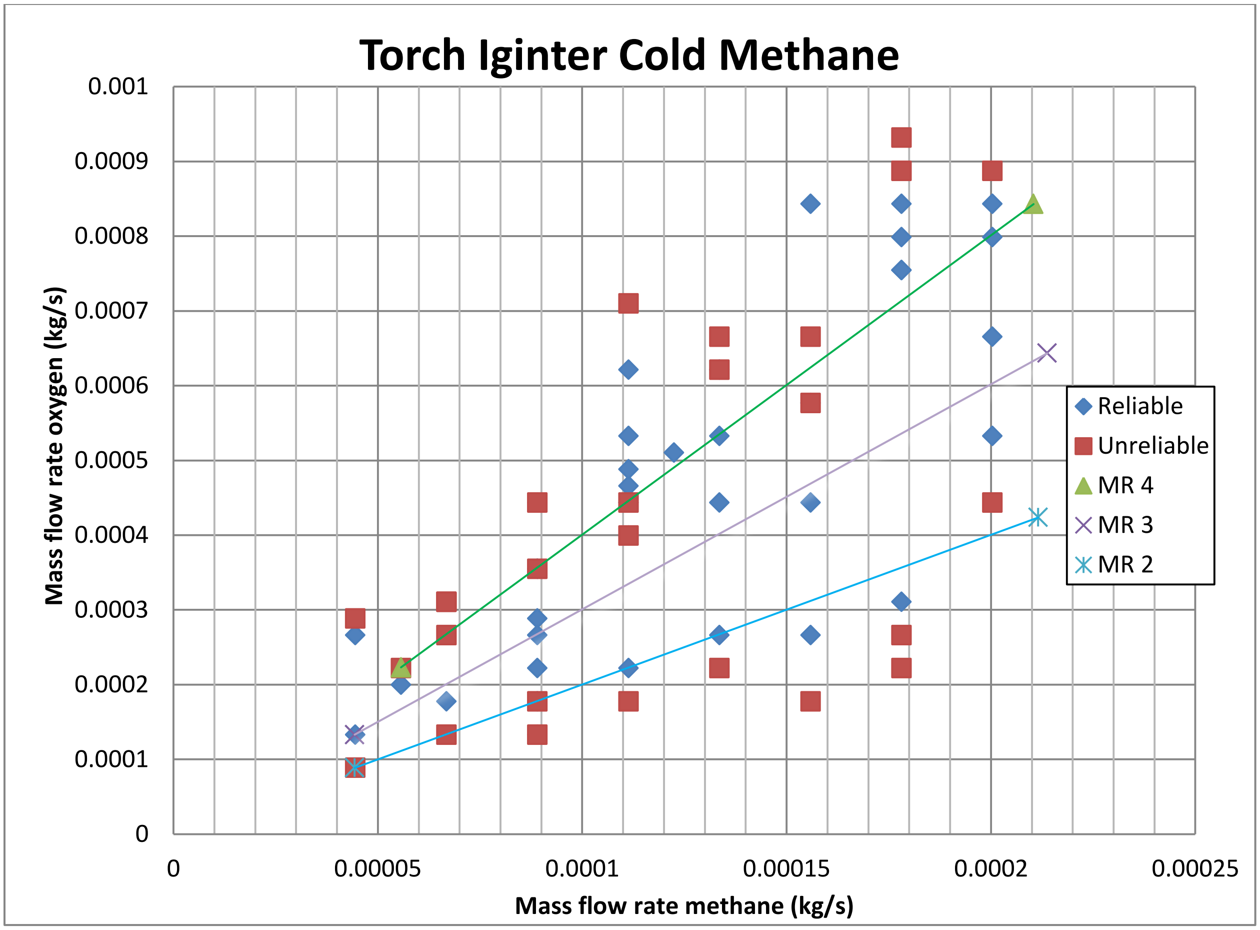

Figure 21 Flammability Maps with set CH4 flows prior to Ignition

3.2.3 Liquid Oxygen/ Cold Gas Methane

Several problems arose from testing this combination of state of the propellants, especially in getting a set Mixture Ratio. The liquid oxygen has a really high density compared to the cold gas methane. The problem was obtaining a really high mass flow rate from the gaseous methane and a low mass flow rate of the liquid oxygen to obtain mixture ratios around the stoichiometric mixture ratio. Because of these restrains a very small range of tests were completed. This is also a reason that the graph provided in Figure 22 should not be considered very accurate. Another method has been developed in the laboratory to control the mass flow of the liquid propellants more efficiently and will be described later.

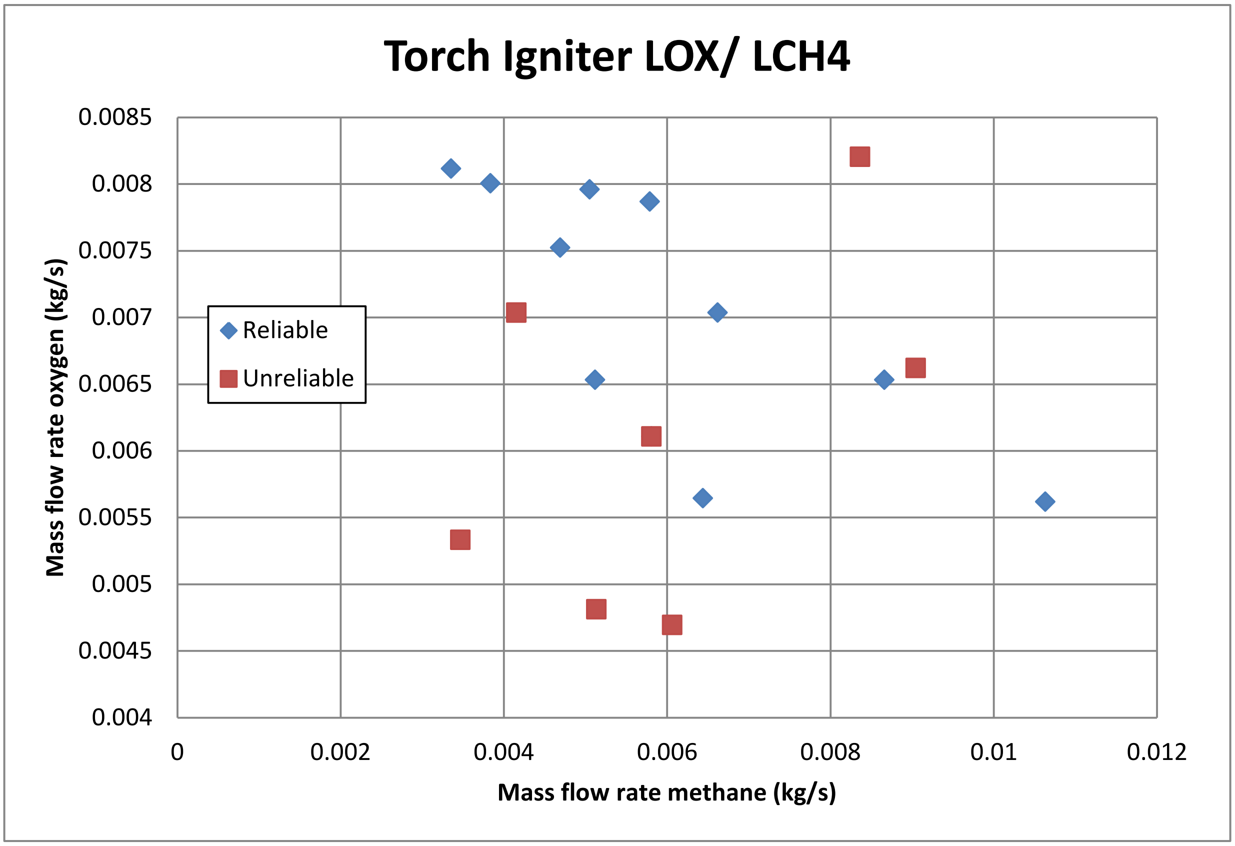

Figure 22 Flammability Map of LOX/Cold gas CH4

3.3 Second Iteration of Swirl Torch Igniter

The design of the second generation of the swirl torch igniter was done in order to try to improve in the ignition of liquid propellants. The main modification done to the second generation of the swirl torch igniter was having a unified body, a converging section, modification to the sparking system, addition of a pressure port, and some modifications in the injections distances.

3.3.1 Unified Body and Injection Distances

The past iteration contained to separate manifolds for the oxygen and the methane. In this iteration the manifold was put into a single body, given it better aesthetics, more compact, and giving a lower probability of leaking. The tubing instead of being on Swagelok fittings was

instead laser-welded to the body, thus eliminating the threaded fittings for the tubing. The interface between the delivery lines and the igniter were a 1/8 NPT thread. The injection distance between the oxygen and the methane was changed from ¼ to a 1 inch; this is the distance from where the oxygen enters the swirl torch igniter and meets the tangential inlets of the methane. Figure 23 shows the Cad model and the drawing of the second iteration of the swirl torch igniter.

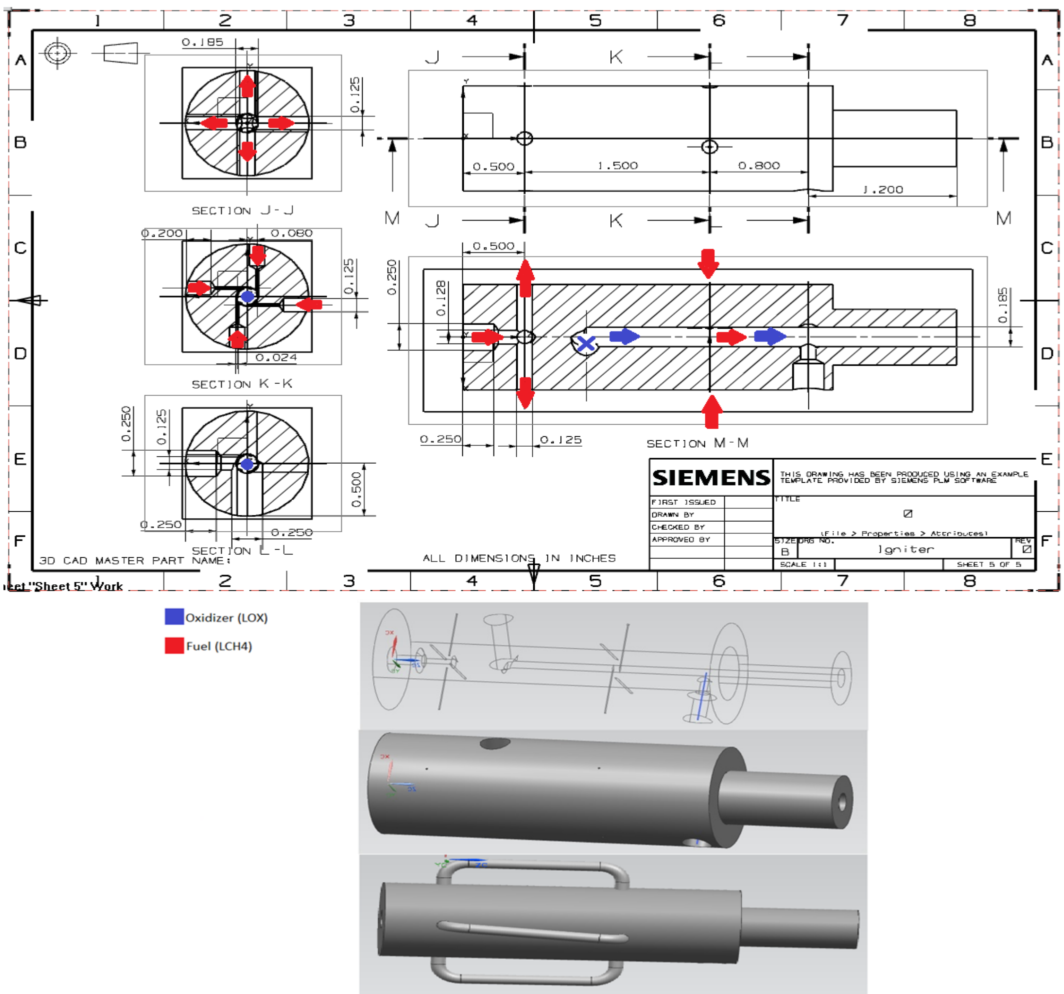

Figure 23 CAD model and Drawing of Second Generation

3.3.2 Sparking System

The diameters of both the fitting and the ceramics were increased to provide better electrical insulation and decreased the stress experienced. The ceramic was modified to have

two diameters to prevent a blow out in case of an overpressure in the igniter, the bottom part having a larger diameter. A tungsten lead was still used for this sparking system. Figure 24 shows a CAD model of the sparking system.

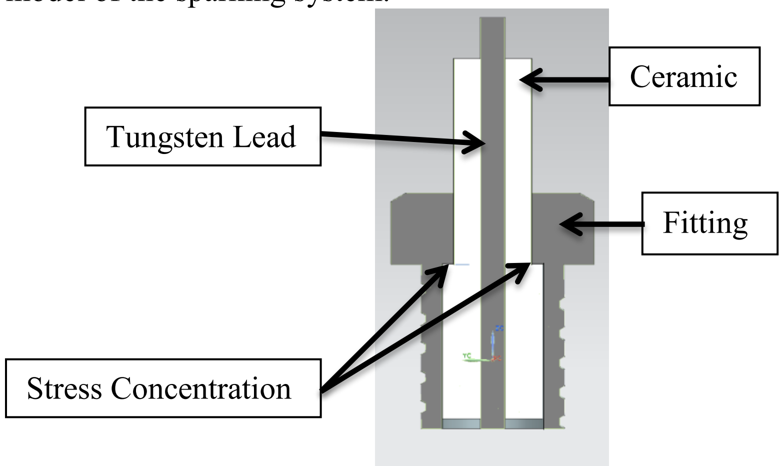

Figure 24 Cross-Section of Sparker

3.3.3 Converging Section

The converging section was added to increase the chamber pressure inside the igniter. According to the NASA Glenn papers discussed in the Literature Review Section increasing the chamber pressure with a converging section improves the combustion inside the igniter. The section took the diameter from 0.185 inches down to 0.145, a contraction ratio of 1.2 and a standard angle of 15 degrees. The drawing of the converging section is shown in Figure 25.

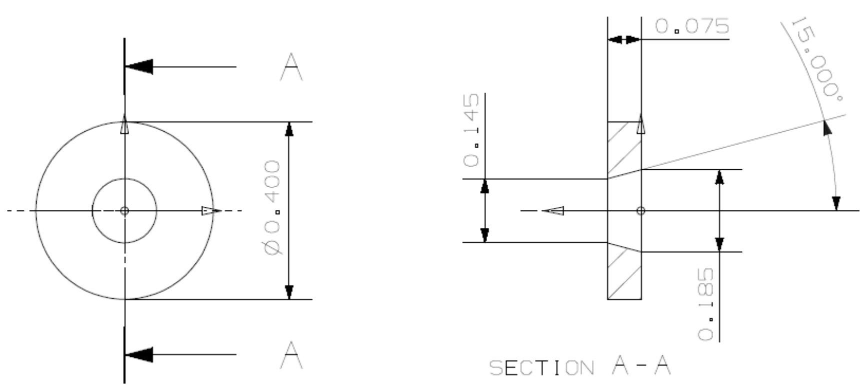

Figure 25 Drawing of Converging Section

3.3.4 Pressure Port

A pressure port was added to this iteration of the swirl torch igniter to be able to monitor the chamber pressure during combustion. The first pressure port was done through a 1/8 NPT thread, in which a 1/8 inch NTP male to a ¼ Swagelok tube fitting served as the interface for the pressure transducer. This was later changed to a 1/8-inch hole in which stainless steel tubing was laser-welded to the test article. Figure 26 shows a CAD model of the swirl torch igniter where the first pressure port can be seen along with the converging section and

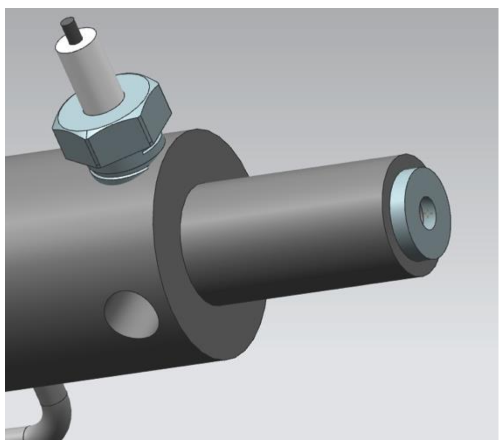

Figure 26 Pressure Port, Converging section and Sparker

3.4 Test Set-up For Second Iteration Torch Igniter

The first propellant combination with this iteration of the swirl torch igniter was LOX/LCH4. To support this propellant combination the Cryogenic Delivery Lines and the MMCU were utilized, and the test article was place inside the Ambient Test Stand. The method for controlling the mass flow rate of both propellants will be mention in the next sections.

3.4.1 Propellant Flow Measurement

To the limit the mass flow rate of the propellants cavitating venturis were installed in the Cryogenic Delivery Lines and in the MMCU, each with different design dimensions. At a given inlet pressure the cavitating venturi will limit the mass flow to a maximum due to reaching the vapor pressure at the throat, provided that downstream pressure is maintained below the critical pressure ratio (Pcr = 0.68Pinlet). The pressure was monitored upstream and downstream of the cavitating venturis to ensure that critical pressure ratio was maintained. The following formula was used to calculate the mass flow rate obtained with the use of the cavitating venturis.

$$\dot{m} = C_d A_{th} \sqrt{2\rho(P_1 - P_{th})}$$

P1 in this formula stands for the pressure inlet at the venturi, Pth is cavitating pressure at the throat, ρ is the propellant density taken with the inlet temperature, and Cd is the coefficient of discharge. The coefficient of discharge is taken from a calibration curve that was made from testing; this is shown in Figure 27. Figure 28 shows the CAD model and drawing of the cavitating venturi placed in the LOX delivery line.

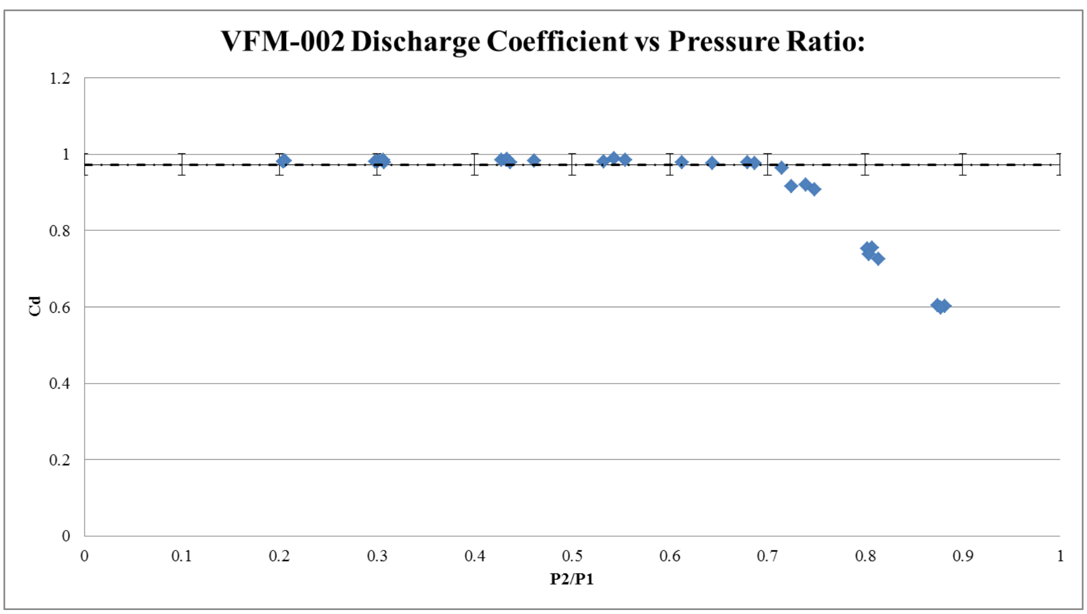

Figure 27 Discharge of Coefficient curve

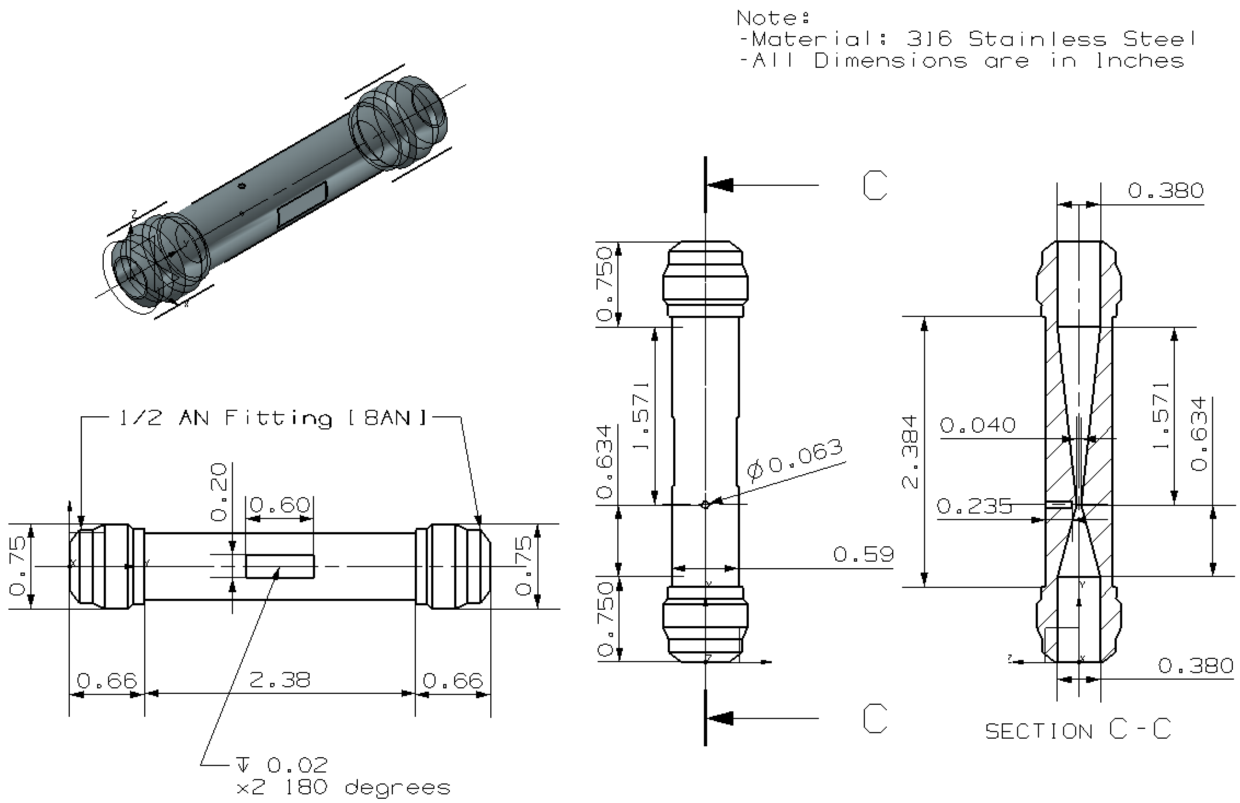

Figure 28 Cavitating Venturi placed on LOX delivery line

3.4.2 List of Instrumentation

The flowing table shows all the instrumentation used in the cryogenic delivery lines as well as in the MMCU.

Table 1 List of Instrumentation

Comp. Type	*Component Name*	*Functional Description*	*Manu-Facture*	*Model*
MEASURE	*Cryogenic Pressure Transducer*	*Measure the pressure of cryogens*	*Omega*	*PX1005*
MEASURE	*Thermocouple*	*Measure the temperature of fluids*	*Omega*	*E-Type*
MEASURE	*Thermocouple*	*Measure temperature of the surface of the Igniter chamber*	*Omega*	*K-Type*

REGULATE	Nitrogen Tank Regulator	Regulate the pressure from the source gas tank		
REGULATE	Methane Tank Regulator	Regulate the pressure from the source gas tank		
REGULATE	Helium Tank Regulator	Regulate the pressure from the source gas tank		
VALVE	Solenoid Valve	Control fluids flow in the delivery lines	Gems Sensors & Controls	D2064-LN2-C203
VALVE	Solenoid Valve	Control fluid flow in the delivery Lines	Jefferson	YC1390BT4UCT-0
VALVE	Pressure Relief	Release pressure in lines if pressure goes above 220 psi	Generant	CRV-500B-K-220
Filter	Cryogenic Filter	Filter particles in Oxygen delivery line	Norman	4375TG-40VM
Valve	Cryogenic Check Valve	Allow the flow of fluids in one direction only	Ratterman	CCV-F12

3.4.3 System Fluid Schematic

Figure 6 shows the Cryogenic Delivery Lines Schematic, back in Chapter 2. Figure 29 shows the schematic for the MMCU and Figure 30 shows the schematic of the instrumentation place inside the Ambient Test Stand.

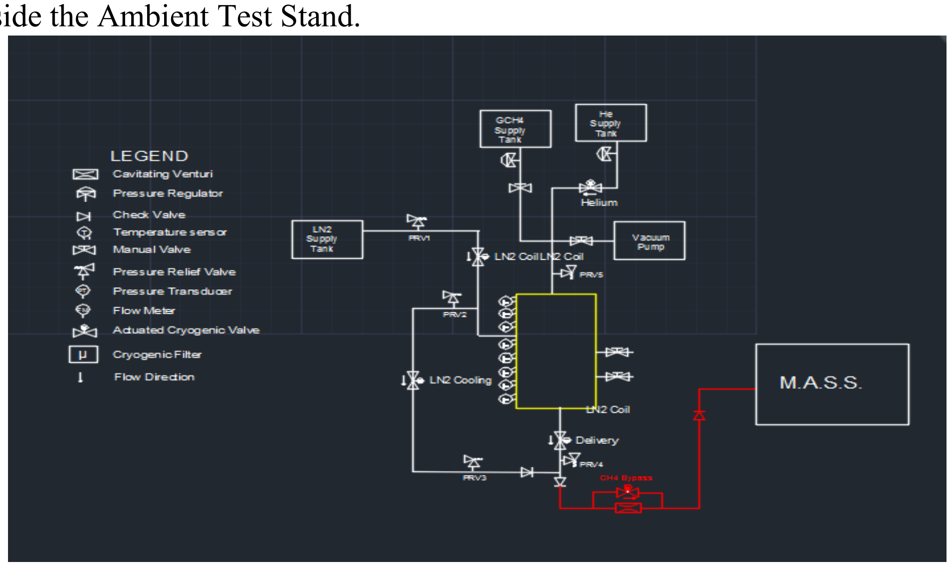

Figure 29 MMCU schematic

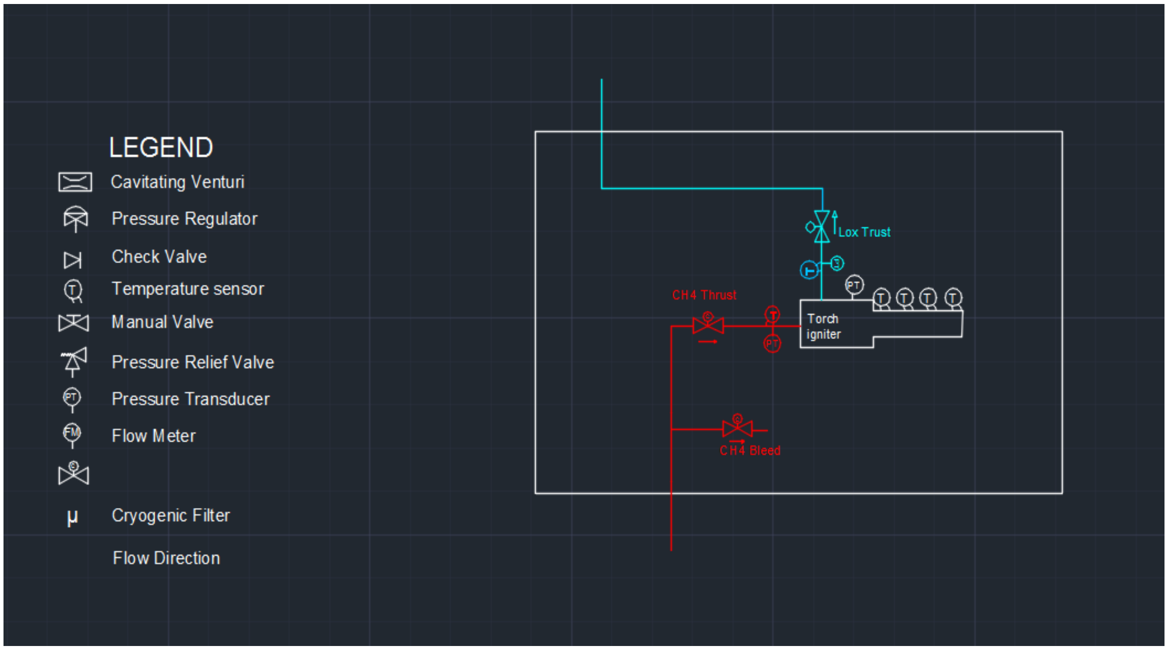

Figure 30 ATS schematic

3.5 Liquid Oxygen/Liquid Methane Data

This section will include the few data obtained and tests done with both liquid propellants. A previous student of the cSETR conducted the first test described. The tests that were conducted after were a continuation of the work that was initiated by the student. The reasons for the test failures will be described over the next sections.

3.5.1 First Stage of Testing

During the first stage of testing the swirl torch igniter was damaged. The damage was irreparable and was caused by an error in the control system. The goal duration of the flame was set to be 5 seconds, but a freezing of the LabVIEW program caused for the flame duration to be longer until the manual shut-off button was hit. The nozzle section and part of the chamber melted during this stage of testing. There was only 4 seconds of data acquired by DAQ system before the program froze. The following Figure are images taken from the video acquired during testing.

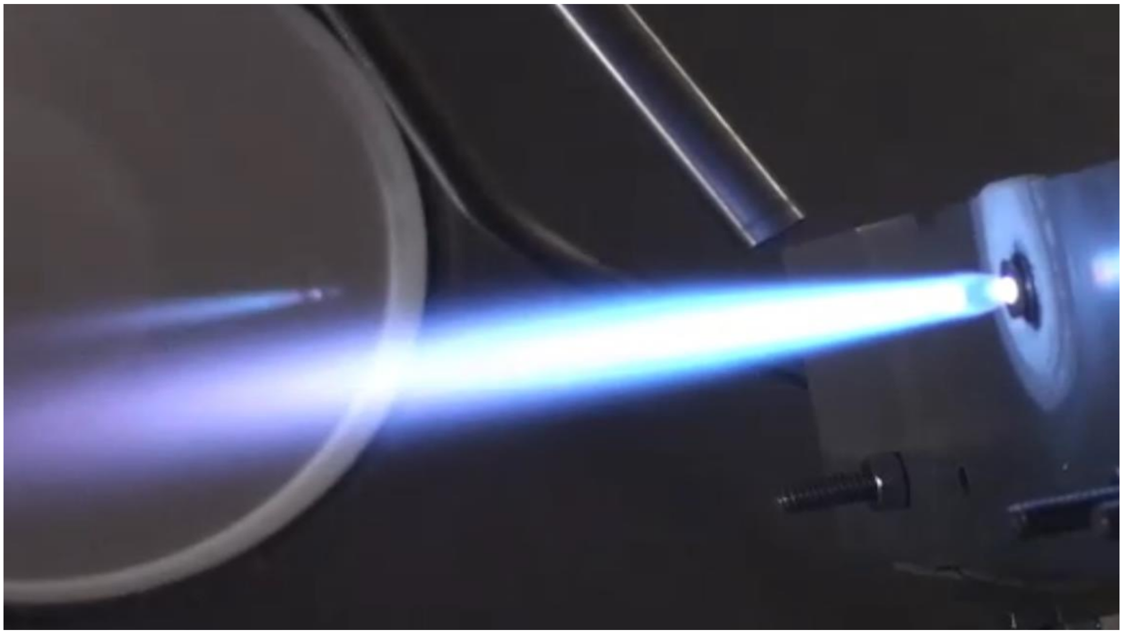

Figure 31 Achieved Ignition of liquid propellants.

Figure 32 Melting of Swirl Torch Igniter

The goal mixture ratio set for this test was of 4.0. During ignition the mass flow rate of liquid methane drop and led to a mixture ratio of about 5.0. This drop in the mass flow of methane was due a drop in pressure in the methane tank pressure. Figure 44 and 45 show data obtained during the test. It can be seen that the temperature of liquid methane remained constant while the temperature in the oxygen side increased by a factor of about 10 degrees Kelvin. Form the

graphs of the mass flows the point where ignition was achieved it can be seen how the mass flow of the methane drop while the liquid oxygen mass flow remained pretty much constant.

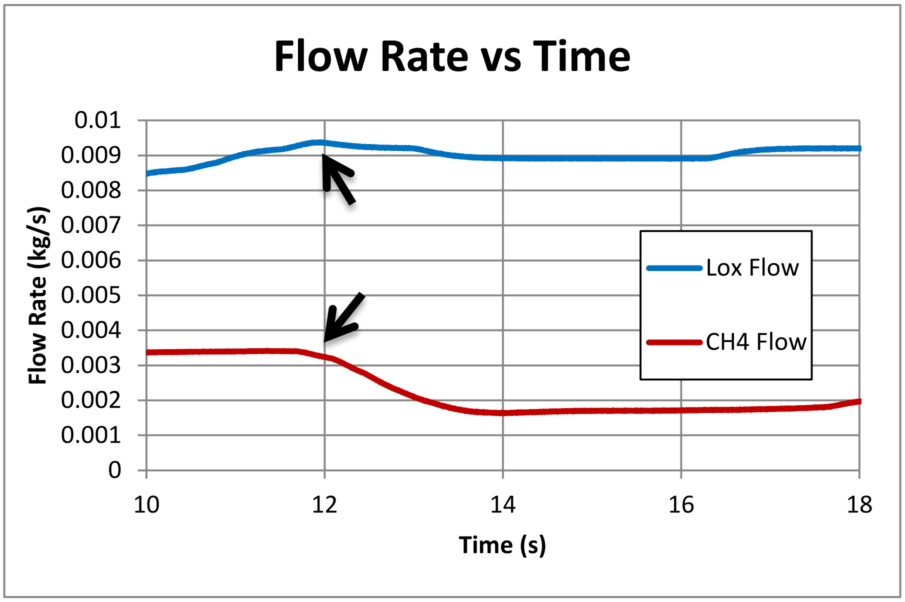

Figure 33 Mass Flow during testing

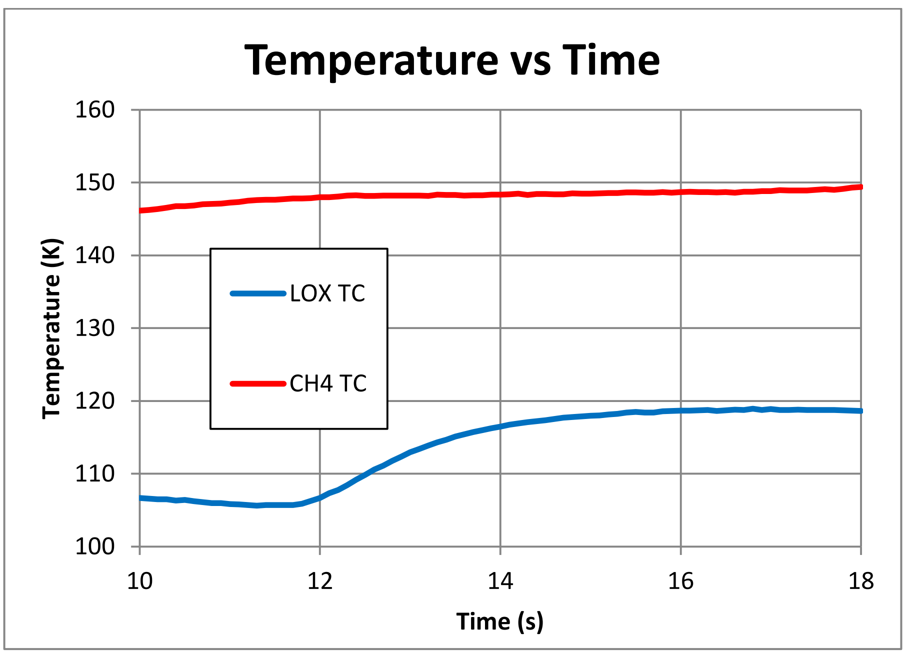

Figure 34 Temperature of propellants during testing

3.5.2 Second Phase of Testing

Another swirl torch igniter with the same design features and pressure port was built for this phase of testing. The same automatic test sequence was used from the previous test. The goal of this automatic test sequence was to have flame duration of 5 seconds. The test sequence is written in a text file which is read and interpreted by LabVIEW software into the commands. These commands are to specific channels in the relays, which close the relay channel and allow the voltage to flow to its specific destination, which opens and closes solenoid valves and give the sparker power. Two tests were conducted during this phase of testing in which during the second test a failure happened and this time the nozzle section melted. Figure 35 shows the initial ignition of the first test, it shows part of the blue flame and as well as a red color in the flame which indicates being a hardware rich flame. Figure 36 show a blue flame, which what was expected to see, Figure 37 shows a very hardware rich flame. What was concluded from these images was that parts of the rough edges inside the torch igniter as well as the tungsten tip of the sparker were being melted.

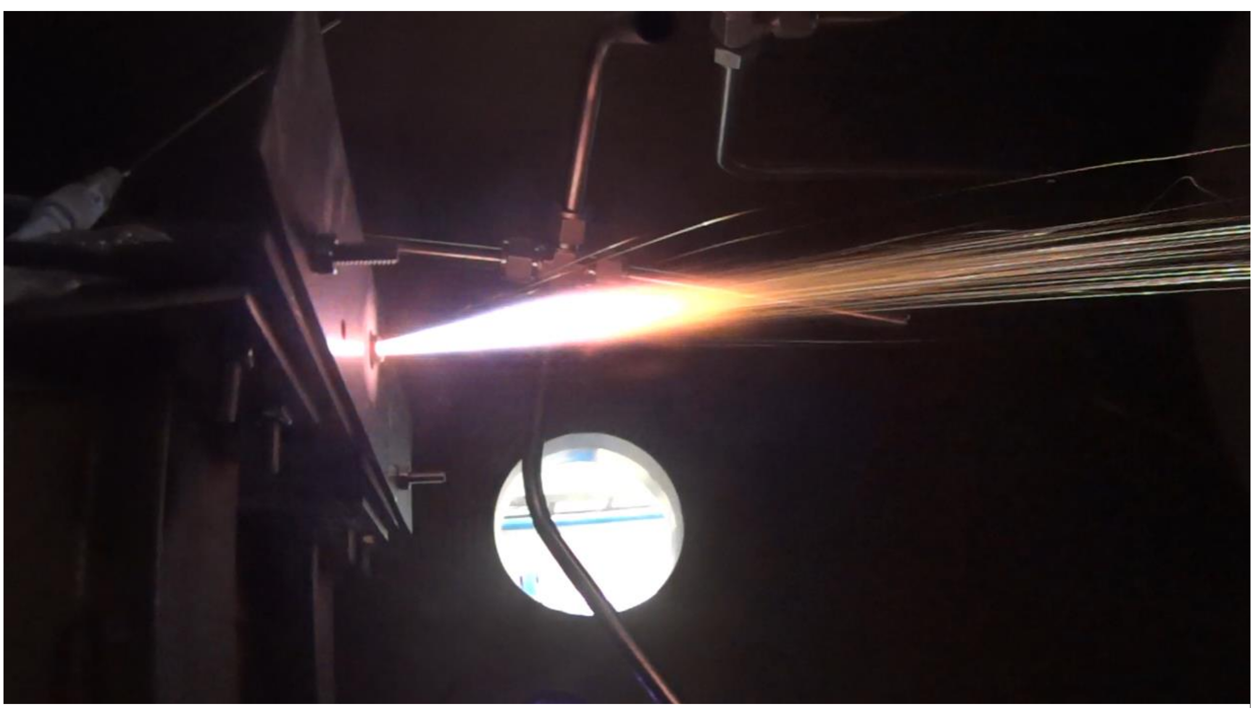

Figure 35 Initial Ignition of First Test of Second Phase

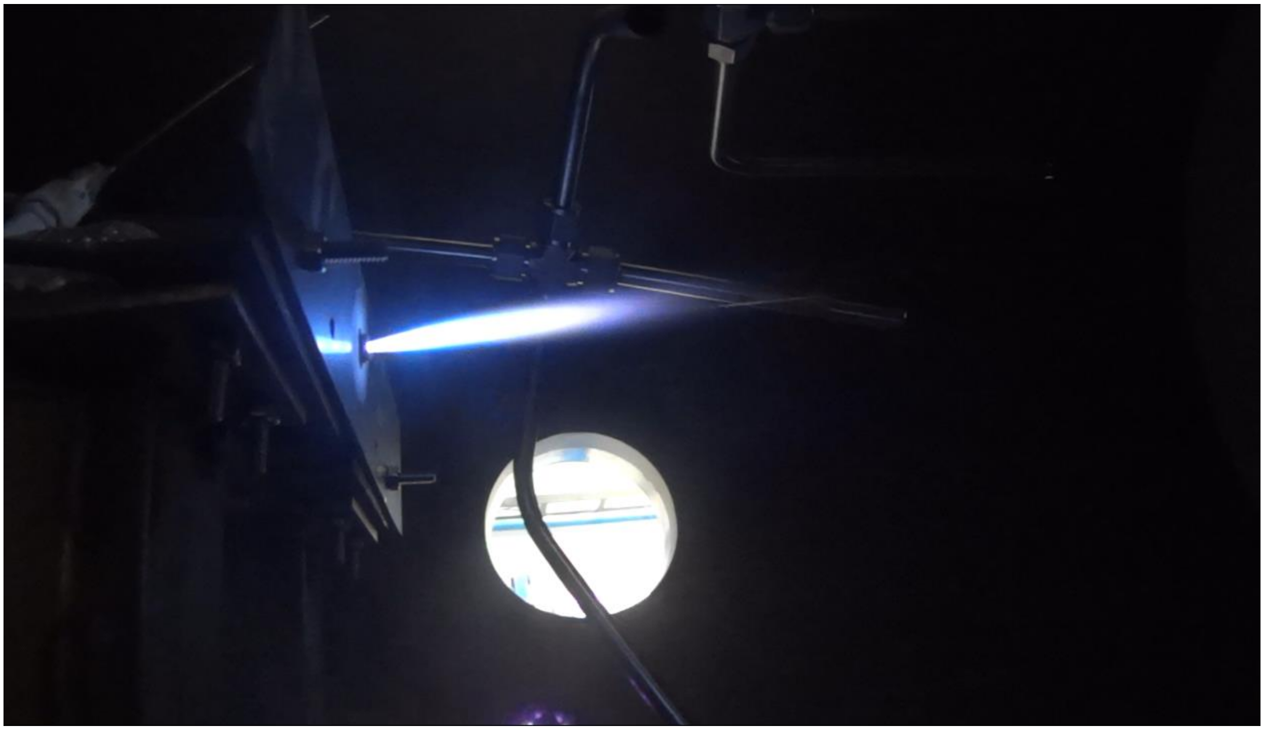

Figure 37 Blue Flame

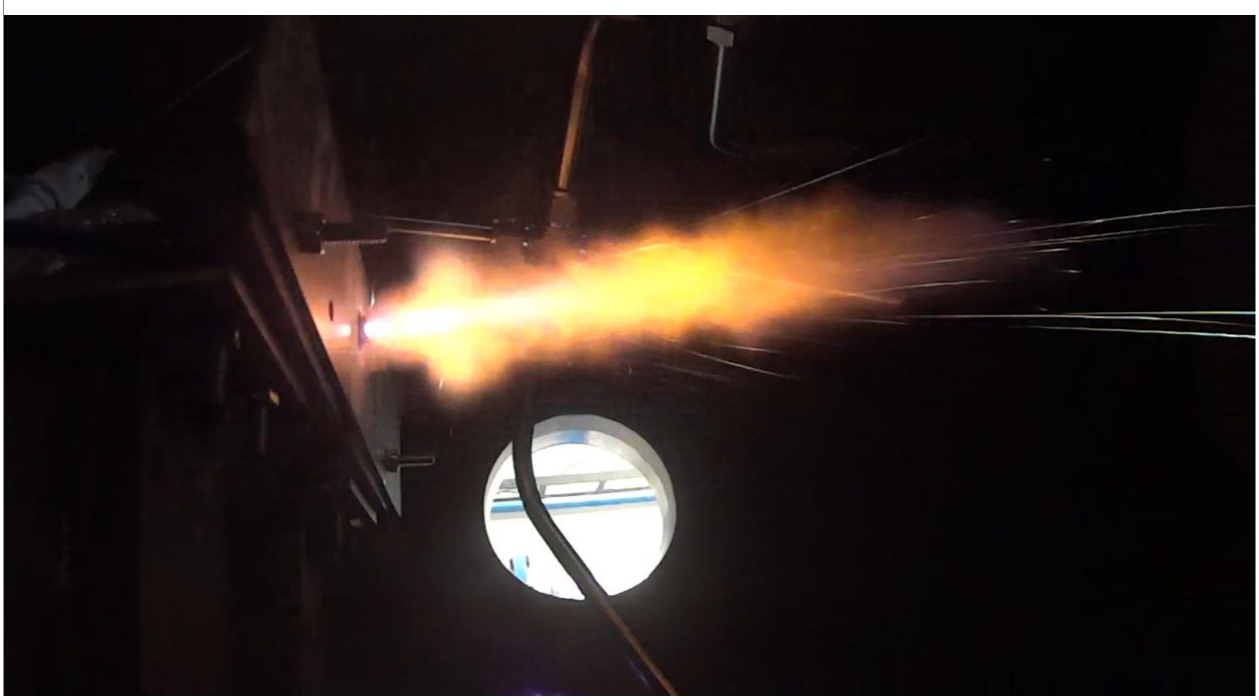

Figure 36 Hardware Rich Flame from First Test of Second Phase

The next couple of figures show the images of the second test, in which the throat of the nozzle section melted. Figure 39 show the moment when the throat was being melted by the flame, particles can be seen being expelled out of the igniter. Figure 38 shows when a small flame and the throat section of the swirl torch igniter in a red hot color. Both tests were run at the same mass flow rates and inlet conditions. The difference between the tests was that for the second test there was not as much cooling done to the system, and for the second test a malfunction in the testing sequence caused LabVIEW software to freeze. When the software froze it left the valves opened, causing the flame as well to last longer. The power had to be stop with the manual shut off button so the solenoids valve would close and the propellant stopped flowing. Figure 40 shows the picture of the melted throat section.

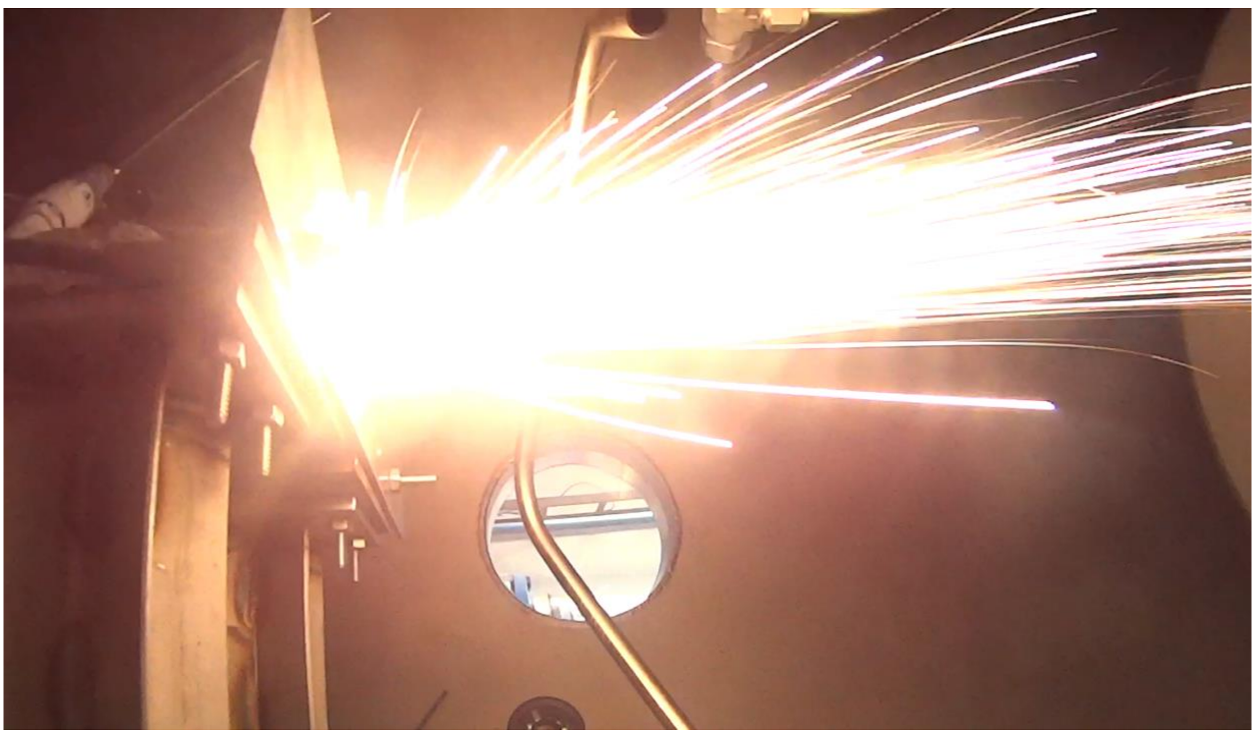

Figure 38 Test 2 Throat Melting

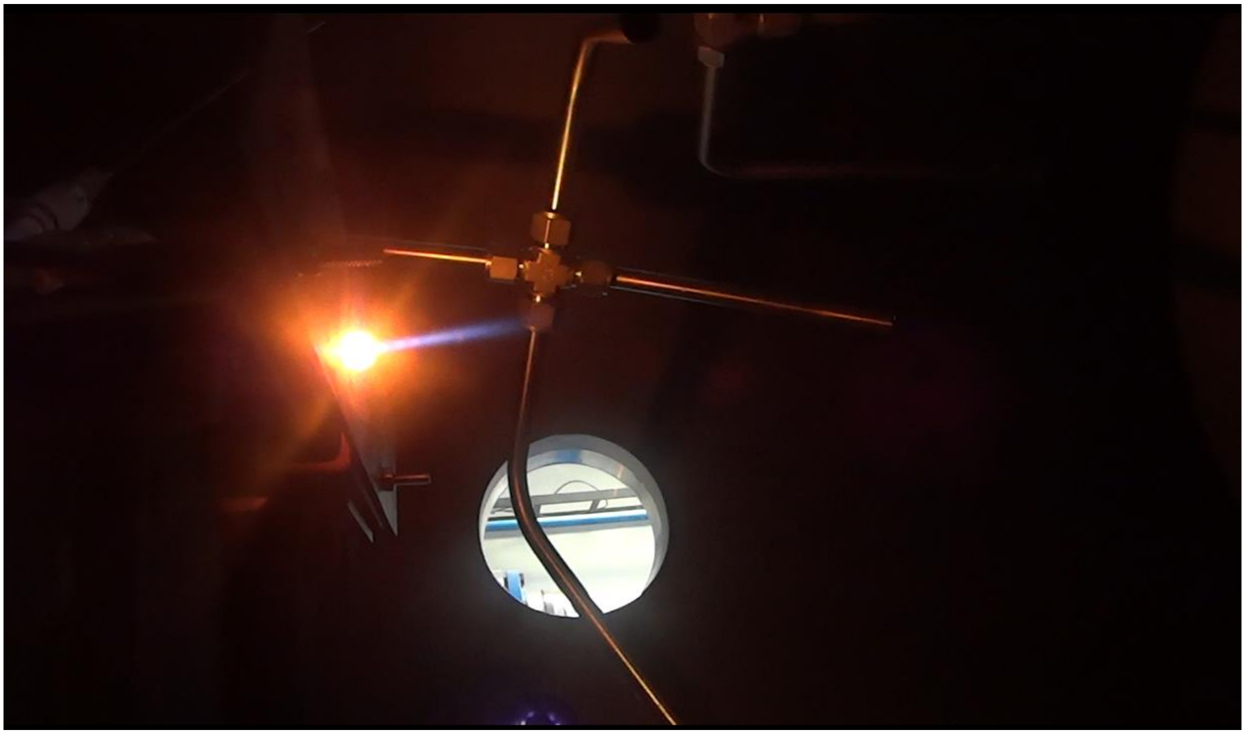

Figure 40 Red Hot Throat Section

Figure 39 Swirl Torch Igniter melted throat

The data obtained over the two tests will be shown over the next figures. Figure 41 shows the pressures registered upstream and downstream in the CH4 line, and the pressure registered downstream in the Oxygen line. The pressure upstream was not written correctly by LabVIEW software since the signal conditioner assigned for the Oxygen upstream had a malfunction, it would display itself the correct pressure but it would send a bad signal to the DAQ. The pressure was monitored by a student and written down; it stayed constant throughout the test at 163 +/- 2 psia. The pressure upstream of the CH4 stayed constant at about 140 psia throughout the test, the upstream pressure were the most critical to stay constant since the mass LabVIEW software since the signal conditioner assigned for the Oxygen upstream had a malfunction, it would display itself the correct pressure but it would send a bad signal to the DAQ. The pressure was monitored by a student and written down; it stayed constant throughout the test at 163 +/- 2 psia. The pressure upstream of the CH4 stayed constant at about 140 psia throughout the test, the upstream pressure were the most critical to stay constant since the mass flow limited by the cavitating venturis depended on it. Figure 42 shows the chamber pressure achieved during the test, with a maximum of 53 psi, which is believed to be achieved during the start of the ignition of the flame.

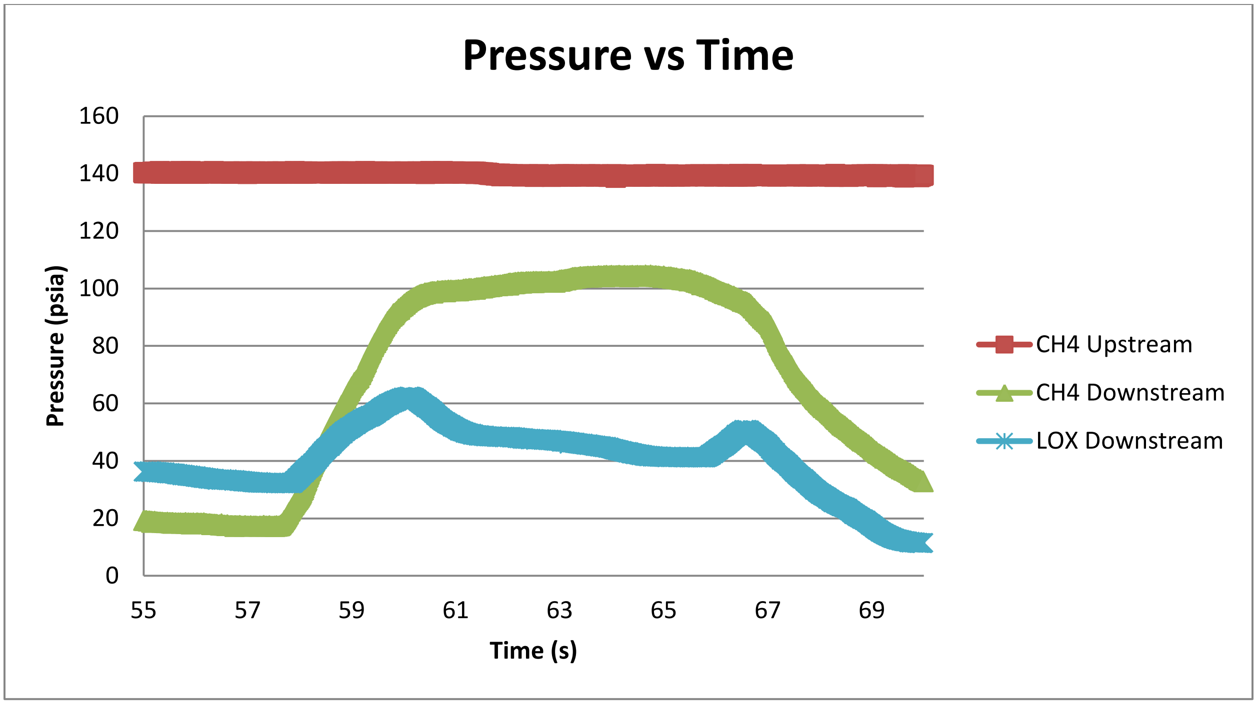

Figure 41 Test # 1 System Pressure

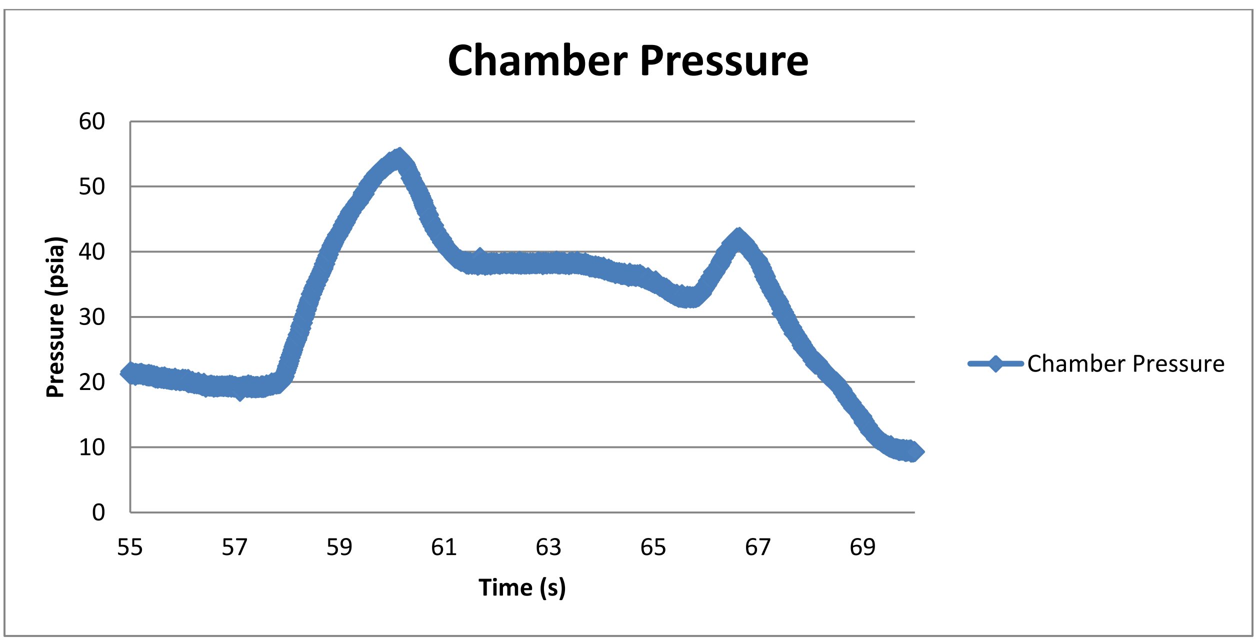

Figure 42 Test # 1 Chamber Pressure

Figure 43 shows the graph of the calculated mass flow rate achieved by the propellants during testing. The mass flow rates were calculated using the formula mentioned in section 3.4.1 with the data achieved in the test. The oxygen mass flow rate achieved was of 0.023 +/- 0.001 kg/s and the mass flow rate of the methane during ignition was of 0.0069 +/- 0.0003 kg/s. Figure 44 shows the graph of the mixture ratio achieved during ignition.

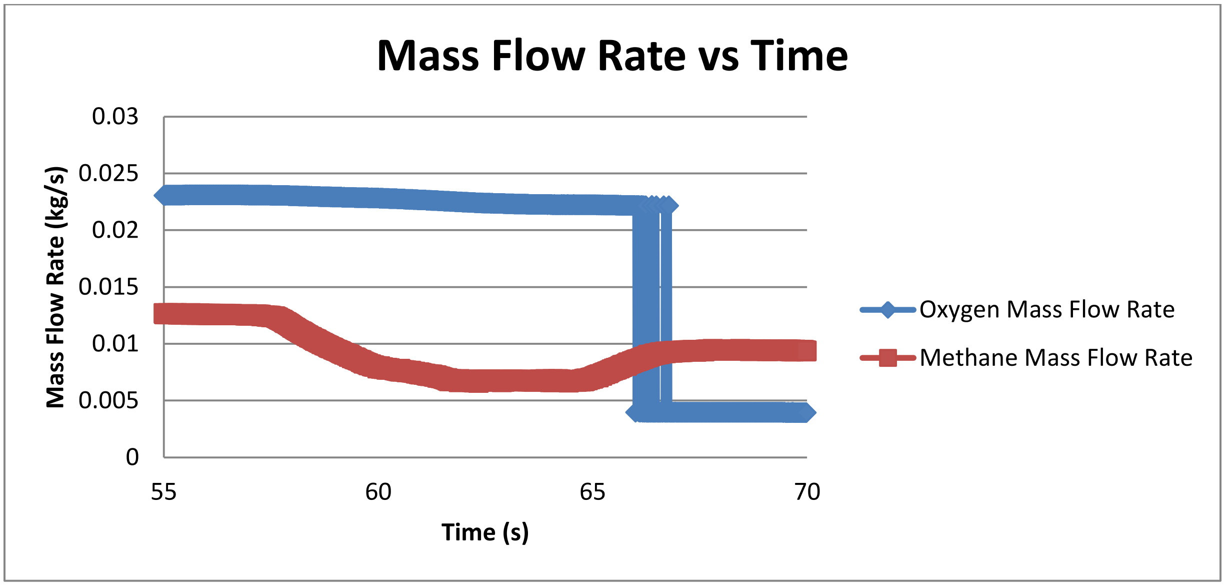

Figure 43 Test # 1 Mass Flow

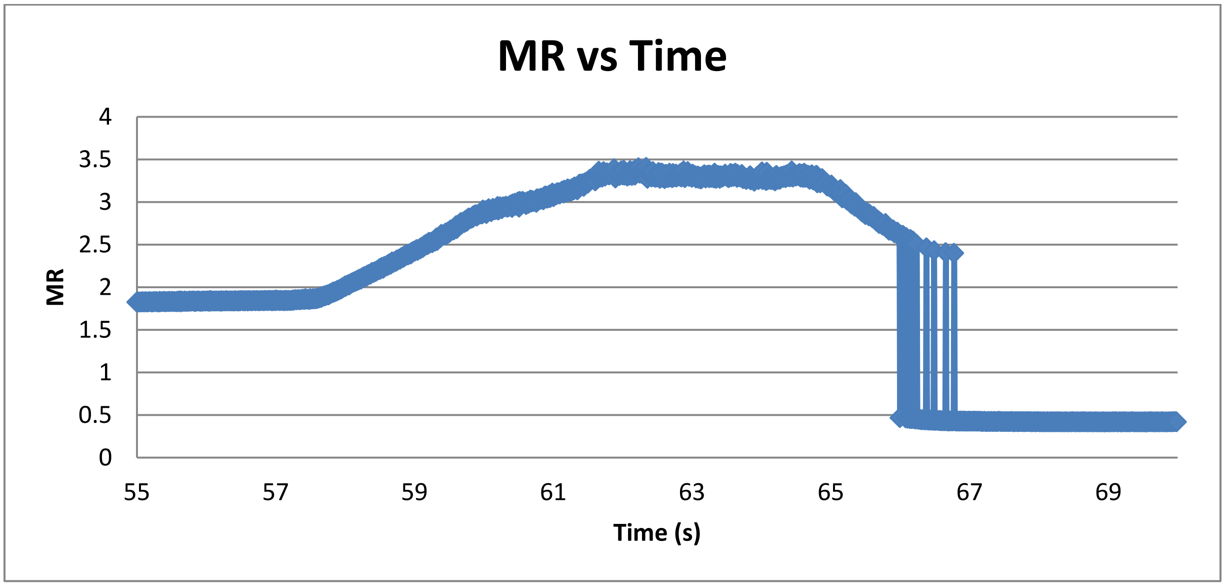

Figure 44 Test # 1 MR

The conditions for Test # 2 were set to be the same; the same upstream pressure over the cavitating venturis to achieved the same or very similar mass flow rates. The data obtained during the second test was corrupted after ignition was achieved due to the freezing of LabVIEW software. Figure 45 shows the graph of the pressure achieved during testing, Figure 46 shows the chamber pressure achieved. As it can be seen in the graphs, after the tenth second when ignition was achieved the pressure data from the methane drops and stays constant for about 8 seconds and then rises, and the oxygen pressures drops the remaining of the time. A maximum pressure registered in the Chamber was approximately 45 psi. It is believed that this data is not very accurate since the program froze after the tenth second.

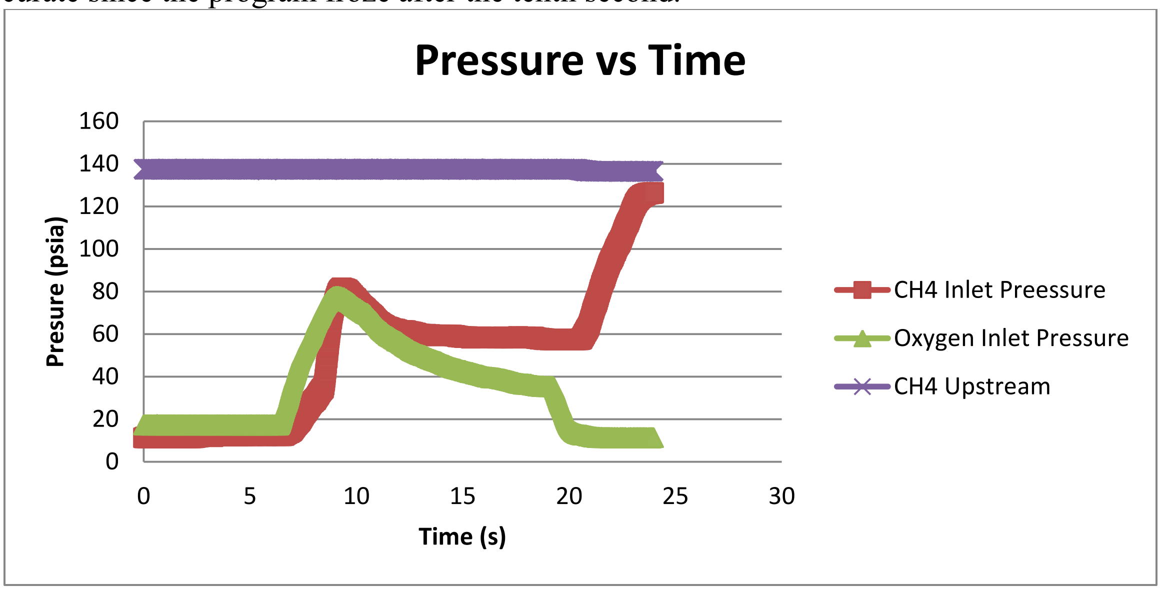

Figure 45 Test # 2 System Pressure

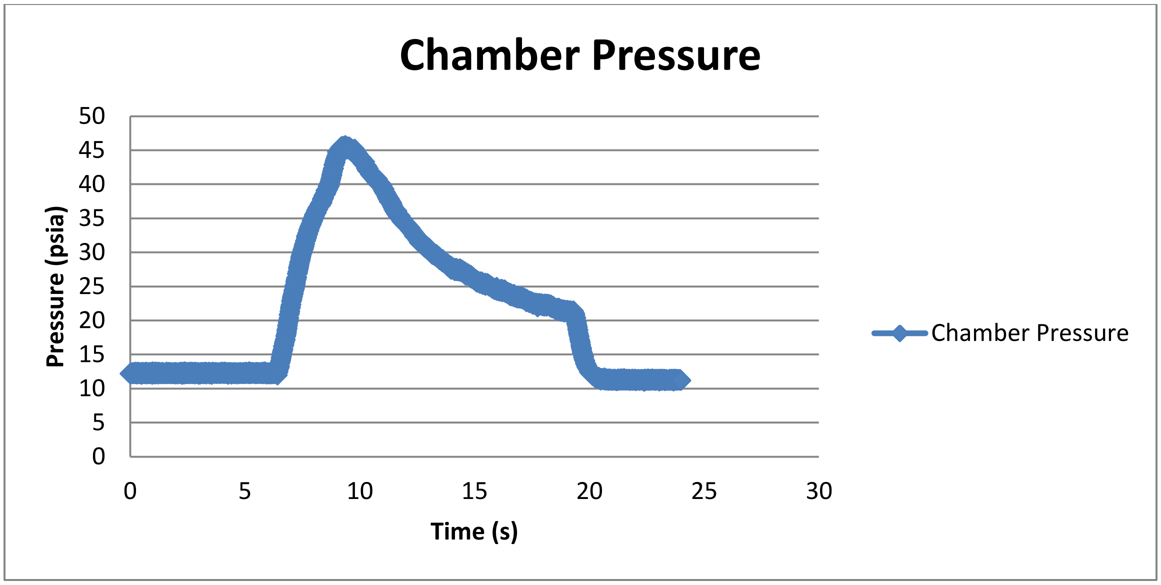

Figure 46 Test # 2 Chamber Pressure

Figure 47 shows the graph with the mass flow rates seen in the second test and Figure 48 shows the Mixture Ratio. As it can be seen from these graphs as in the past graphs the data is not reliable after the tenth second. The mass flow rate of the liquid methane after the tenth second dropped to zero and the liquid oxygen mass flow rate increased to almost 0.027 kg/s and then drops. The mixture went to about 2.3 the dropped to zero.

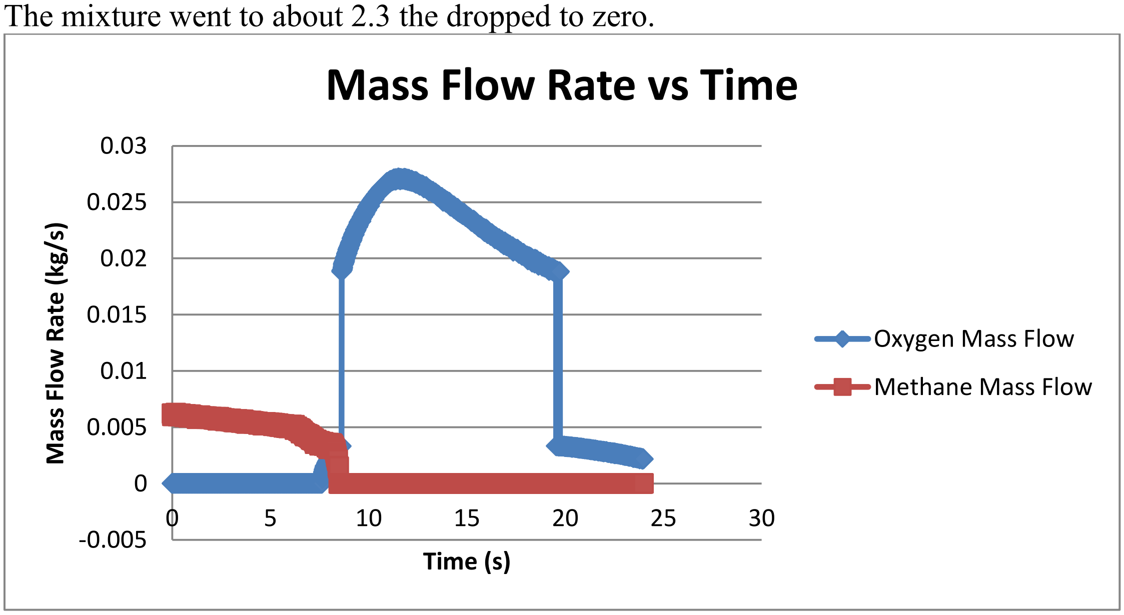

Figure 47 Test # 2 Mass Flow

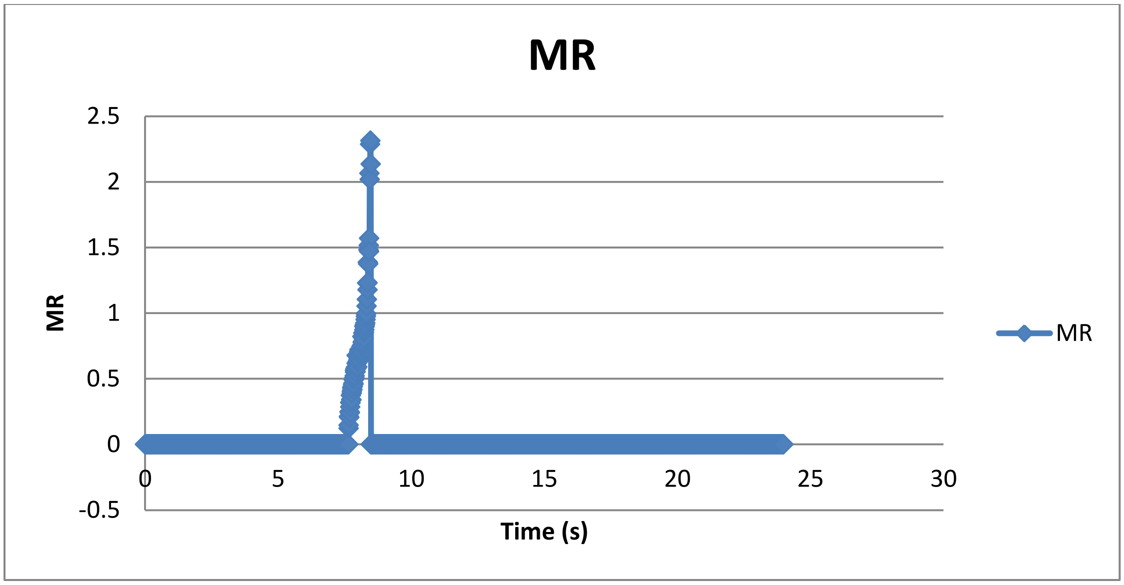

Figure 48 Test # 2 MR

3.5.3 Third Phase of Testing and Thermal Analysis

For the third phase of testing the same design of the swirl torch igniter was fabricated, with exception of the pressure port. As mentioned before, the pressure port was changed from a threaded 1/8 NPT interface to a 1/8 inch hole with a 1/8 inch Swagelok tubing welded to it. To that tubing a fitting was added that went from a 1/8 Swagelok tube fitting to a ¼ inch Swagelok tube fitting, to this fitting the Pressure transducer was attached. The actual firing sequence was fixed since there were some mistakes done with the previous sequence. Four thermocouples were laser welded to the igniter chamber body to monitor the temperatures and have a red line in the LabVIEW program to stop the test if the temperature was to rise to above 1260 Fahrenheit, which is 30 % less than the service temperature (1800 °F). The material was changed from Stainless Steel 304 to Inconel 625.

To determine the allowable run time for the torch igniter a transient thermal analysis in ANSYS Mechanical was done. The transient thermal analysis was set up for a ten seconds run. The igniter iteration 2.0 was damaged at 8 seconds and hence setting up the transient thermal analysis at 10 seconds is important to define transient temperatures and set limits. Testing would verify the transient thermal analysis and assess the confidence in the prediction of the heat

transfer in the igniter. Inconel 625 provides superior resistance to high temperature corrosion and stress corrosion cracking at service temperatures up 1800°F (982°C).The transient thermal analysis will show when the maximum service temperature (1800 F) for Inconel 625 is exceeded.

The boundary conditions implemented in the transient thermal analysis are presented in table 1. The convection coefficients for the propellants (LOX/LCH4) were obtained via hand calculations. The boundary conditions for the propellants were obtained with the inlet properties of the propellants at the igniter and the mass flow rates. The boundary condition for the hot gas was obtained for the JSC 2k engine thermal analysis. This boundary condition is for hot-gas from combustion of liquid oxygen and liquid methane.

Table 2 Boundary Conditions

	Convection Coefficient/Heat Flux	**Ambient Temperature**
A-Igniter outer body	5 e -06 BTU/s*in^2*F	71.6 F
B-Liquid Oxygen	1.73 e -03 BTU/s*in^2*F	-260 F
C-Combustion Chamber	2.00 BTU/S*in^2	N/A
D-Methane Igniter Inlet	6.85 e -06 BTU/s*in^2*F	-204 F
E-Methane Manifold	2.30 e -06 BTU/s*in^2*F	-204 F
F-Methane Tangential Injection	1.22 e -06 BTU/s*in^2*F	-204 F

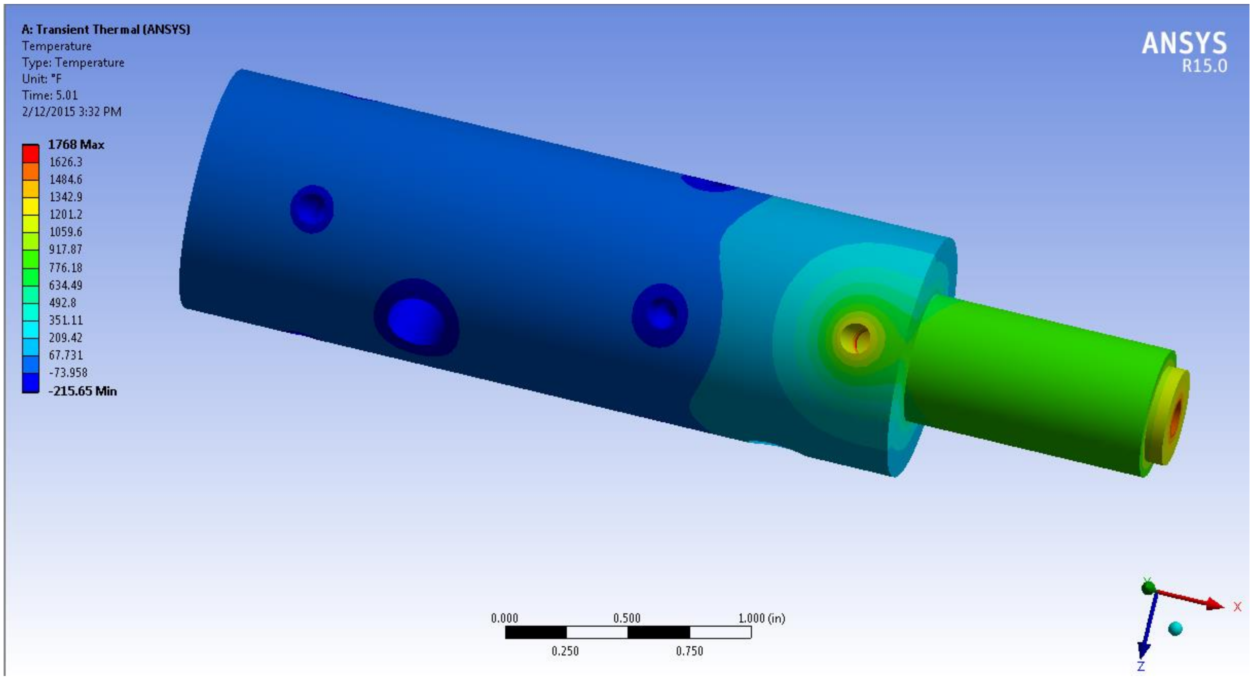

Figure 49 Swirl Torch Igniter Temperature Distributions

The transient thermal analysis results yield the maximum temperature allowable for Inconel 625 reached at five seconds. The temperature obtained from the thermal analysis is of 1768 F. This result will limit the test operation time of the igniter to 3 seconds per run.

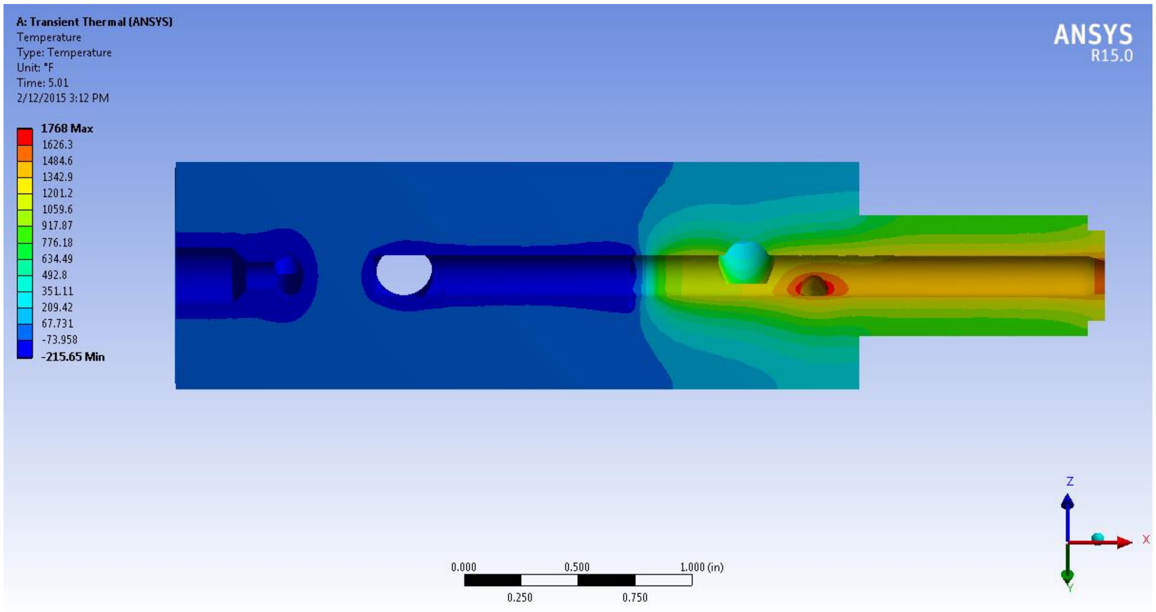

Figure 50 Swirl Torch Igniter Temperature Distribution Section View

As it can be observed in figure 49, there is a temperature concentration at the pressure port and at the throat of the igniter. The previous test igniter was melted during testing and it was observed that the pressure port and throat of the igniter was partially damaged. The test sequence was limited to 3 seconds to avoid thermal damage to the igniter body. The first test was conducted with a firing sequence represented in Table 3.

Table 3 Test Sequence

Time (s)	Action
0	Open Lox Tank Valve, Lox Delivery Valve, Helium, CH4 Delivery
2	Open Lox Thrust Valve, CH4 Thrust Valve
4	Turn Sparker power on
5	Turn Sparker power off
7	Close All Valves

The problem with this specific test sequence was that it allowed the chamber of the swirl torch igniter to fill up with the propellants for two seconds before ignition. When the sparker turned on there was a small detonation inside the chamber that caused the ceramic blow off the fitting, bursting into pieces, and as well as it blew off the converging section of the igniter. The Test Matrix that was to be followed is shown in Table 4. A constant total mass flow was to be kept throughout the test, which meant to change the pressures of both propellants to accommodate. Figure 51 shows a picture of the swirl torch igniter inside the Ambient Test Stand.

Table 4 Test Matrix of Third Phase of Testing

c	Goal Mixture Ratio (o/f)	LCH_4 Tank Pressure	LOX Pressure	Goal LOX Mass Flow Rate (kg/s)	Goal LCH4 Mass Flow Rate (kg/s)	Total Mass Flow Rate (kg/s)
1	1.78	145 +/- 2 psia	140 +/- 5 psia	0.024 0.025	0.014	0.039 +/- 0.001
2	1.9	130 +/-2 psia	140 +/-5 psia	0.024 0.025	0.013	0.038 +/- 0.001
3	2.25	115+/- 2 psia	160 +/-5psia	0.027 0.028	0.012	0.039 +/- 0.001
4	2.5	100 +/- 2 psia	160 +/-5psia	0.027 0.028	0.011	0.038 +/- 0.001

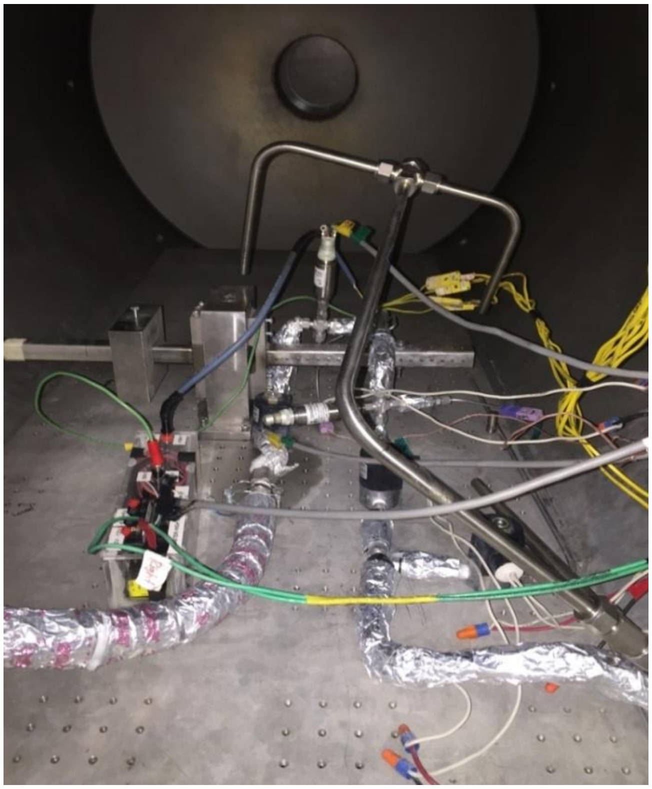

Figure 51 Swirl Torch Igniter inside ATS

Figure 52 and 53 show images taken from the video recording of the first test. Figure 52 is a second before ignition and where the propellants can be seen flowing through the swirl torch igniter. Figure 53 is milliseconds after ignition is achieved and it can be seen that the ceramic has already been blown off and the converging section is no longer in place.

Figure 53 Test # 1 Phase Before Ignition

Figure 52 Test # 1 After ignition, without Sparker

The point that was aimed to be achieved from the Test Matrix was number 3, with a LOX pressure upstream of the cavitating venturi of 160 psia and LCH4 pressure upstream of the cavitating venture of 115 psia. Figure 54 shows the Pressures achieved during testing, with the LOX pressure being about 6 psia of the desired; this happens sometimes with the cryogenic dewars that are self-pressurized. These cryogenic tanks some of the times, especially when they are half full or less, don't give a constant pressure and it fluctuates. It also can be seen from that figure that the detonation affected the LOX Downstream Pressure Transducer, since it was reading a pressure of about 62 psia and then it increased until it reached 264 psia and stayed at that point, which could have not been achieved.

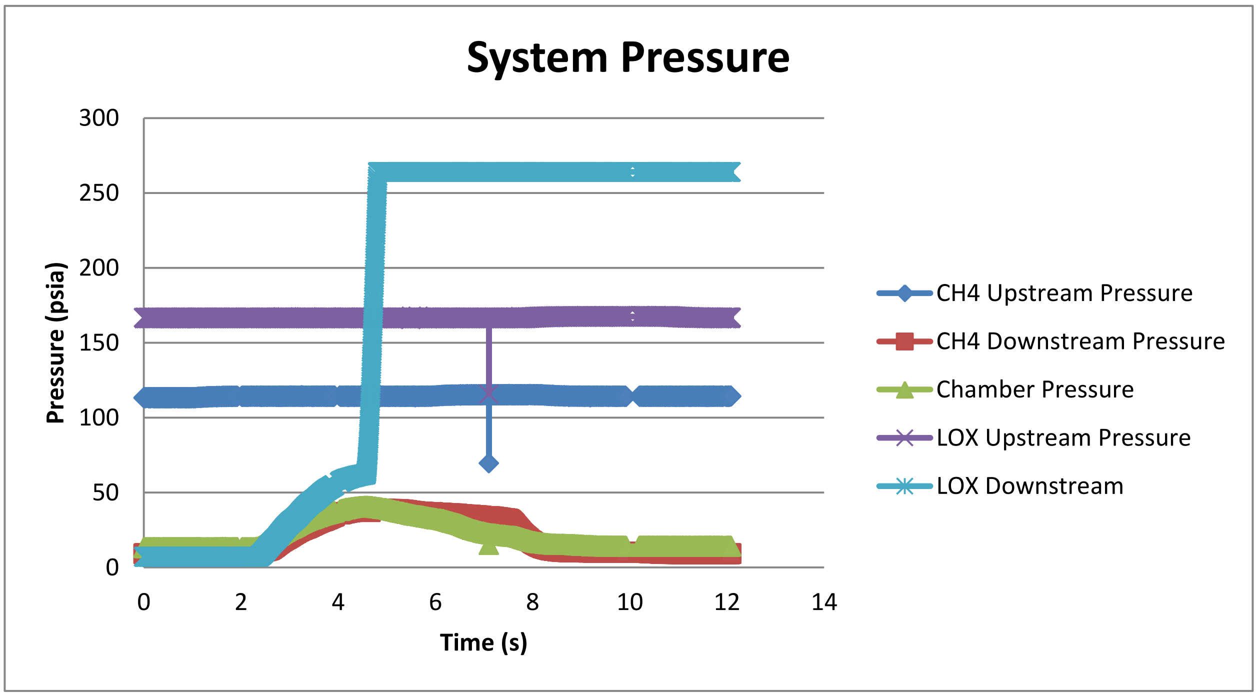

Figure 54 Test # 1 Third Phase System Pressure

The mass flow rate of the liquid oxygen was higher than the goal mass flow, 0.028 kg/s being the goal and 0.032 kg/s being the average mass flow achieved. This was due to the pressure of the LOX being higher and to the temperature being a few degrees lower than expected therefore giving the LOX a higher density thus a higher mass flow. The mass flow of

the LCH4 was somewhat higher to the desired, 0.012 kg/s being the desired and 0.013 kg/s being the achieved. This as well was attributed to the temperature being a few degrees lower and thus the methane having a higher density, the mass flow can be seen in Figure 55. Figure 56 shows the MR achieved during the test and Figure 56 shows the temperatures seen in the swirl torch igniter, which only increased during the detonation but did not registered a really high temperature since no flame was sustained.

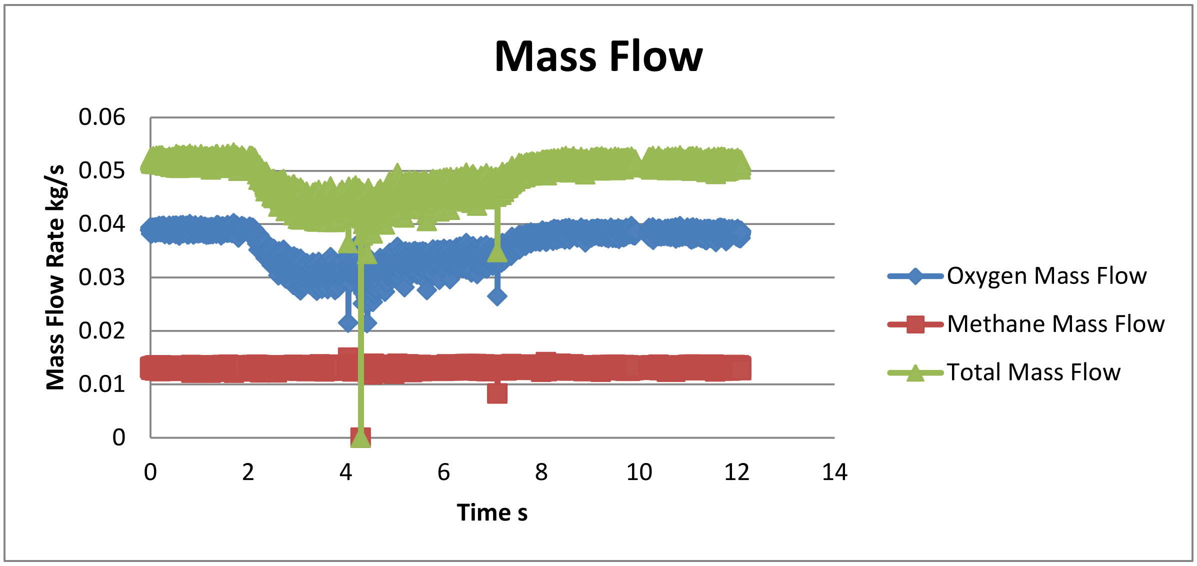

Figure 56 Test # 1 Third Phase Mass Flow

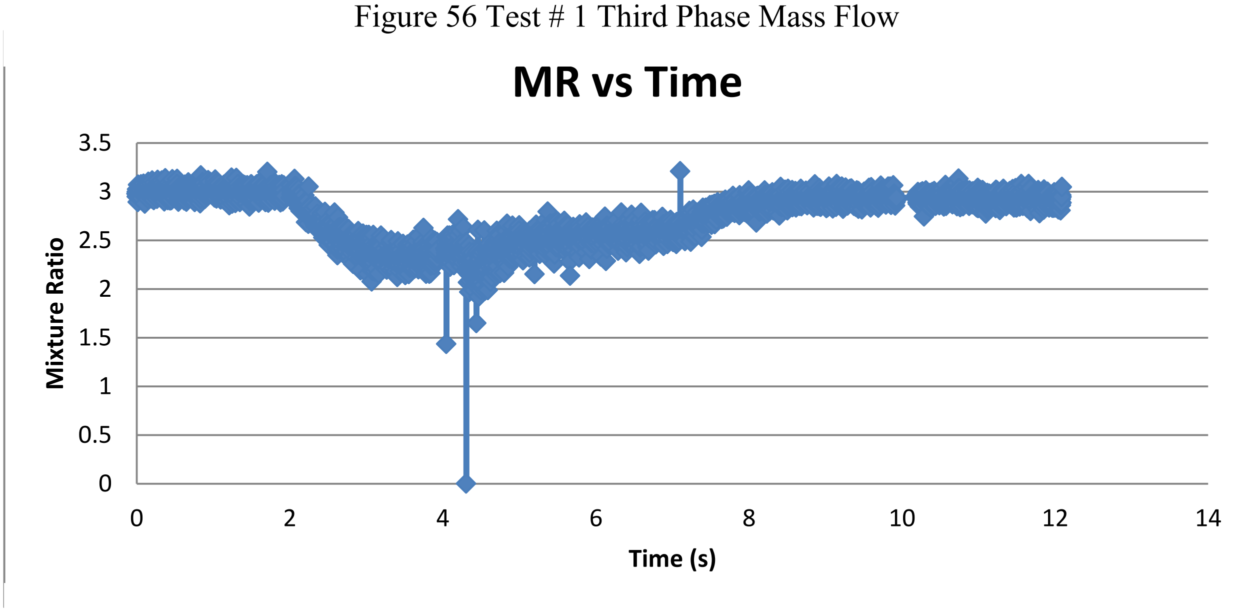

Figure 55 Test # 1 Third Phase MR

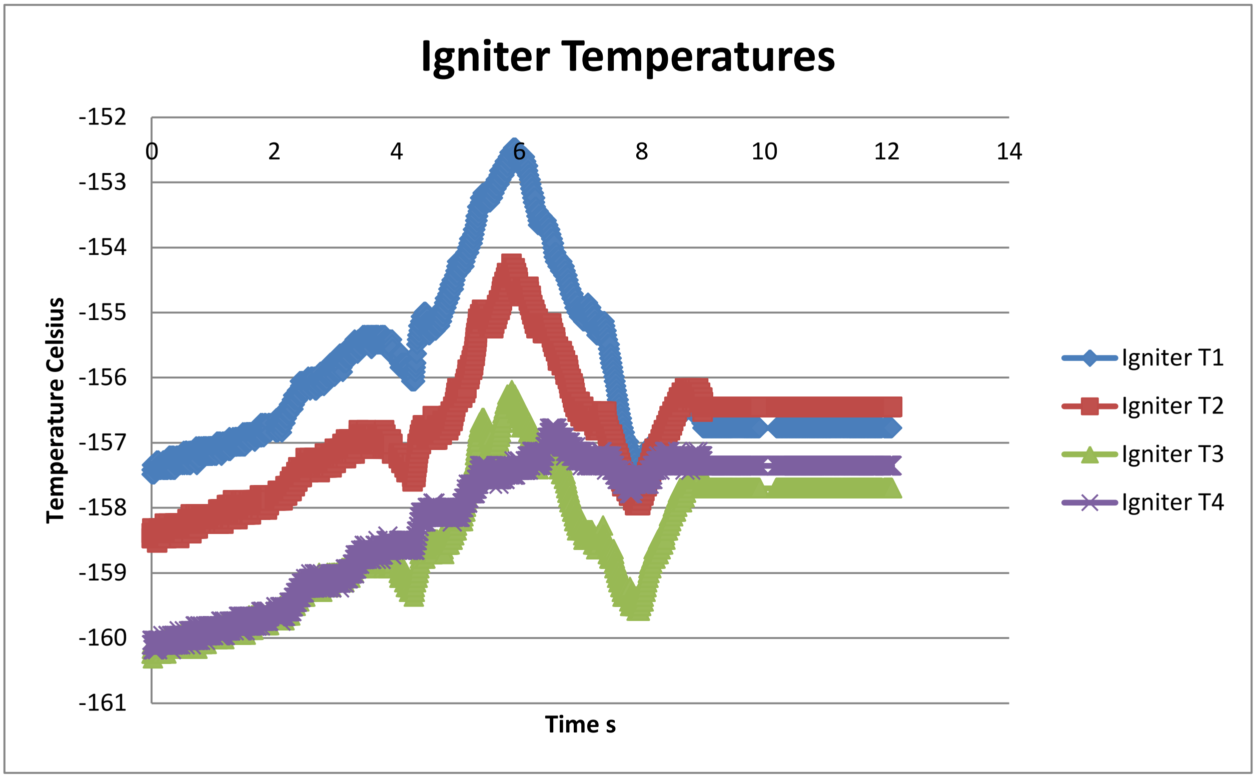

Figure 57 Igniter Temperatures

For the second test of this phase of testing there was a miscommunication between the test conductor and the hardware technician on the pressure to be set for the LCH4 so no actual point in the test matrix was followed. The LCH4 pressure was set to 153 psia and the LOX pressure was set to 160 psia. The test sequence problem from the previous test was modified to have the sparker on at the same time as the LOX and LCH4 thrust valves were open to prevent another detonation inside the swirl torch igniter and prevent another sparker blow out. For this test the sequence work but the sparker melted during the test, which was attributed to the intensity of the combustion of this propellants as well as for the sparker being in the flow path of the combustion. Figure 58 through 60 shows images taken from the video recording of the test. Figure 58 shows one of the initial flames during the testing, Figure 59 and Figure 60 show a red flame which show a hardware rich flame where the sparker was being melted.

Figure 58 Test # 2 Third Phase Initial Flame

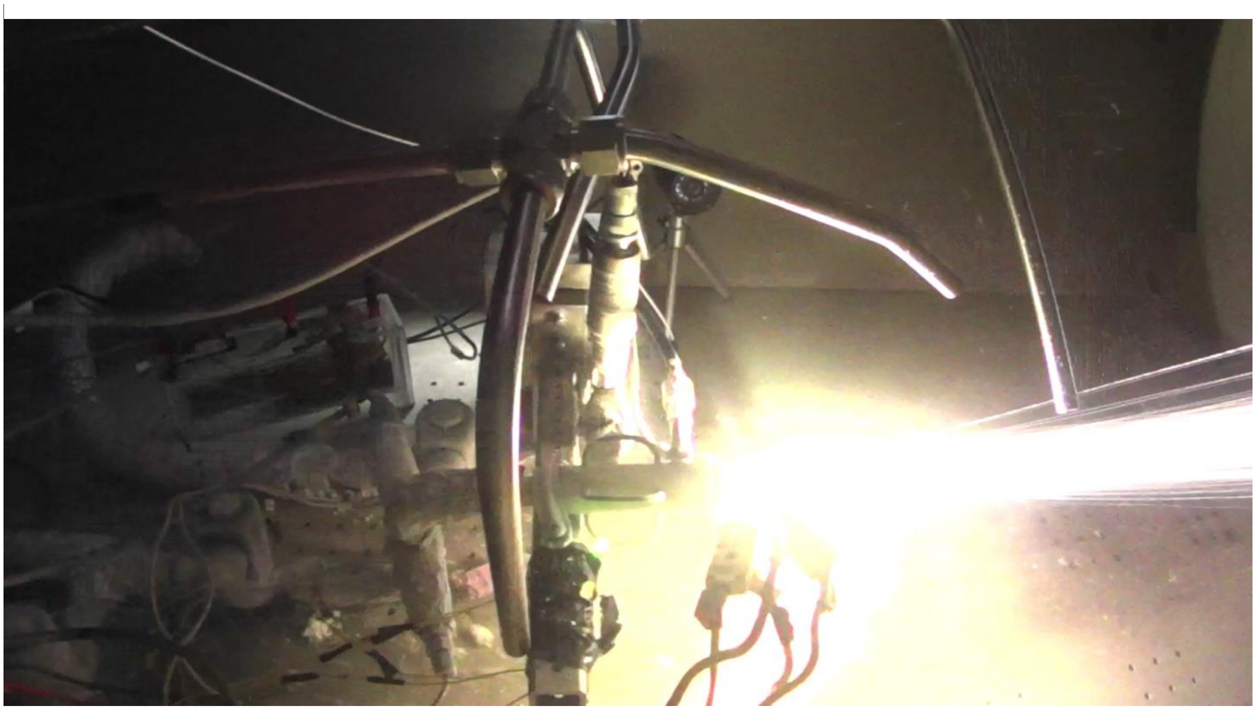

Figure 59 Test # 2 Third Phase Sparker Meltdown

Figure 60 Sparker Meltdown

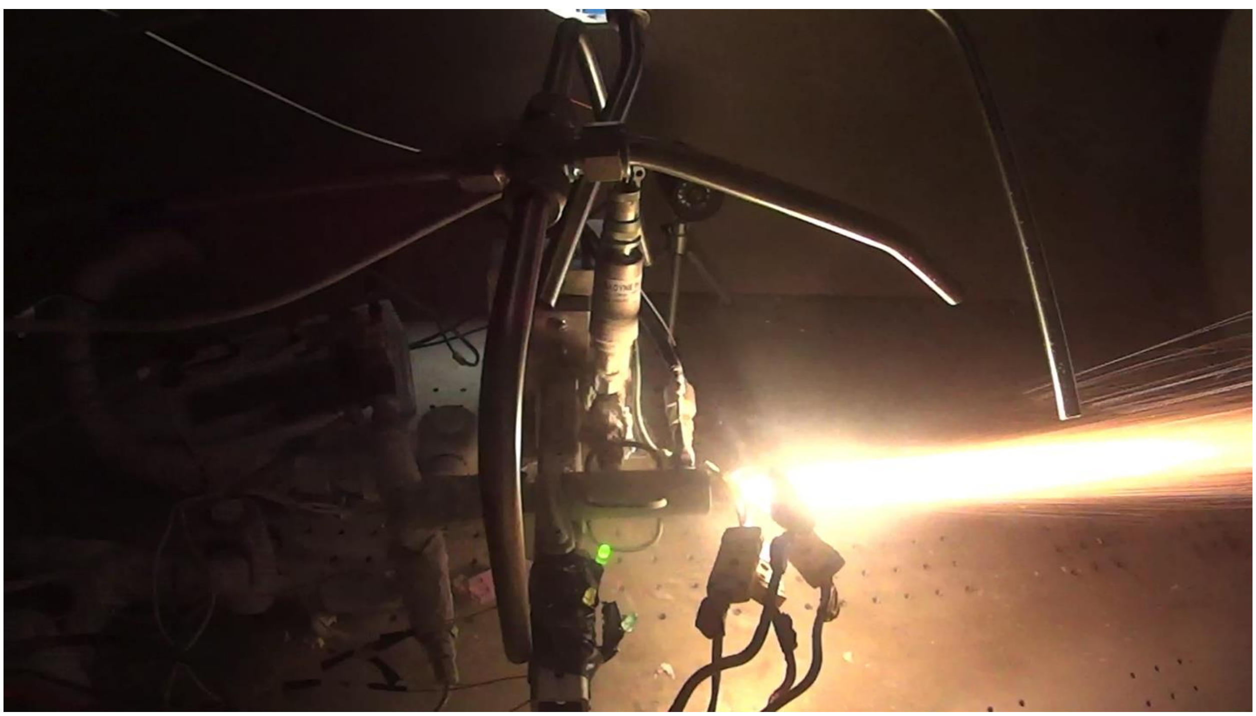

Figure 61 Test # 2 Sparker Meltdown

Figure 62 shows the system pressure, where it can be seem a malfunction of the Chamber Pressure Transducer, as it didn't record any pressure inside the chamber. Figure 63 shows the calculated mass flow rated achieved during testing, where at second 12 power was given to the sparker and ignition was achieved. Figure 64 show the temperatures that were read by the thermocouples placed in the chamber section of the swirl torch igniter. The igniter temperatures increased from the converging section back, expected from the results obtained in the Thermal Analysis. The Temperatures did not rise above 162 Celsius, so the red line set was not met.

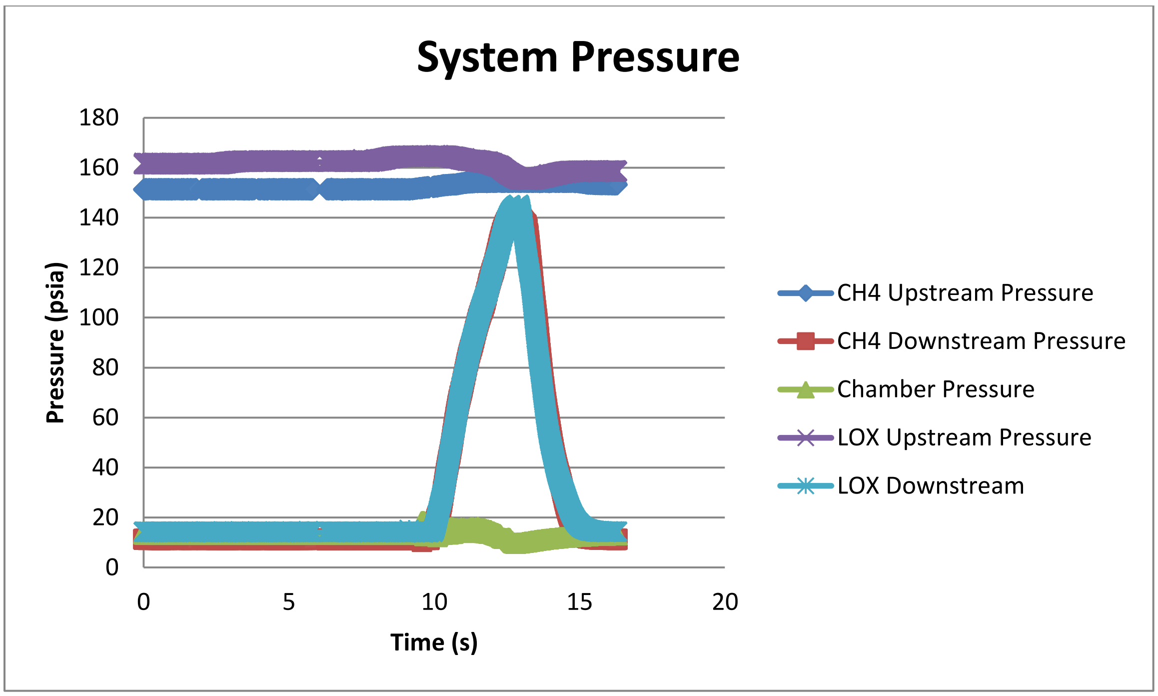

Figure 62 Test # 2 Third Phase System Pressure

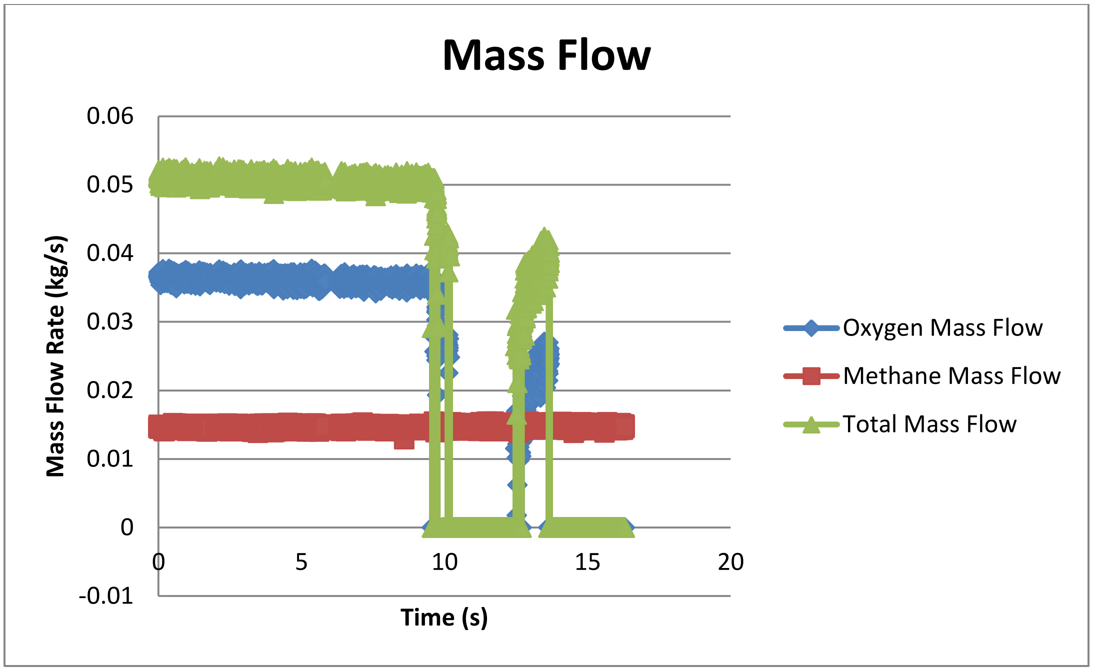

Figure 63 Test # 2 Third Phase Mass Flow

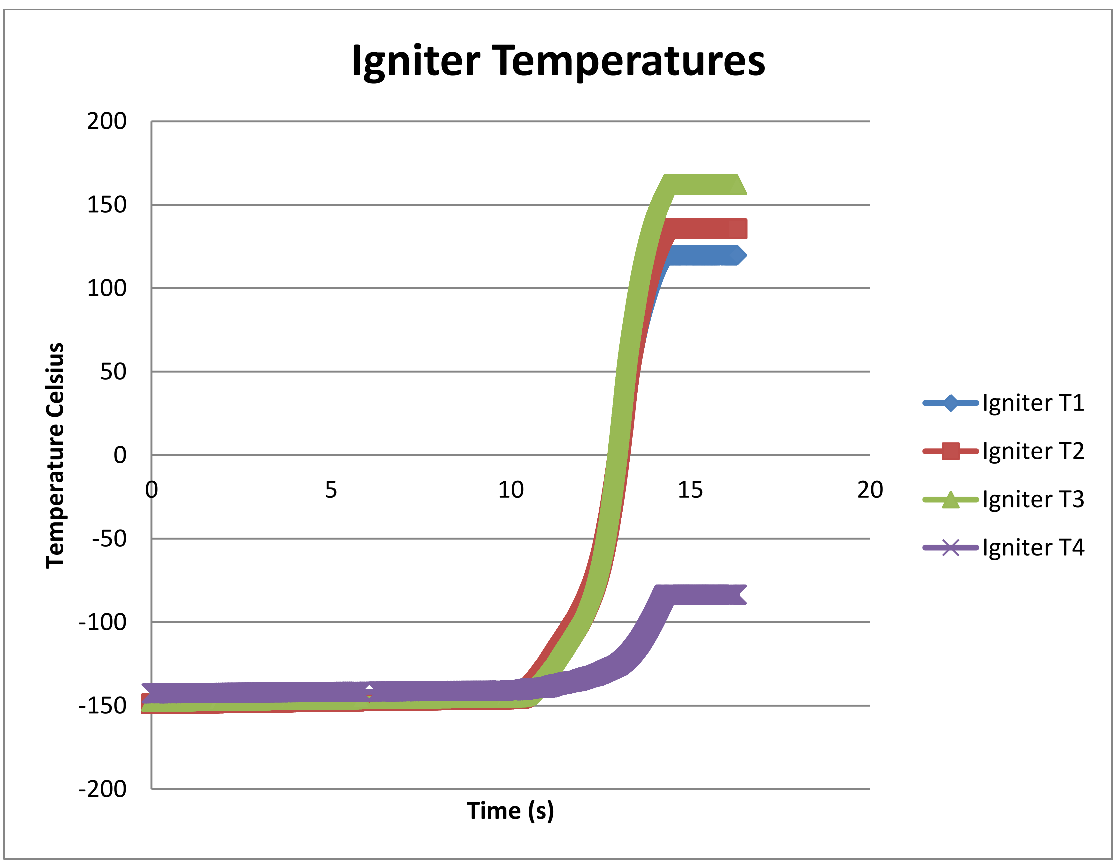

Figure 64 Test # 2 Igniter Third Phase Temperatures

For the third test the second point in the test matrix was followed, having the LOX pressure at 145 psia and the LCH4 pressure at 130 psia. The flame for this test only lasted one second, and the sparker was damaged again. The sparker for this test had a melted tip and again the ceramic partially broke. Figure 65 and 67 show the flame achieved during testing, in which particles can be seen coming out of the swirl torch igniter. Figure 66 shows the damaged sparker, in which the ceramic is broken.

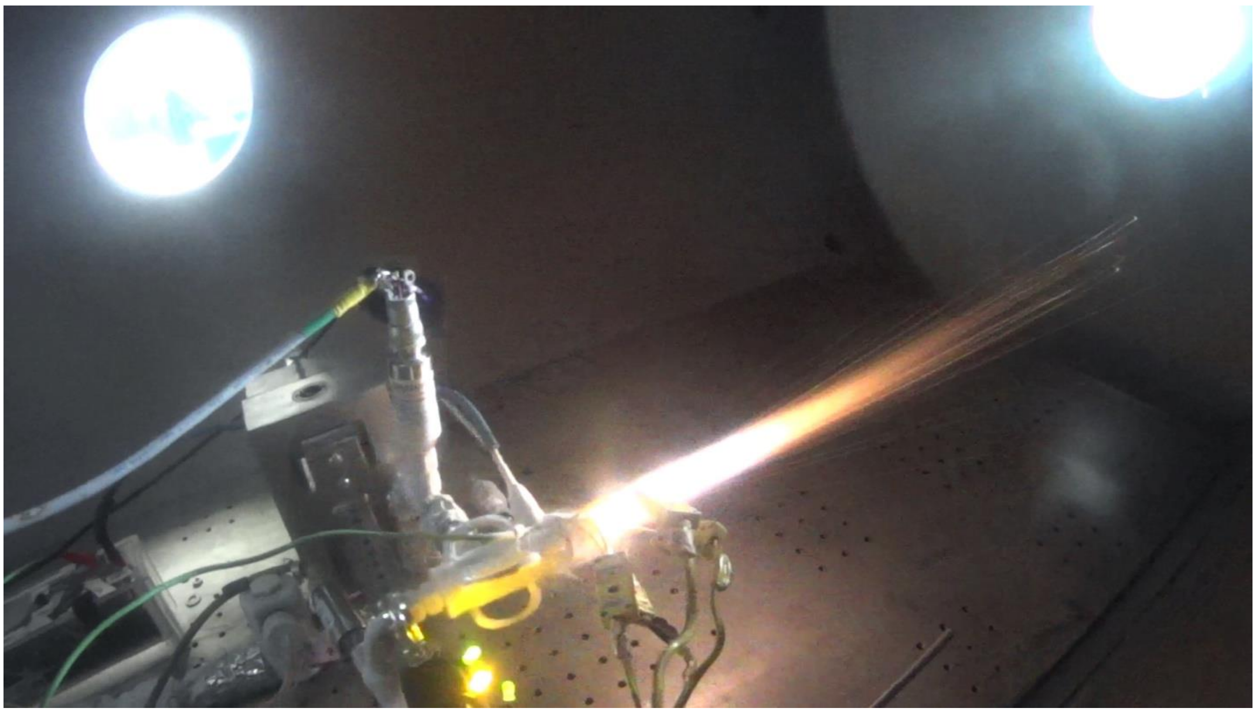

Figure 65 Test # 3 Ignition with particles flying out of igniter

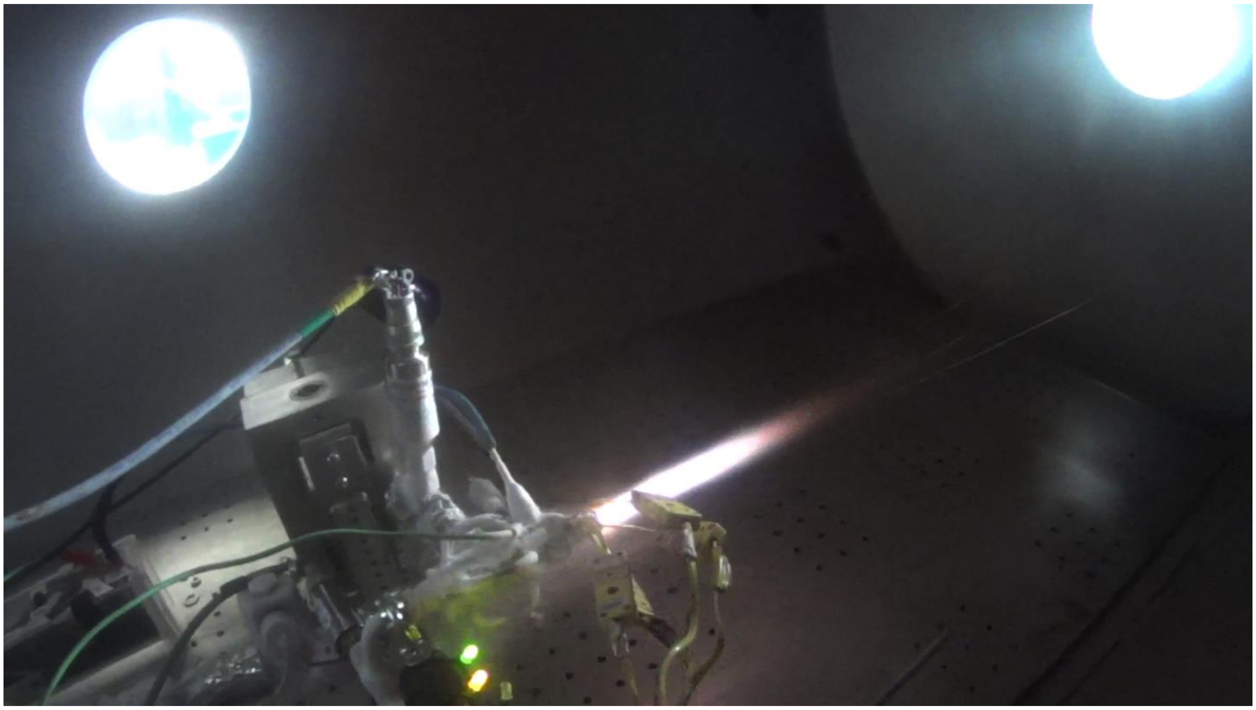

Figure 67 Test # 3 Third Phase Ignition

Figure 66 Test # 3 Sparker with broken ceramic

The pressure data downstream was corrupted, since no pressure was registered during ignition. Figure 69 shows the system pressures, Figure 68 shows the calculated mass

flow rate of the propellants and Figure 70 shows the temperatures registered by the thermocouples.

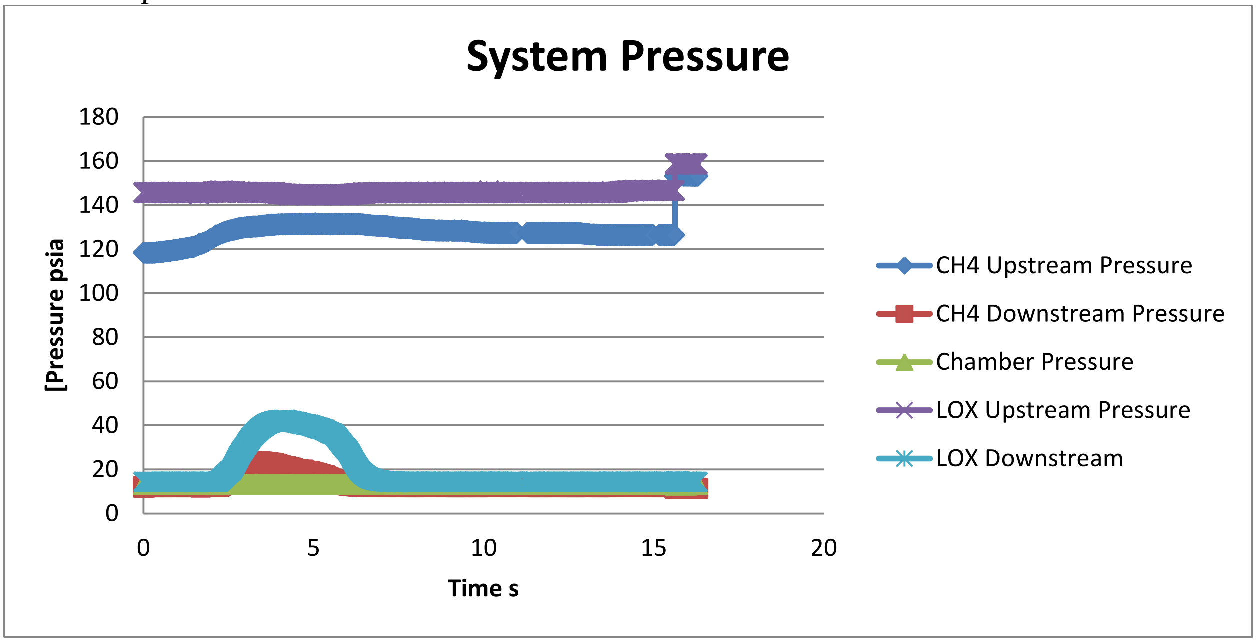

Figure 69 Test # 3 Third Phase System Pressure

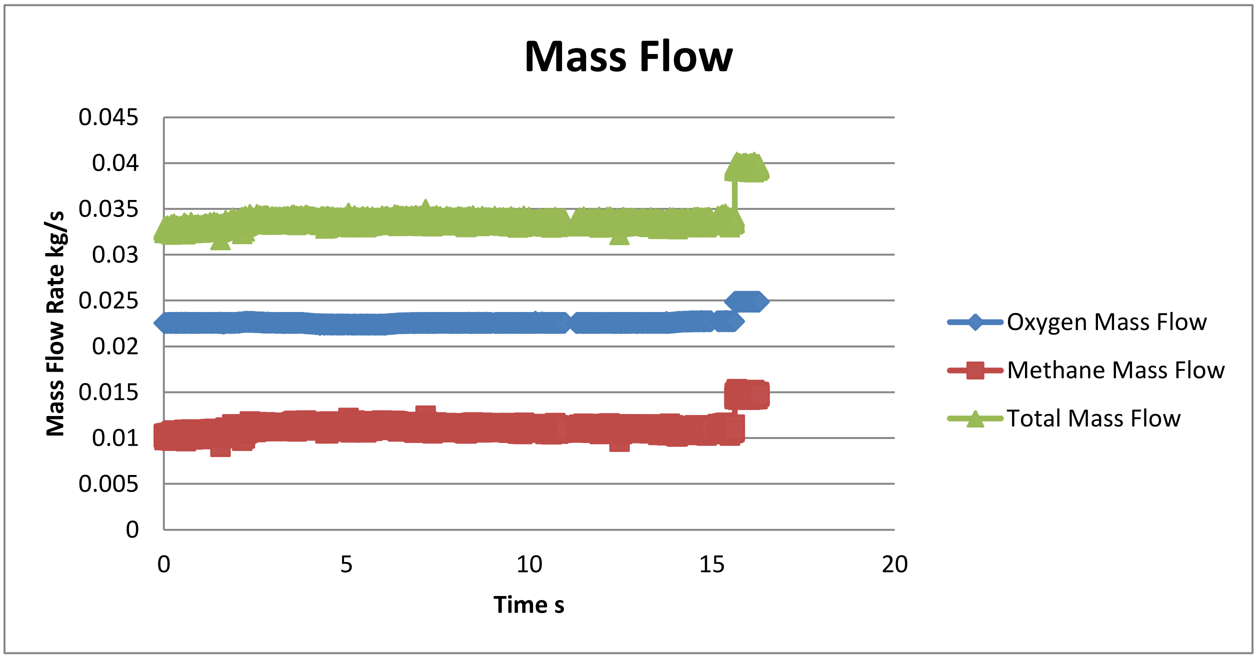

Figure 68 Test # 3 Third Phase Mass Flow

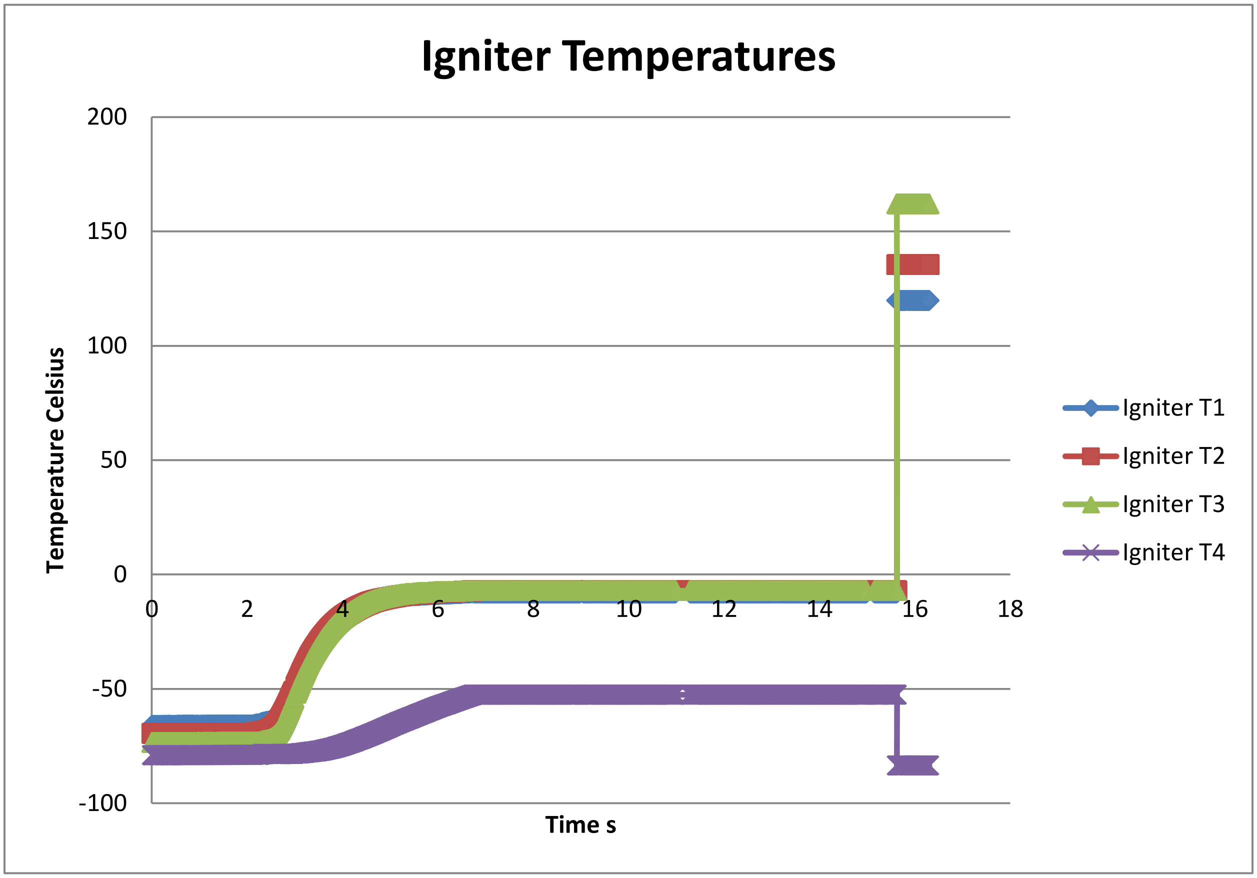

Figure 70 Swirl Torch Third Phase Ignite Temperatures

It was concluded from all the LOX/LCH4 tests that with the second iteration of the swirl torch igniter that repeatable ignition with no be obtained. In the second phase of testing only two ignitions were achieved before the failure of the igniter, and in the third phase of testing only one ignition per sparker was achieved, meaning no reliability in the sparking system. Another thing noted was that with the change in the Methane injection point in the igniter there was choked flow through the injection ports, meaning that the flow was limited.

Chapter 4

This chapter will contain information on the third iteration of the swirl torch igniter. The design, testing and data obtained will be discussed. The following requirements were followed while designing the swirl torch igniter:

- Contain a swirl coaxial injection design, similar to a mN class Thruster previously developed and investigated in the cSETR
- Oxygen and Methane as propellants
- Compatible with LOX
- Axial Propellant Inlets

4.1 THIRD ITERATION OF SWIRL TORCH IGNITER

The third iteration of the swirl torch igniter kept the injection port dimensions the same as in the first iteration. The major changes from previous iterations are the sparker location, having both propellants inlets axially, the methane manifold, the throat section, and the addition of a nozzle. The material for this iteration was selected to be Inconel 625, as the third phase of testing on the second iteration. Two swirl torch igniters with different chamber lengths were manufactured to study the effect of the Characteristic Chamber Length (L*) on the combustion.

4.1.1 Propellant Inlet and Methane Manifold

In this third iteration of the swirl torch igniter both the methane and oxygen inlets were selected to be axial, unlike in the previous iteration that had the methane inlet axial and the oxygen inlet perpendicular to the body. The methane manifold was changed from having an inlet split into 4 Swagelok tubing and then injected tangentially, to having a ring manifold as seen in Figure 71. The manifold drawing is shown in Figure 72; this manifold is to be welded to the swirl torch igniter body.

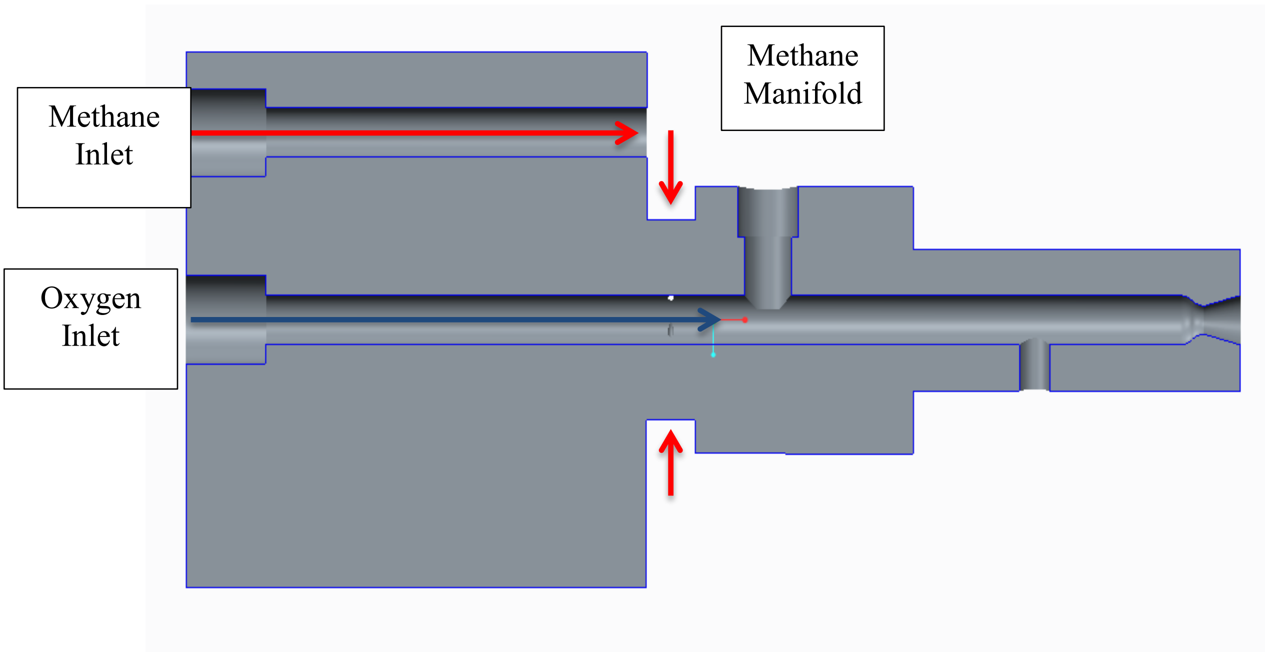

Figure 71 Swirl Torch Igniter # 1 Cross-Sectional View

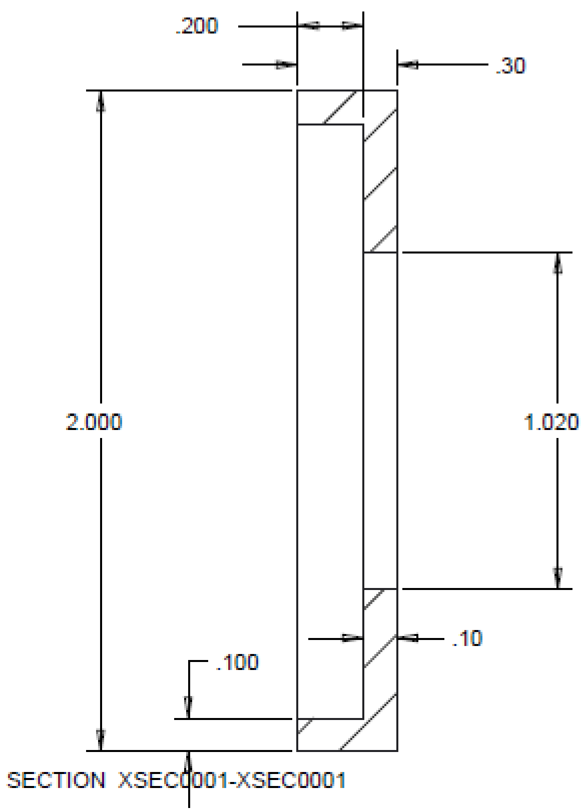

Figure 72 Methane Manifold Drawing

4.1.2 Throat and Nozzle Section

A chamber contraction ratio of 3 was selected for the swirl torch igniter. This ratio gives a throat radius of 0.053 inches (0.013 meters) and throat area of 0.009 squared inches (8.39e-6 squared meters). This throat was added to give an increase in the chamber pressure which will increase the igniter performance.

A conical nozzle with a 15 degree half angle was selected for the swirl torch igniter, since it is the simplest to manufacture. It has an expansion ratio of 3, which gives an exit radius of 0.092 inches (0.023 meters) and an exit area of 0.027 squared inches (0.00015 meters squared). Figure 73 shows the drawing of the nozzle section.

4.1.3 Sparker System

The sparker was changed from previous iterations. Instead of manufacturing the in-house designed sparker an already manufactured spark plug was selected. This spark plug is much smaller in diameter than previous sparkers used, having only a threaded section of ¼-32. Being this small it allowed moving the spark plug closer to the methane injection ports, allowing the spark plug to get more film cooling from the methane. It was noticed from the previous igniter which were cut in half, as it can be seen in Figure 74, that the section closest to the methane injection ports did not suffer damage.

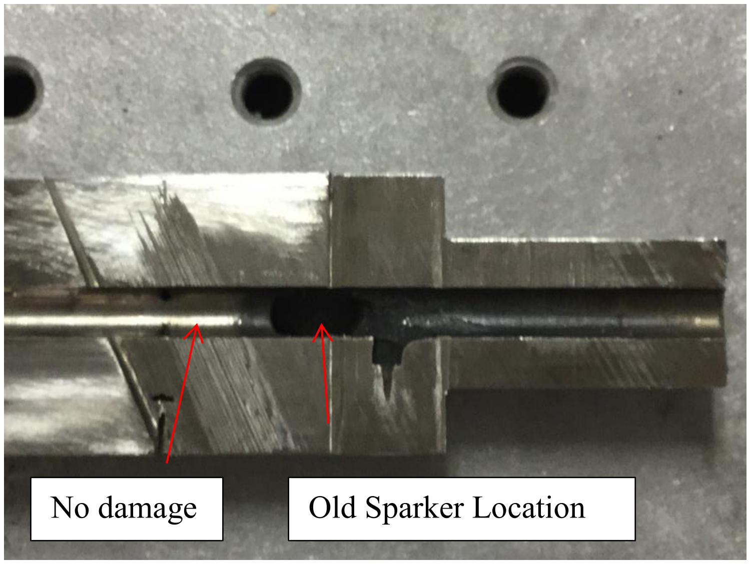

Figure 73 Cross-section of second iteration

The location was set to 2.45 inches from the propellant inlets, at it can be seen in Figures 75 and 76 in the next section, which show the drawing of the three swirl torch igniters. The dc-dc converter was changed in this set of test. The previous dc-dc converter used a 12 Volt for power and 5 Volt signal, and it outputted 25,000 Volts. The new dc-dc converter uses 8 Volts for power and 5 Volt for signal, as well as a signal generator with a frequency of 150 Hz.

4.1.4 Characteristic Chamber Length

Two swirl torch igniters with different chamber lengths were manufactured to test the effect of the Characteristic Chamber length has on the performance of the combustion of Oxygen and Methane. The chamber volume is defined as the volume up to the nozzle throat section; it includes the volume starting from the injection points and the volume from the converging cone frustum of the nozzle. The chamber volume, Vc is calculated as follows:

$$V_c = A_1 L_1 + A_1 L_c (1 + \sqrt{A_t/A_1} + A_t/A_1$$

In this equation L_1 stands for the length of the cylindrical part of the combustion chamber, L_c is the length of the conical frustum and A_1/A_t is the chamber contraction ratio. The approximate surfaces that are exposed to the heat transfer from the hot gas produced during

combustion. There are many considerations taken into the selection of the volume and shape of the combustion chamber, such as

1. Volume has to be large enough for adequate mixing and complete combustion of the propellants
2. Chamber diameter and volume can influence the cooling requirements
3. All inert components should have minimum mass
4. Manufacturing considerations favor a simpler chamber geometry
5. In some applications the length of the chamber and the nozzle relate directly to the overall length of the vehicle
6. Gas pressure drop for accelerating the combustion product within the chamber should be a minimum
7. For the same thrust the combustion volume and nozzle throat area become smaller as the operating chamber pressure is increased

This chamber considerations conflict with each other, for example is impossible to have a large chamber that gives complete combustion but has a low mass. It depends in the application to have a compromising solution that will satisfy the majority of these considerations. For our application considerations 1 and 4 are the ones taken.

The characteristic chamber length (L*) is defined as the length that a chamber with the same volume would have if it were a straight tube without a converging nozzle section. The L* is calculated as follows:

$$L^* = V_c/A_t$$

Vc is the chamber volume which was mentioned before, and A_t is the nozzle throat area. Since this parameter only involves the variable of the throat area and the length of the chamber, it is useful for only one propellant combination and a range of mixture ratios. Figure 75 and Figure 76 show the drawing of the swirl torch igniters with the different chamber lengths.

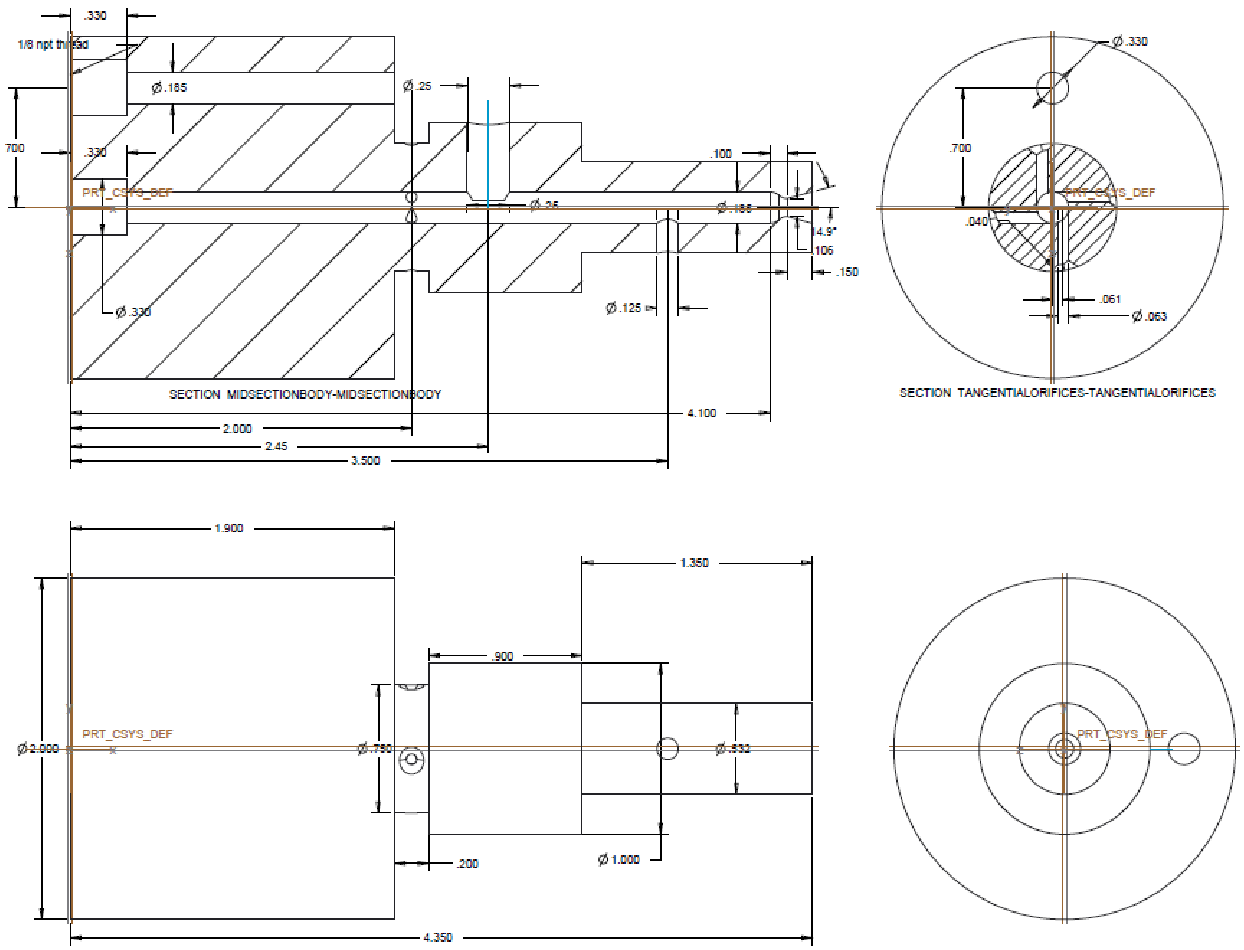

Figure 74 Swirl Torch Igniter # 1

With the stated measurements in the previous Figures for the igniters, the Chamber Volume and the L* were determined. The formulas mentioned before were used to determine these values, which are shown in Table 5.

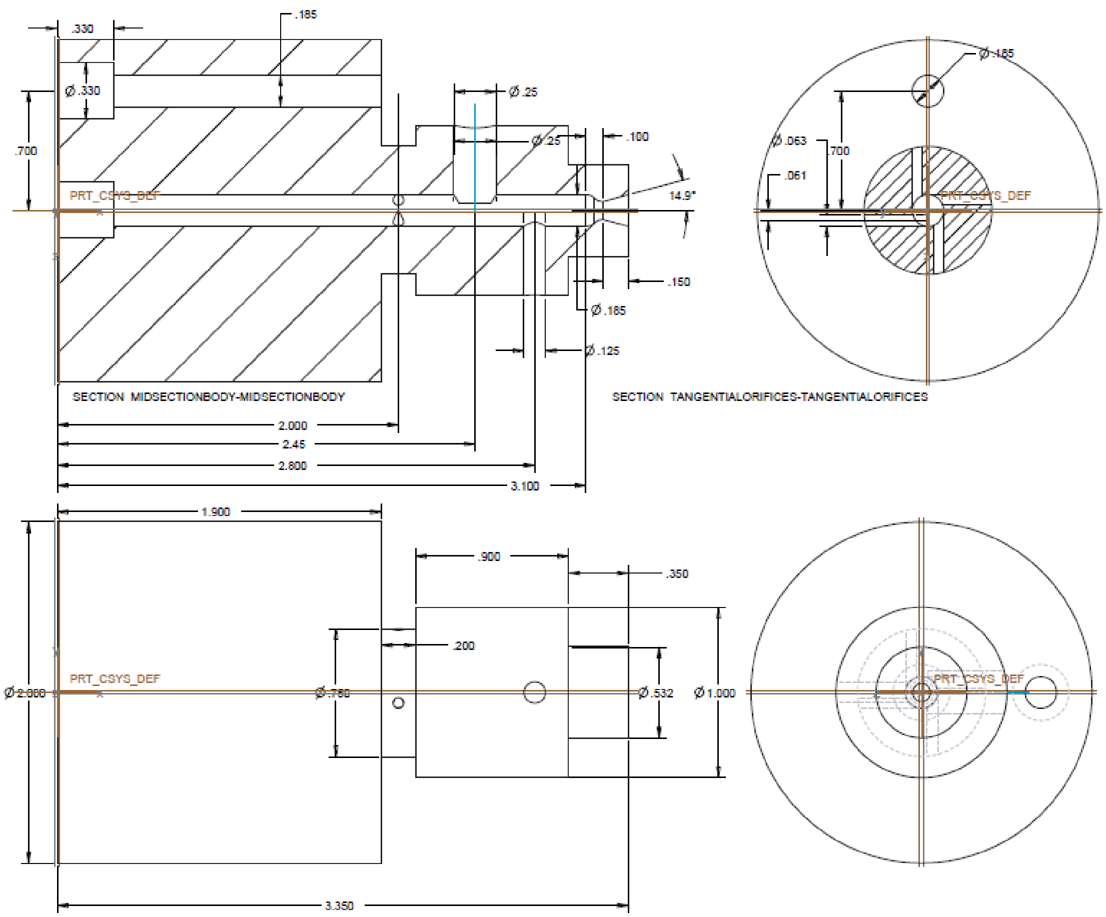

Figure 75 Swirl Torch Igniter # 2

Table 5 Calculated Chamber Volume and L*

Igniter #	L_1 in	L_c in	A_t/A_1	$V_c\ in^3$	L^*
1	2.1	0.1	0.33	0.062	6.87
2	1.1	0.1	0.33	0.035	3.87

4.2 Test Set up

For this set of test methane and oxygen at their gaseous state were used. The Ambient Test Stand was used to place the test articles inside. There were some modifications done to cryogenic delivery line as well as to the methane delivery line. A fluid schematic, a list of instrumentation and the method for propellant measurement will be discussed in this section.

4.2.1 Fluid Schematic

There were some modifications done to the cryogenic delivery line from how it was being used in the liquid-liquid tests. The cryogenic filter was taken off the line, since there was no need for it, and it as well was done to eliminate the pressure drop it was creating in the line. The cavitating venturi was taken off as well from the line since there was no use for it and as well to eliminate the pressure drop by it. Needles valves were added to the system as well as two pressure transducers inside the ATS. Figure 78 shows the Fluid schematic.

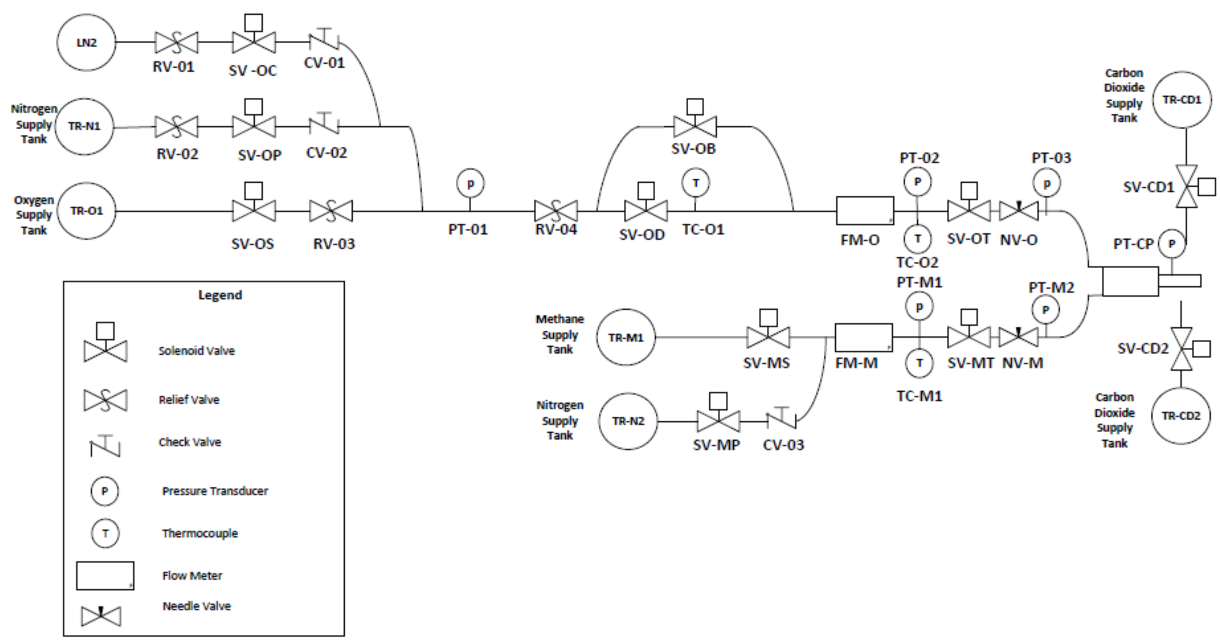

Figure 76 Fluid Schematic

4.2.2 List of Instrumentation

The next table shows the list of instrumentation used for testing.

Table 6 List of Instrumentation

Comp. Type	Component Name	Functional Description	Manu-Facture	Model	Identifier
MEASURE	Cryogenic Pressure Transducer	Measure the pressure of cryogens	Omega	PX1005	PT-O1 PT-O2 PT-M1 PT-M2 PT-CP
MEASURE	Thermocouple	Measure the temperature of fluids	Omega	E-Type	TC-O1 TC-O2 TC-M1
MEASURE	Mass Flow Meters	Measure volumetric flow rate of fluids	Omega	FMA 1700/1800	FM-O FM-M
REGULATE	Nitrogen Tank Regulator	Regulate the pressure from the source gas tank	Harris Harris	9296 425-125	TR-N1 TR-N2
REGULATE	Methane Tank Regulator	Regulate the pressure from the source gas tank	Airgas	Y11-215F-350	TR-M1
REGULATE	Oxygen Tank Regulator	Regulate the pressure from the source gas tank	Smith	35-125-540	TR-01
VALVE	Solenoid Valve	Control fluids flow in the	Gems Sensors & Controls	D2064-LN2-C203	SV-OB SV-OT SV-MT

		delivery lines			SV-MP SV-OS
VALVE	Solenoid Valve	Control fluid flow in the delivery Lines	Jefferson	YC1390BT4UCT-0	SV-OP SV-0S SV-OD SV-CD1 SV-CD2
VALVE	Pressure Relief	Release pressure in lines if pressure goes above 220 psi	Generant	CRV-500B-K-220	RV-01 RV-02 RV-03
Valve	Cryogenic Check Valve	Allow the flow of fluids in one direction only	Ratterman	CCV-F12	CV-01 CV-02 CV-03
Valve	Needle Valve	Control Fluid Flow in the Delivery Lines	Swagelok		NV-O NV-M

4.2.3 Propellant Flow Measurement

The propellant flow was measured with Omega mass flow meters. This flow meters output the volumetric flow of the propellants in Liters per minute. These flow meters are calibrated by the manufacturer using nitrogen gas, and they provide a Table with the conversion factors to convert the given reference flow rate to the actual. For this case to obtain the actual flow for the oxygen the given flow rate had to be multiplied by a conversion factor of 0.9926, and for the methane flow the conversion factor is of 0.75.

4.2.3 Test Sequence

There were several tests done in order to have a set test sequence to run the tests. There were several variables in the time given to the spark plug to be sparking, as well has the timing in the solenoids opening and closing. It was noted that when one second lead was given to the

oxygen the flame was steadies and did not pulse as when there was no lead in any of the valves. The sequence used for this set of testing is shown below.

Table 7 Test Sequence

Time	Action
0	Nothing
1	Open SV-OS, SV-OD,SV-MS
2	Open SV-OT
3	Open SV-MT, Spark Plug On
4.5	Spark Plug Off
6	Close SV-OT, SV-MT
8	Close SV-OD,SV-OT,SV-MS

4.3 Data Obtained

This section will include the test matrices followed. It will describe the data points obtained for each igniter. And it as well includes some of the difficulties encountered during testing.

4.3.1 Test Matrix

The point of this test matrix was to repeat the data points as close as possible in the two igniters so the performance could be evaluated. Cold flows with gaseous nitrogen were done to observe the mass flows obtained in each line at different set Tank Pressures. A range of MR between 2 and 6 were to be tested to map the chamber pressure obtained to the mixture ratio.

Table 8 Test Matrix

Oxygen Tank Pressure psig	Methane Tank Pressure psig	MR	Total Mass Flow lb/s
128	115	2	0.035
120	110	3	0.035
120	105	4	0.035
125	105	5	0.035
125	100	6	0.035

4.3.3 Data with Swirl Torch Igniter # 1

The first point tested was a mixture ratio of 4. Figure 78 shows the plotted data obtained from the test. There are to y-axis plotted along the Time, the x-axis. The axis to the left shows the mass flow and the y-axis to the right shows the pressures. The plotted pressures are the pressures after the flow meters, the injection pressures and the chamber pressure.

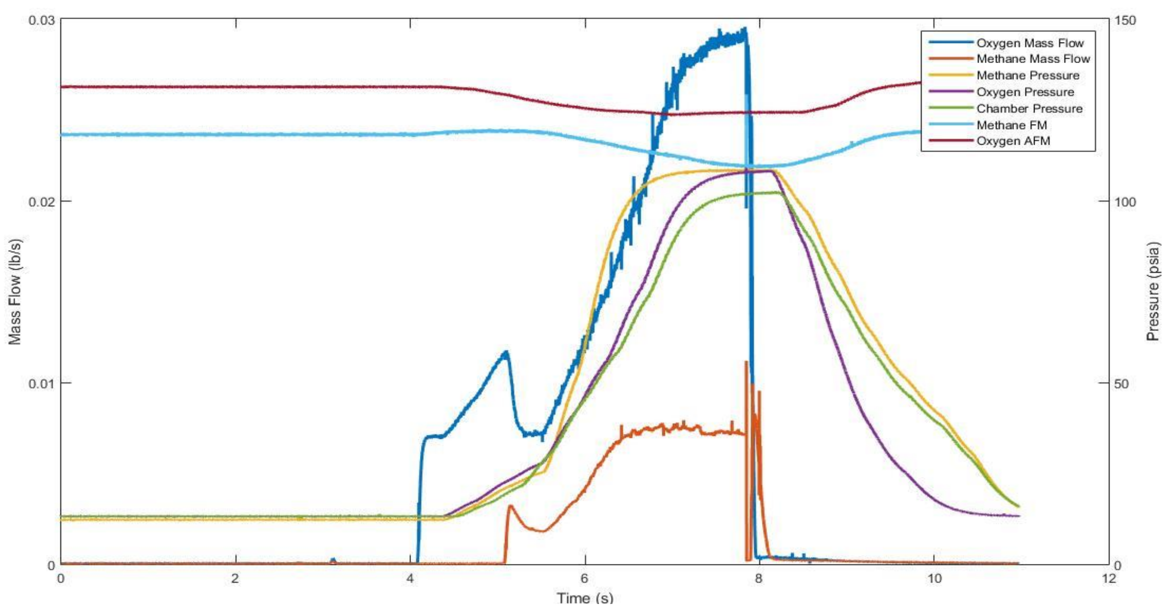

Figure 77 First plot for mixture ratio of 4

From this figure it can be seen that there was about a second and a half of about steady state burn data. This is seen when the Chamber Pressure evens out through the burn. The table below shows the data obtained during the steady state burn. Figure 79 and 80 show the 2 repeated tests for this mixture ratio.

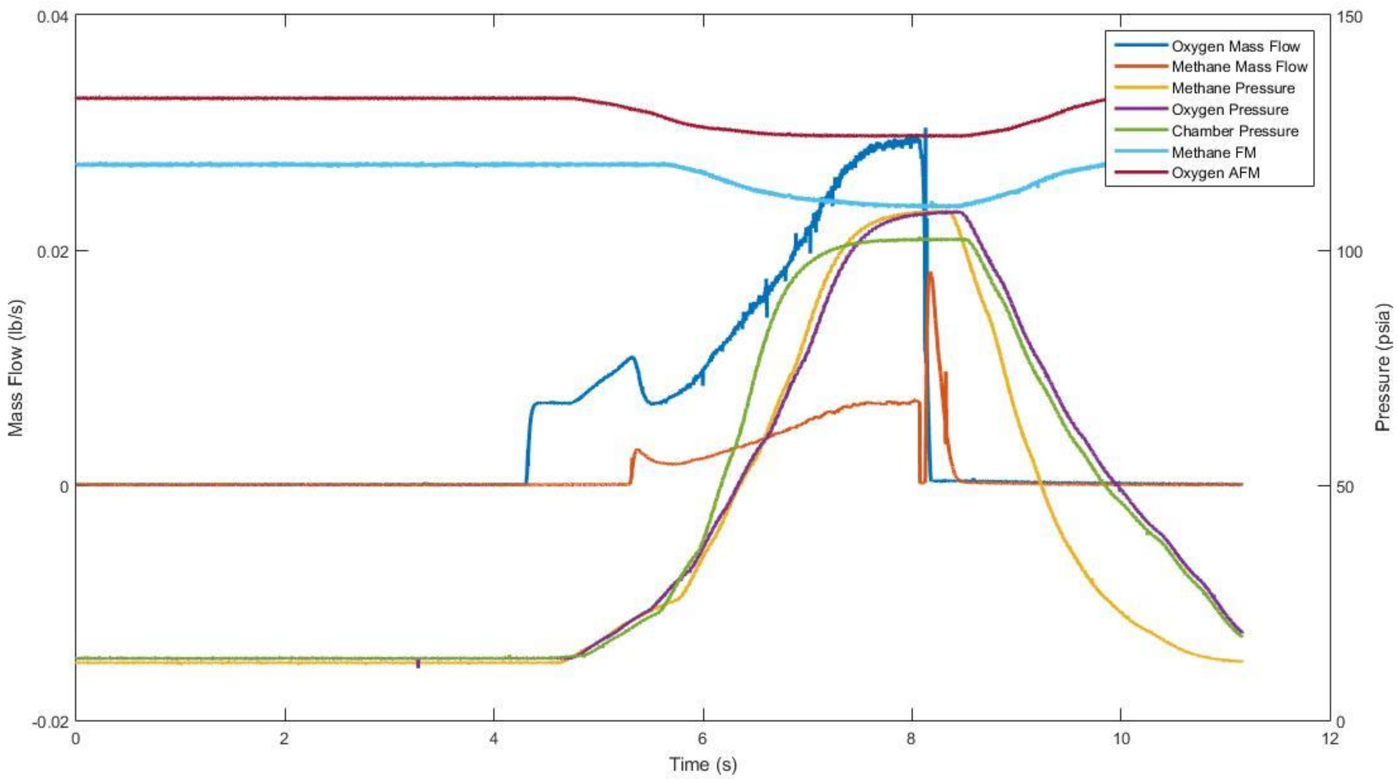

Figure 78 Second plot for MR 4

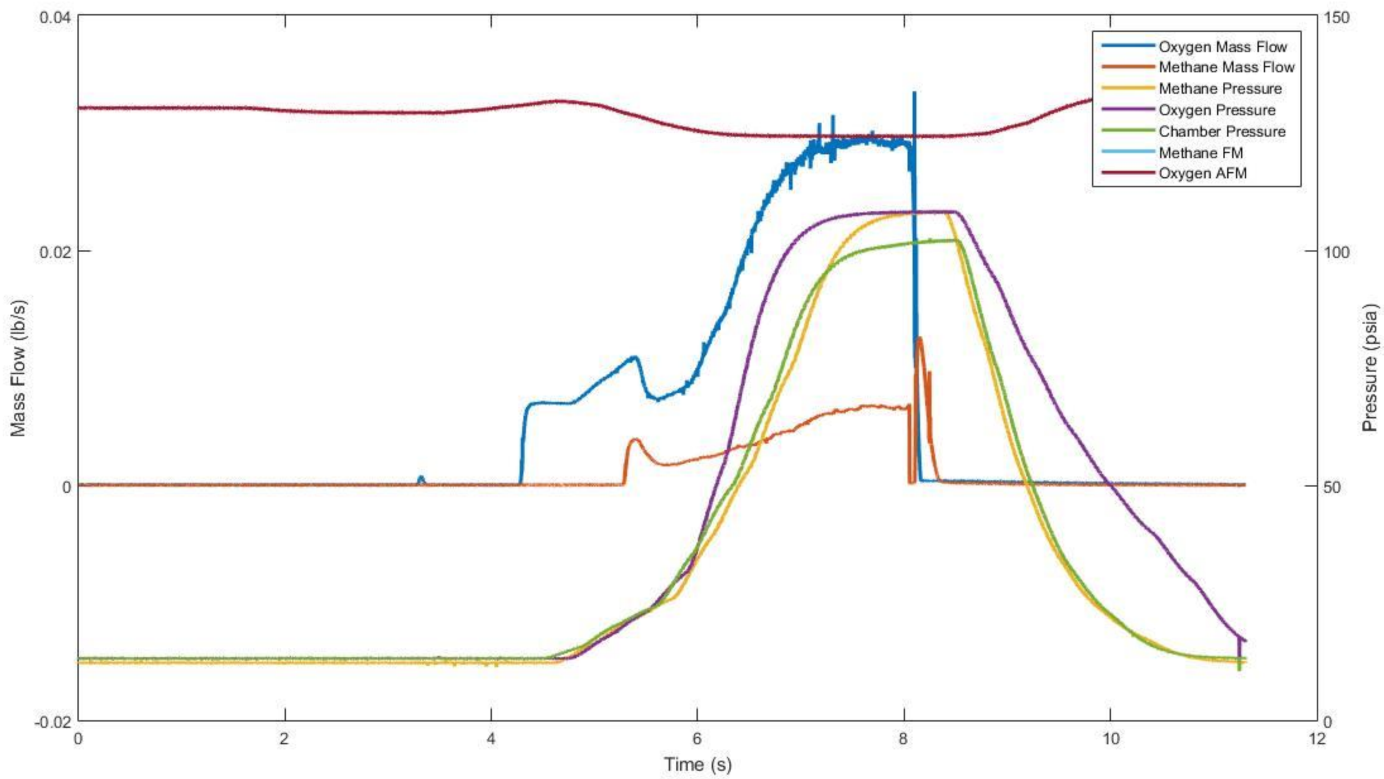

Figure 79 Third plot for MR 4

The three tests had similar output data. The table below shows the pressures and mass obtained in each test. Figure 81 shows a snapshot taken from the first test for this mixture ratio.

Table 9 Data for MR ~ 4

	Test # 1	Test # 2	Test # 3
Oxygen Mass Flow lb/s	0.029	0.029	0.029
Methane Mass Flow lb/s	0.0072	0.0072	0.0072
Chamber Pressure	102	102	102

psia			
Oxygen Injection Pressure psia	108	108	108
Methane Injection Pressure psia	109	108	108
MR	4	4	4

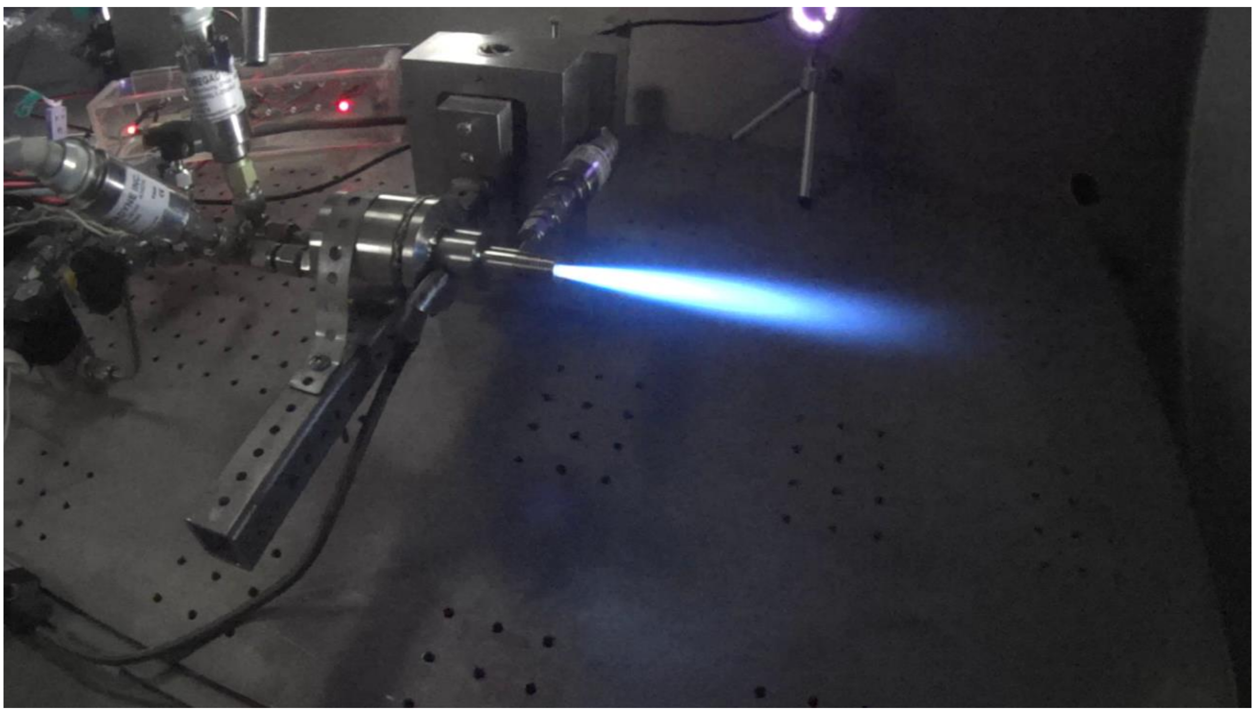

Figure 80 Picture form MR 4 test

The next point tested was a mixture ratio of about 5.6. The set tank pressures for these tests were of 125 psig on the oxygen and 100 psig on the methane. Figure 82 through 84 show the three repeated tests. The first tested showed a noise in the signal from the mass flow meter. The third test shows a big spike around 7.5, it is considered to be a noise that comer from when the solenoid thrust valves close.

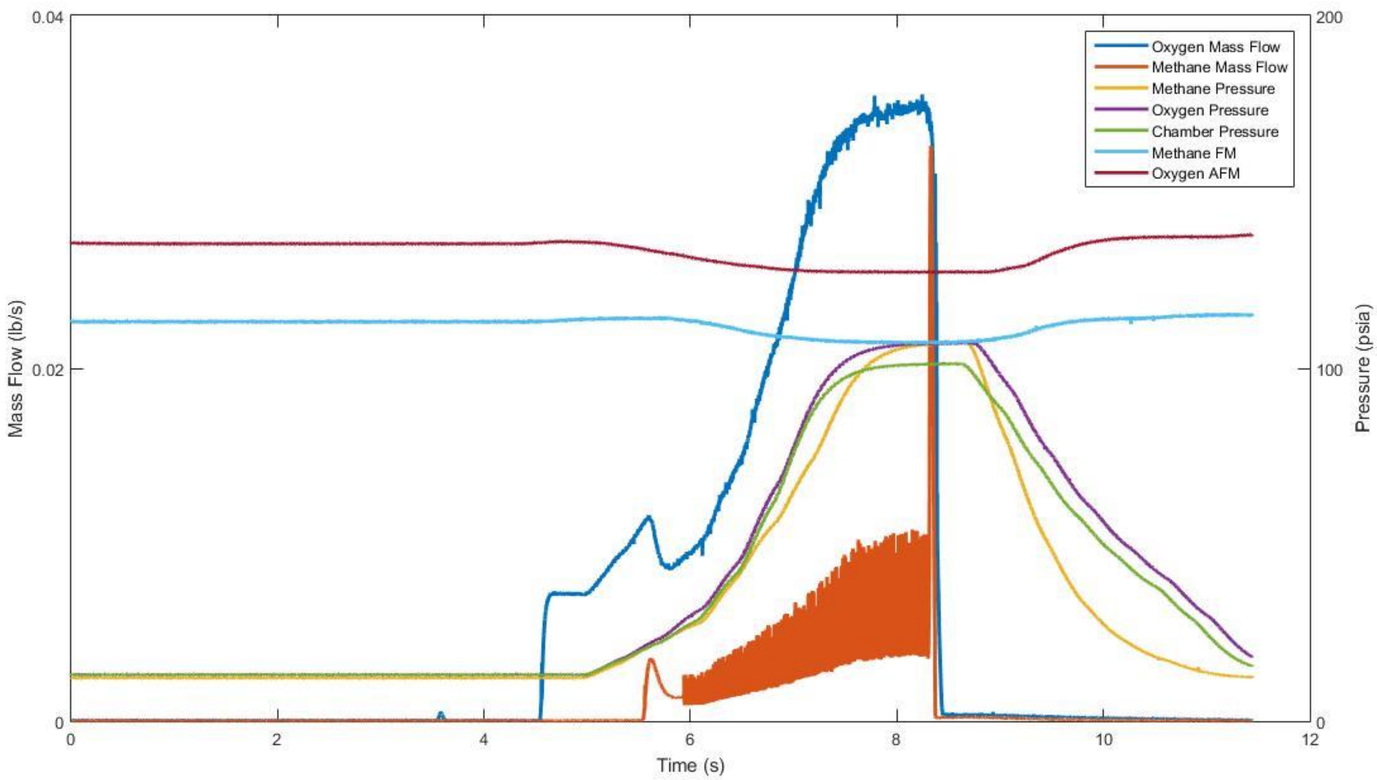

Figure 81 First plot for MR ~ 5.5

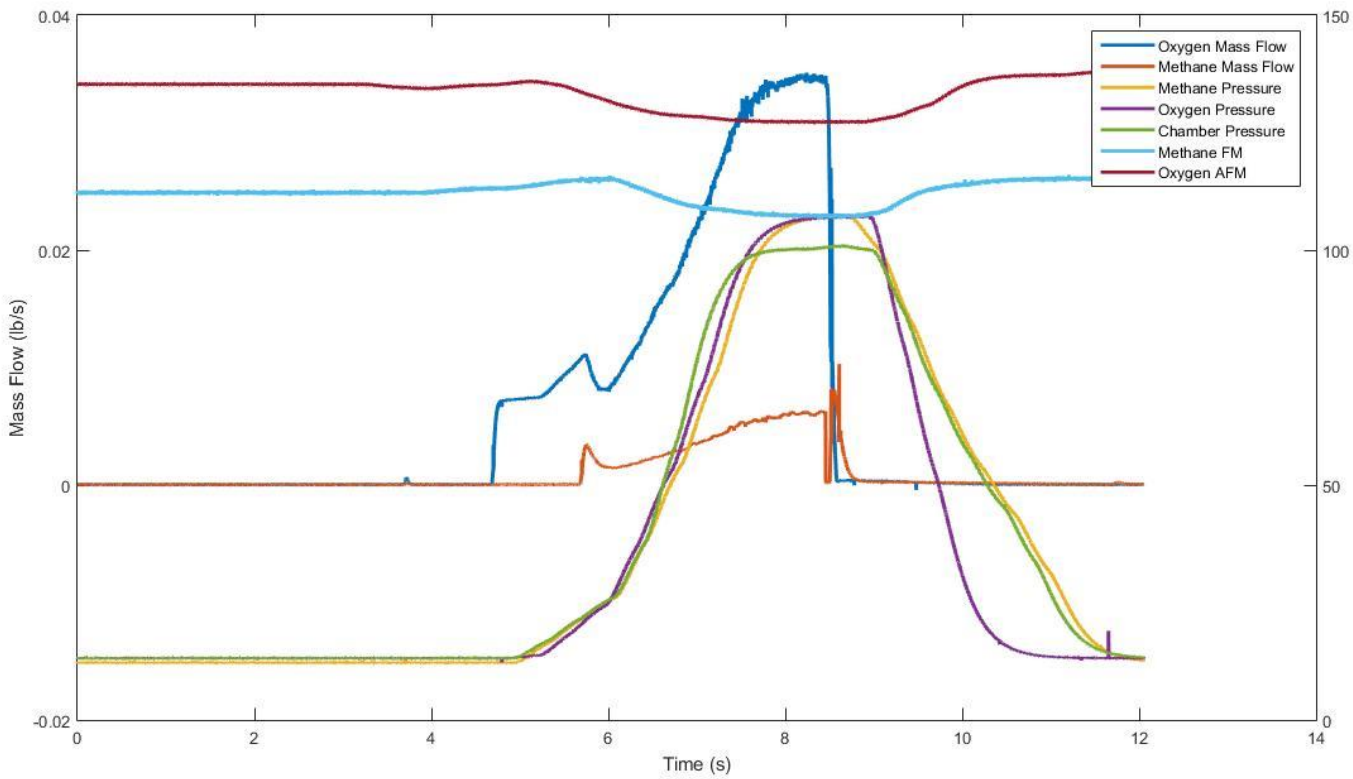

Figure 83 Second plot for MR ~ 5.5

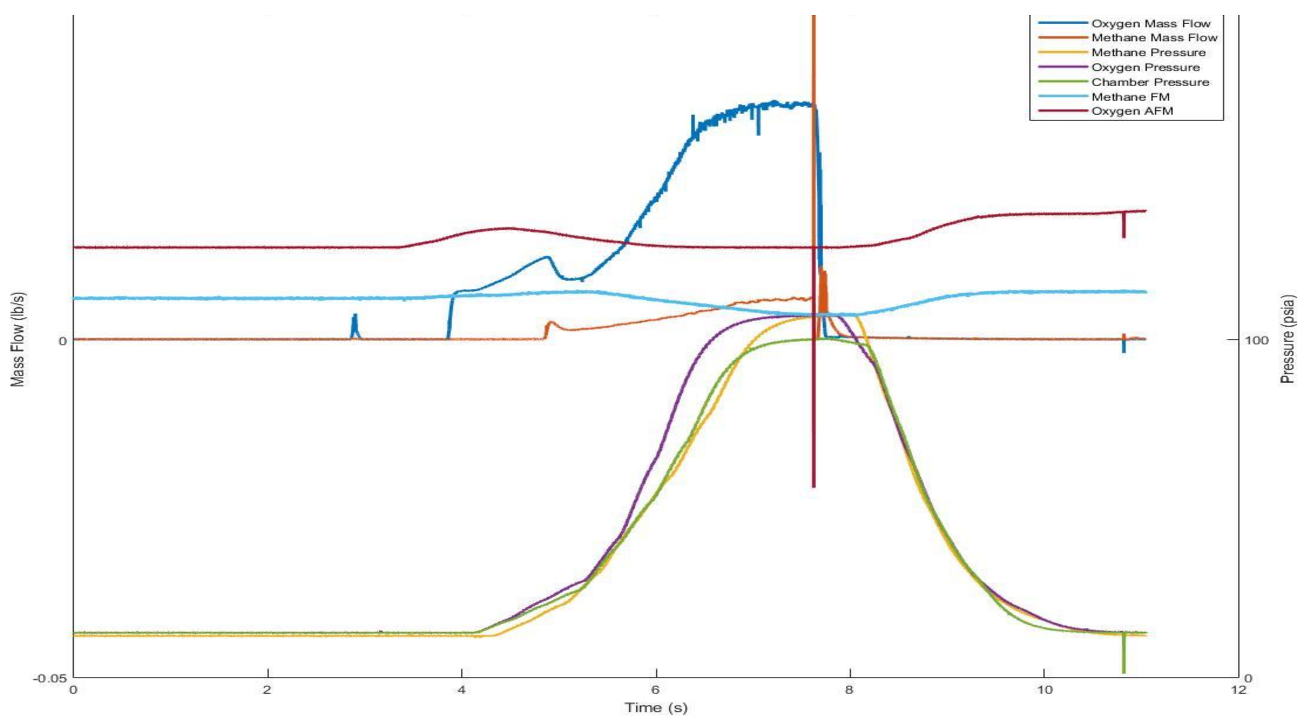

Figure 82 Third plot for MR ~ 5.5

The following table shows the pressures and mass flows obtained in each test during the steady state data obtained from the steady burn.

Table 10 Data for MR ~ 5.6

	Test # 1	Test # 2	Test # 3
Oxygen Mass Flow lb/s	0.034	0.034	0.034
Methane Mass Flow lb/s	0.006	0.0061	0.006
Chamber Pressure psia	101	100	100
Oxygen Injection Pressure psia	107	107	107
Methane Injection Pressure psia	107	107	107
MR	5.6	5.57	5.6

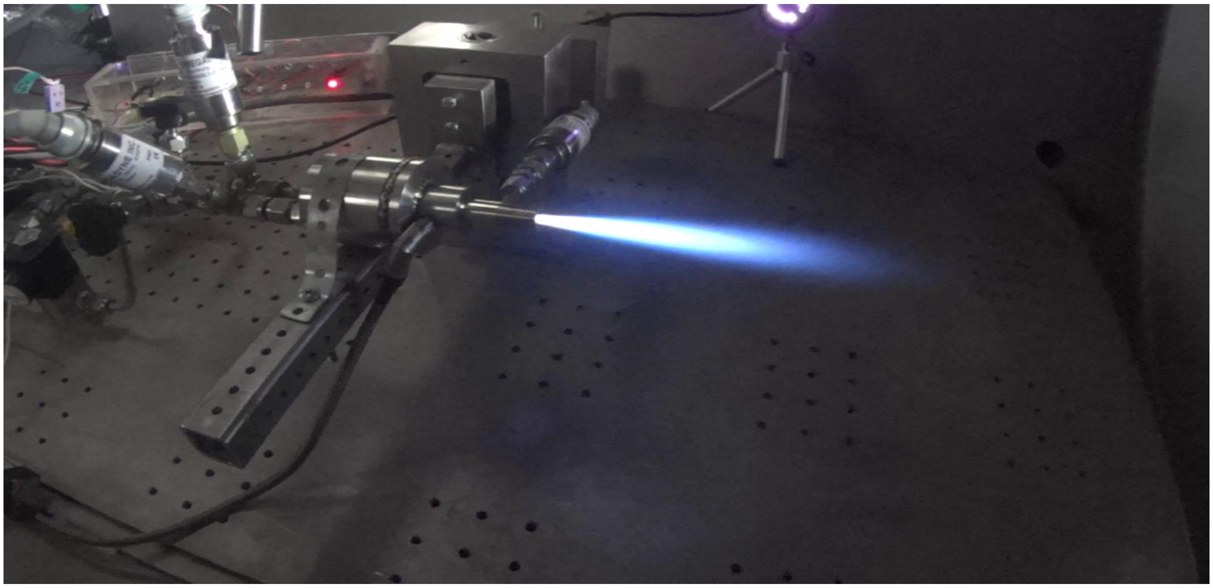

Figure 84 Picture from MR 5.6 test

The next point shows a mixture ratio of 3.5, with set tank pressures of 120 psig for Oxygen, and 108 psig for the methane. Figure 86 and Table 11 show the data obtained from this test, and Figure 87 shows an image taken form the test. This point could not be repeated because chamber pressure transducer failed, this can be seen in the data were the pressure in the chamber reads 500 psia. This failure is believed to have been caused by having combustion occur inside the chamber port, which can be seen in Figure 88 in a calibration test. It can be seen that tubing in the pressure port glows red, which is an indication that combustion may be happening inside this port.

Table 11Data for MR 3.5 Test

Oxygen Mass Flow lb/s	0.027
Methane Mass Flow lb/s	0.0077
Chamber Pressure psia	Unknown
Oxygen Injection Pressure psia	108
Methane Injection Pressure psia	108
MR	3.5

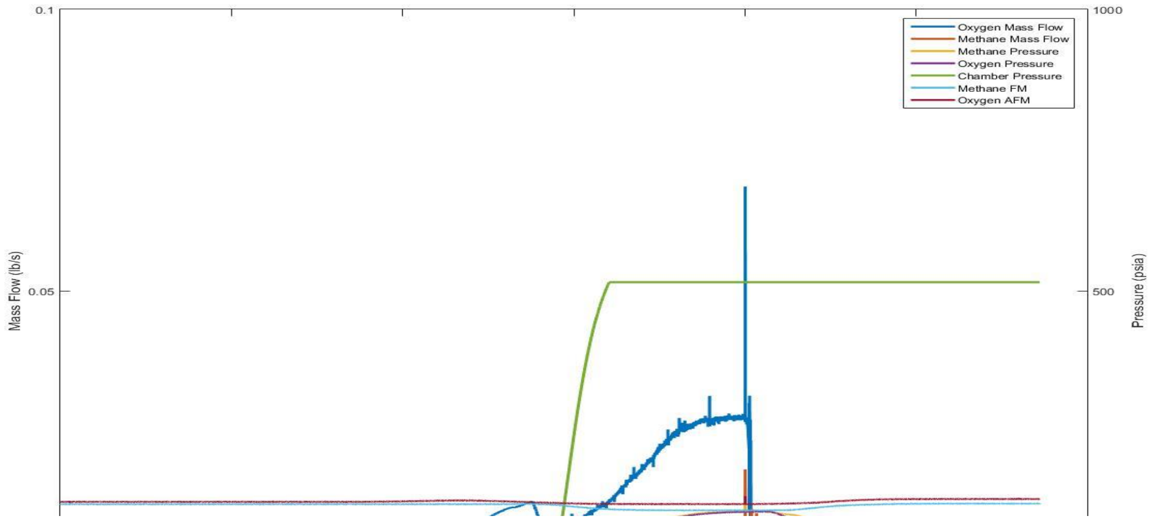

Figure 85 Data from MR 3.5 test

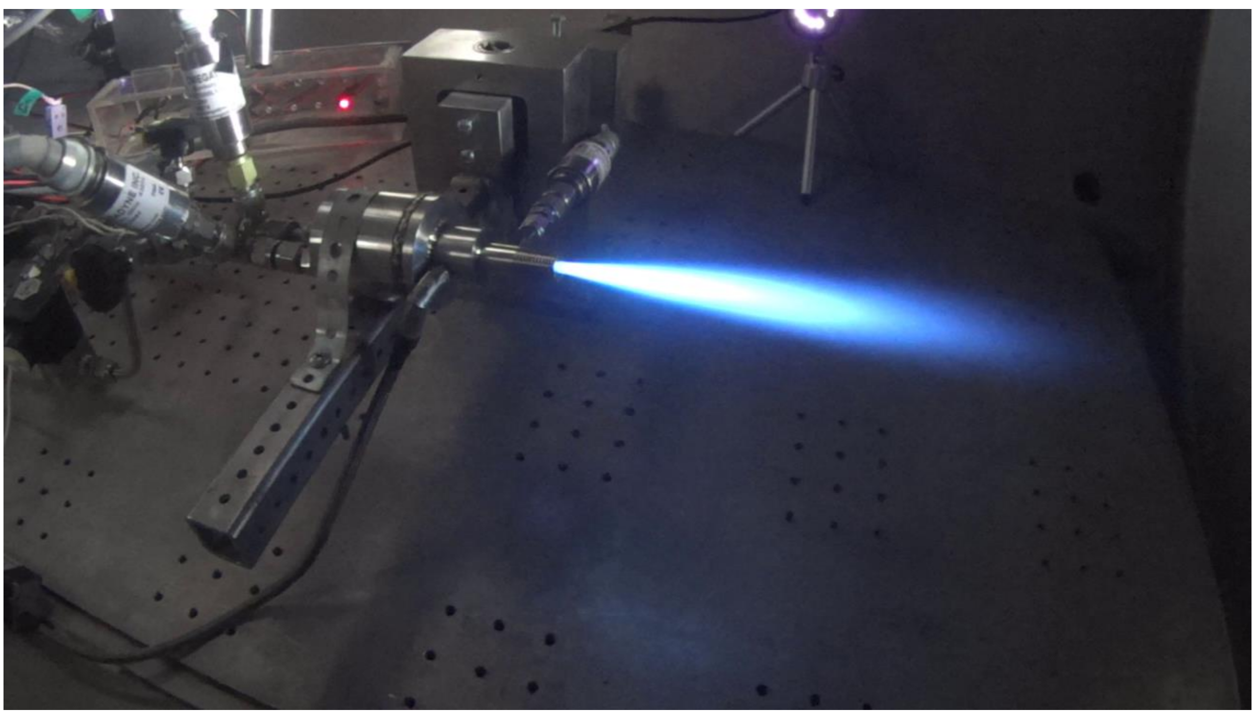

Figure 86 Image taken form MR 3.5 test

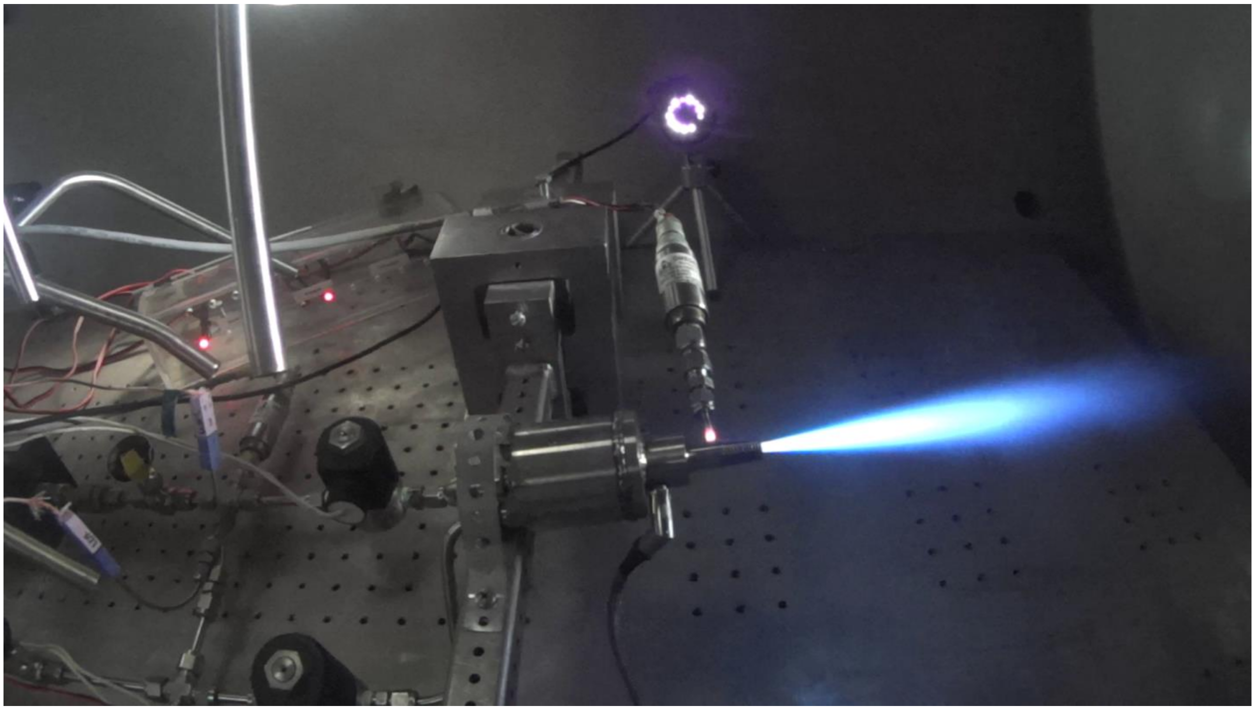

Figure 87 Calibration Test with glowing red pressure port

4.4 THRUST, C*, AND SPECIFIC IMPULSE CALCULATIONS

With the data obtained from the test the thrust, C* and Isp were calculated. With the use of the chamber pressure, the mass flow rates of each propellant, specific heat ratio, the following formulas were used to determine thrust and Isp.

$$C^* = \frac{P_c * A_t * gc}{\dot{m}_t}$$

$$Isp = \frac{Cf * \ C^*}{gc}$$

$$F = Isp * \dot{m}_t$$

In this formulas Pc stands for chamber pressure, A_t stands for the area at the throat, gc stands for the gravitational constant, Cf stands for the thrust coefficient, and $\dot{m}_t$ stands for the total mass flow rate. Table 12 shows the results from the calculations done with the data from the 2 tested mixture ratios. The data used was taken during the steady state burn.

Table 12 Thrust and Isp Results

MR	Pc (psia)	Cf	C* (ft/s)	Isp (s)	F (lbs)
4	102	1.5	792	37	1.35
4	102	1.5	804	37.6	1.36
4	102	1.5	801	37.6	1.36
5.5	101	1.5	740	34.8	1.34
5.5	100	1.5	732	34.79	1.34
5.5	100	1.5	702	33	1.33

The thrust generated by the swirl torch igniter was almost the same in all 6 tests. Isp, C*, and Chamber pressure were higher at a mixture ratio of 4.0. Many conclusions cannot be taken from this data, just that the performance was higher at an MR of 4.0 based on having a higher Isp.

4.5 Future Work

The pressure port should be modified to a smaller orifice. This could prevent combustion from happening inside the pressure port, but may have other setbacks. One of the setbacks that could happen from reducing the pressure is that the response from the pressure transducer to read the pressure in the chamber may be slower, does having to increase the burn time. More thermal analysis should be done in order to determine how much the burn time can be increase.

One consideration could be in changing some of the instrumentation used in this gas/gas testing. For example the cryogenic pressure transducers are not required for this testing, and less expensive transducers could be used for this application. As well as the transducer used for measuring the chamber pressure should be taken into consideration, since having a highly sensitive transducer close to combustion may lead to damage.

Another consideration for the swirl torch igniter should be reducing the mass. This extra mass besides making the igniter heavy may lead to having to cool down the igniter for much longer to keep cryogens liquid. And if liquids are achieved it would be a matter of how long could this cryogens be maintained liquid. This igniter could be made lighter by removing the excess material surrounding both propellant inlets up to the fuel manifold.

Chapter 5

5.1 CONCLUSION

The continuation work on the flammability map of liquid oxygen and liquid methane was stopped due to having several setbacks. Some of the setbacks were having a sparker melt in very test as well has the test article meltdown. This setbacks lead to the designing of a third iteration of the swirl torch igniter. This iteration included changes in the flue delivery, sparking system, and chamber length. The characteristic chamber length was to be tested by comparing the performance of two igniters, each with a different chamber length. The modification of the chamber port should be taken in consideration in order to prevent the damaging of more pressure transducers. More mixture ratios should be tested in both igniters to compare the performance. From the small amount of data gathered

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Vita

Gabriel Ricardo Trujillo was born in El Paso, Texas in the year 1990. He was raised in Ciudad Juarez, Chihuahua, Mexico until the age of 14, when his family moved to El Paso. He received a Bachelor of Science in Mechanical Engineering in May of 2013. He has attended to internships with NASA, the first one was the Johnson Space Center in the summer of 2013, and the second one was at Marshall Space Flight Center in the summer of 2014. This thesis was written to provide as much detail about the project as possible so future generations working at cSETR would be able to reference it and know how to repeat the tests shown.

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