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# Development and Testing of an Ignition Physics Test Facility and an Oxygen/Methane Swirl Torch Igniter

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DEVELOPMENT AND TESTING OF AN IGNITION PHYSICS TEST FACILITY AND AN OXYGEN/METHANE SWIRL TORCH IGNITER

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DEVELOPMENT AND TESTING OF AN IGNITION PHYSICS TEST FACILITY AND AN OXYGEN/METHANE SWIRL TORCH IGNITER

A DISSERTATION

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# Executive Summary

There are many advantages to LOX/methane propulsion, such as in-situ resource utilization from Mars and the Moon, and simplicity of ground operations due to its non-toxic nature. There exists a lack of fundamental understanding of the ignition physics, and flame characteristics of these propellants when related to rocket propulsion, which has created undesirably long design cycles and flight hardware that is not optimized. Motivated by these issues, a study of the ignition physics of a shear coaxial injector is proposed, in which the flow field dynamics and ignition transients will be observed through a visually accessible combustion chamber. The main goal of this work is to study the effects of geometric differences of the injector, such as recess in the liquid oxygen post and thickness of the LOX post, on the jet breakup downstream of the injector, and the flame anchoring mechanism and location. A facility was developed to support this endeavor in a safe and efficient way, including a cryogenic delivery system, a Multipurpose Optically Accessible Combustor (MOAC) with torch igniter, and a bunker with a Data Acquisition and Remote Controls system (DARCS). A swirl coflow premixed torch igniter was designed, manufactured and developed with the intent of using it as the MOAC's main ignition source. It was designed to use oxygen and methane as the propellants in an incremental step towards the goal of a LOX/methane rocket engine. Extensive testing was done on the igniter in the development phase to prove that it will reliable ignite and sustain combustion under a variety of propellant inlet conditions of which include: warm gas, cold gas, and liquid cryogenic conditions. The testing phase also provided data for component reliability and proof of concept for the testing facilities designed, especially for the cryogenic delivery system, and methane condensing unit. Future injector testing parameters of the hardware produced is included along with recommendations to provide a knowledge base for the laboratory.

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# Chapter 1

## 1.1 Introduction

It is a well-known fact that liquid methane is an excellent propellant candidate for rocket engine propulsion due to its high specific impulse, and high density. The interest in this propellant, however, has been intermittent throughout the past few decades, with most of the research and hardware development efforts directed towards more traditional fuels such as hydrogen and kerosene [1]. Aside from the high bulk density impulse of liquid methane, other advantages include: the ability to store both fuel and oxidizer at similar temperatures ($LCH_4$ requires storage temperatures around 110 K to maintain its cryogenic state, whereas LOX requires 90 K), and simplicity of ground testing operations due to its non-toxic nature and relative low price, compared to liquid hydrogen and hypergolic propellants.

Recent developments in the commercial space exploration sector, along with the potential for developments that drive down the cost of space commercialization, have turned the focus back to LOX-hydrocarbon propulsion, especially the combination of LOX/Methane. One of the reasons that LOX/Methane is of great interest is because it can be obtained from Martian and lunar in-situ resources [3]. Unfortunately, this new research effort has focused on modifying existing hardware such as injectors, thrust chambers, and igniters, used previously for LOX/hydrogen, or LOX/ethanol. This practice of trial-and-error has led to an undesirably long design cycle with high monetary cost making this endeavor a difficult one to succeed in. Another consequence of this is the lack of fundamental understanding of technical issues such as ignition physics, regenerative cooling, and main chamber ignition. As a result, LOX-methane rocket engines have not been optimized for flight hardware performance.

One can make educated guesses of the behavior of the propellants as they are injected into the combustion chamber, as well as model the process with Computational Fluid Dynamics (CFD) software, and include a chemistry engine to model the mixing and combustion process. These techniques are helpful only if they have been validated and anchored with experimental

data. A visually accessible combustion chamber can help resolve these issues, along with fluid flow visualization techniques such as Schlieren Imaging, Particle Image Velocimetry (PIV) techniques, intensified images of the combustion process, and Phase Doppler Particle Analyzer (PDPA), in addition to other light scattering techniques. A thorough understanding of the ignition physics, along with its transients, and the flame anchoring will provide the rocket engine designer with the information needed for sound engineering decisions.

Ignition has been identified as the highest risk for LOx/$CH_4$ propulsion systems [1]. Literature suggests that the preferred method of ignition so far is spark torch ignition, however, there has been work done with microwave, piezoelectric, catalytic ignition, non-resonant laser ignition, and combinations of spark torch and glow plug. Requirements for duty cycle, precision of pulse width, thermal control and the reliability of power exciter units have been the main challenges to overcome for torch igniters and oxygen/methane propulsion systems as a whole.

## 1.2 LITERATURE REVIEW

### *1.2.1 LOX/Methane Rocket Engine experience*

Aerojet, USA has been testing an 870 lbf thrust LOX/$LCH_4$ engine with a LOX/$LCH_4$ torch igniter [1]. The hardware was originally designed for LOX/ethanol thruster residual from the Kistler Program; with minimal modifications done to convert to LOX/$CH_4$. The injector orifices were enlarged in the split-triplet design injector plate with film cooling to improve combustion stability. The start sequence had a fuel lead which resulted in an initial Mixture ratio (MR) overshoot as expected. The test conditions tested were chamber pressures from 111 to 190 psia with mixture ration varying from 1.45 to 3.59 with hotfire durations of up to 30 sec. It was noticed that methane is not as good a film coolant as other propellants. The igniter used for these experiments was a GOX/ethanol igniter from the original Kistler OMS injector located at the center of the injector plate. A 97% energy release efficiency and stable combustion was demonstrated at all operating conditions.

Another Aerojet Reaction Control Engine was tested in collaboration with the NASA Johnson Space Center, Glenn Research Center and White Sands Test Facility [2]. It was a 100 lbf LOX/$LCH_4$ with the same injector design as the described above with an integral igniter/injector constructed from nickel alloy materials for LOX compatibility and Aerojet proprietary platelet fabrication process. With chamber pressures varying from 160 to 210 psia, thrusts ranges from 84 to 115 lbf, were achieved with specific impulse (Isp) of 320 s. This same engine was tested in vacuum conditions in the NASA John H. Glenn Research Center at an approximate altitude of up to 130,000 ft, where the engine performed to an Isp of 305 sec, very close to its theoretical target of 317 sec. It was noticed that warmer propellants have higher performance due to the available enthalpy they present, while colder propellants displayed greater efficiency. In the future they plan to explore the ignition margin testing, as well as pulsed operation testing.

### *1.2.2 Uni-element Shear Coaxial injector studies*

In the study of shear coaxial injectors, the literature agrees that there are several parameters of importance for the liquid sheet breakup, atomization, and turbulent mixing of the propellants. These parameters are the Weber number, which is the inertia of the fluid divided by its surface tension; the Ohnesorge number, which is the relationship between viscous forces to surface tension; the bond number, which characterizes the shape of drops moving in a surrounding fluid or the proportionality of buoyancy force divided by surface tension; velocity ratio, and momentum flux ratio of the propellants. All of these parameters can be related to the liquid breakup regimes ranging from Rayleigh Mechanism, where the droplets produced are of the same order of magnitude as the diameter of the original jet, to the the first and second wind induced regime, and finally atomization when the Weber number is large enough [6].

Delphine Salgues and Robert Santoro et al. experimentally studied two different single element swirl coaxial injectors with LOX/$GCH_4$ as propellant and compared it to a shear coaxial injector under the same conditions [4]. They analyzed the flame structure and liquid core

breakup using OH Planar Laser Induced Fluorescence (OH-PLIF), OH* chemiluminescence, laser light scattering and shadowgraph imaging. The target flow conditions were: 4 bar, with propellant flowrates of .12 kg/sec for LOX and .04 kg/sec for $GCH_4$, to provide a MR of 3. The only difference in the two swirl injectors is the inner LOX diameter, with the diameter on the second injector being larger. Under the same conditions, the shear coaxial injector is at a disadvantage since the swirl injector will exit the LOX post as a hollow cone expanding radially, creating more contact with the high speed methane around it. The authors consider the velocity ratio of propellants of importance for better atomization of the propellants along with other parameters to be calculated with these velocities such as Weber Number, Momentum Ratio, and Momentum Flux ratio.

The Weber number calculated for the swirl injectors is calculated to be 65,400 and 8,400 for the swirl injectors, while the We for the shear coaxial injector was an order of magnitude larger at 438,293. As it was expected, the C* efficiencies for the swirl injectors, 95 and 91 respectively, were higher than the 85 efficiency of the shear coaxial injector. Under the shadowgraph technique, liquid sheet disintegration is seen in all three cases, with better disintegration in the swirl injectors. The shear coaxial does not exhibit dramatic changes to the liquid core until further downstream. When the combustion process is observed under OH-PLIF with a laser wavelength of 283.93, the signal is closer to the injector face on the most efficient injector, and it is scattered away from a centerline for the other injectors. The authors hypothesize that the presence of combustion away from the center of the chamber is due to recirculation of unburned methane which in turn is associated with lower combustion efficiencies. The OH-PLIF signal closely follows the methane flow in all cases, but as expected, combustion is not present in areas of high methane concentration.

From the OH* chemiluminescence measurements it can be seen that in all cases the propellants are burning in a nearly symmetrical cone surface with the swirl injector showing a larger cone angle due to its conical liquid sheet characteristics at the exit of the injector. The images were averaged over time, and compared to each other on the basis of breakup length for

all three injectors and flame penetration toward the centerline. The OH* signal diverges and extends away from the liquid core further downstream due to the atomization and final evaporation of the LOX. The authors theorize that there could be an inner flame front close to the LOX core evaporating due to the disagreement of the OH* chemiluminescence and the OH-PLIF signal position. They blame the line-of-sight nature of instantaneous chemiluminescence that cannot be directly compared to the OH-PLIF which is a 2D method. A very important thing to point out is the fact that the authors found the LOX/$GCH_4$ mixture very difficult to ignite and they achieved ignition transitioning slowly form hydrogen as fuel to $CH_4$.

### *1.2.3 Ignition Characteristics*

Published in 2009 by Chiara Manfletti, Joachim Sender and Michael Oschwald, the article "Theoretical and experimental discourse on laser ignition in liquid rocket engines", explores the different ignition sources for the environmentally friendly "green" propellants. The method of ignition of principal interest is laser ignition, which can be categorized into four groups: thermal, photochemical, resonant, and non-resonant. After providing a theory review of the flame kernel growth as a function of the laminar flame speed, the authors consider a shear coaxial injector, and provide possible laser ignition points very close to the injector face on the shear layer between the two coaxially injected jets. Several different parameters are tested in which the MR varied from 3.4 to 4.7, with a chamber pressure of maximum 1 bar, and We numbers in the range from 10180 to 43000 and momentum flux ratios from .26 to 1.74. All experiments were done on a 60x60x140 mm optically accessible combustor horizontally mounted.

Schlieren images are provided to observe the ignition with an Nd:YAG laser, which takes place one fifth of a chamber downstream of the ignition source, and the flame kernel growth is not symmetric in the upstream and downstream directions. It is clear that the flame growth process is initially slower than the injector flow dynamics. It was also observed that depending of the parameters of injection there appeared to be three types of initial ignition: smooth, transition

and hard ignition. Smooth ignitions can be observed under OH intensified images to begin as a flame kernel growth and anchor the flame near the center of the injector. Upon initial laser pulse to create the plasma necessary for ignition there appears to be no flame, then the flame moves downstream and slowly travels towards the injector plate. They were characterized by low ignition delay, low spikes of the chamber pressure, high momentum flux ratios (J) and low We number. Hard ignitions presented high We and low J values, with the highest peak chamber pressure and highest ignition delay. The intensified images displayed rapid flame kernel growth beyond the injector stream to encompass the entire chamber. This characteristic sudden expansion of the propellants as they are almost instantaneously combusted makes the flame occupy the entire chamber and sometimes is extinguished since the chamber pressure rose beyond the injection pressure starving the flame from fresh propellants. Transition ignitions displayed characteristics of both smooth and hard ignitions with relatively high chamber pressures, but featuring low J and We. They are characterized by a rapid expansion of the flame kernel which usually traveled downstream. The expansion is slower, however, than the hard ignition and the flame does not encompass the entire chamber, and the flame stabilizes close to the injector faster.

The authors go on to establish relationships between a high mass flow rate to a high ignition overpressure, which is expected since ignition overpressure is a function of mass of unburned propellants and their mean residence time. There is however a set of tests that presented a high peak chamber pressure with a relatively low mass flow. These are transition ignitions and are explained by the comparison of the We number to the J; in which it is clearly seen that a low We and J which is usually accompanied by a high LOX Mach number, presents an ignition with smooth and hard characteristics. It is also demonstrated that the graph of the Oh number vs. the Re number follows a similar trend as the LOX Mach number and J, a graph which is also commonly used to determine liquid jet breakup regime [6].

### *1.2.4 Comparison of LOX/$H_2$ sprays with LOX/$CH_4$*

Under the premise that LOX/$H_2$ shear coaxial injectors have a big database of research behind it, a Oschwald, M. et al. set out to compare the characteristics that these injectors exhibit using LOX/$CH_4$ [8]. The authors develop a systematic approach to study the spray pattern, flame pattern and ignition characteristics with different We numbers, Momentum flux ratios (J) and chamber pressures. The spray patterns are visualized with Schlieren photography, while the flame imaging is achieved with chemiluminescence of the OH-radical, both applied at frame rates up to 10 kHz to resolve dynamic phenomena.

For the spray pattern is it evident that increasing the J results in higher dispersion of the liquid core, and a decreasing the break-up length. These findings are in accordance with the findings of previous works for cold flow. The authors, however, state that the visible break-up length in the hot fire tests is larger than predicted, but at the same time, a high We will present a sudden change in the atomization behavior. The authors also claim that the We and J, which characterizes the cold flow injection conditions do not necessarily reflect the spray formation mechanisms in hot fire tests. Furthermore, as their Schlieren imaging suggests, atomization is significantly more efficient in the case of $CH_4$ for all injection conditions. The addition of combustion in the hot fire tests completely changes the atomization process, since the liquid oxygen is not directly exposed to the shear forces of the annular gaseous flow, but these forces have to be transmitted by the turbulent mixing layer of reaction products and evaporated oxygen to the liquid surface.

For the flame pattern, the spreading angle of the LOX/$CH_4$ is significantly larger than the LOX/$H_2$ tests, with the quantitative data correlating best with We number than with any other non-dimensional number such as J, velocity ratio, Oh number or liquid Reynolds number. The authors claim that increasing the We results in higher evaporation rate of the LOX core with more efficient atomization and increased reaction products and heat release. Flame anchoring on the LOX post is consistently observed in the LOX/hydrogen test case, however, with methane the flame is lifted from the post and anchored in the turbulent mixing lager of evaporated LOX

and gaseous fuel. In the majority of the tests for methane, the flame was lifted off the LOX post without any correlation to the We or the J.

The effect of the chamber pressure atomization was also explored. According to the Schlieren photography, the spreading angle of the mixture was larger with lower chamber pressure, but this effect started further downstream of the injector, while the spreading angle was lower in higher chamber pressure but was located almost right at the injector. The location of the first breakup of the LOX core can be indicative of where the flame will be anchored, proof that the first and second wind induced breakdown have a positive dependence on chamber pressure since both injection pictures were taken with very similar We and J. Although the process of atomization starts later in the lifted flame condition, it looks significantly more violent downstream of the flame anchoring position.

#### ***1.2.5 Numerical simulations of LOX/methane shear coaxial injector***

Vigor Yang and Nan Zong investigated the mixing and combustion of LOX/methane on a shear coaxial injector with numerical methods. The near-field flow and flame dynamics are resolved for the injector operating under supercritical pressures, with a model that takes into account full conservation laws, real-fluid thermodynamics and transport phenomena over the range of fluid states. Transport properties such as viscosity and thermal conductivity are estimated with the 32-tern Benedict-Webb-Rubin equation of state, while the combustion was modeled by a one-step global reaction model involving four species ($CH_4$, $O_2$, $CO_2$, and $H_2O$). Turbulence closure is achieved using the large eddy-simulation technique.

When characterizing a flame regime for turbulent non-premixed combustion, the Damkholer ($D_a$) number is an important parameter to keep in consideration, and it is defined as the ratio of the characteristic time for turbulent integral-scale motion to the characteristic time of the chemical reaction. When the $D_a$ is large, thin flames also known as flamelets exist, and occurs because the chemical time is small. As the chemical time increases, the flame thickness becomes the same order of magnitude of the Kolmogrov eddies, and the unsteady effects must be

taken into account. For low $D_a$ numbers, the flame extinguishes, and indicates that the chemical reaction is taking place very slowly. In most cases vaporization is the slowest process at a subcritical temperature, and allows part of the unburned oxygen droplets to penetrate into the flame.

Two simulation scenarios took place under 100 atm chamber pressure conditions, with a mixture ratio of 3 and momentum ratios of 2.5 and 4.3. The first thing that the authors point out in the results section is a diffusion-dominated flame that begins from the LOX post and propagates downstream from the surface of the LOX stream. The near field flow dynamics are characterized by the development of three mixing layers from the methane inner and outer edges of the annulus, and the LOX post. The middle layer is inhibited by the combustion products expansion where the flame is propagating. Large scale vortices are observed emerging from the outer rim, where they combine with each other, enhancing the mixing of methane and convecting downstream. A higher momentum ratio, as in the second case of the simulation, only increases the vortex pairing creating stronger mixing of methane, hot combustion products, and faster break up the LOX steam.

Enormous density gradients occur due to the liquid nature of the oxidizer core, and the shearing methane, creating a wake of recirculating propellants in the LOX post, where the flame is anchored and propagates along the LOX jet. As the vortices roll downstream of the oxidizer jet, periodic fluctuations are observed, and the amplitudes of the velocity fluctuations are increased with the growth of the vortices. The axial velocities are recorded and a power spectral density is performed on the fluctuations. A frequency of 13.8 KHz is obtained from the first case which corresponds to a momentum flux of 2.5 while the 4.3 momentum flux of the second case causes an increase of vortex shedding frequency of 17.2 KHz. This phenomenon can be attributed to the strong inertia of the LOX jet in comparison with the lighter density of the methane.

### *1.2.6 LOX/$CH_4$ Igniter testing*

Kevin Breisacher and Kumud Ajmani from the NASA Glenn Research Center tested the feasibility of using LOX/ Methane as the propellants for a spark torch igniter for the Lunar Surface Access module ascent main engine. They tested the igniter under different conditions such as igniter body temperature, propellants temperature, and mixture ratio, obtaining data for the effects of methane purity and spark energy level. Their tests were conducted in an altitude simulation chamber in Cell 21 of the Research Combustion Laboratory, where they achieved 10 Torr backpressure with igniter body temperatures down to 144 K (260 R).

The igniter consisted of a three piece design where the oxygen was injected at the head end very close to the spark plug, and the methane was introduced slightly downstream through a manifold around the spark. The methane was made to swirl inside of the combustion chamber to provide a cooling to the chamber wall. The third part of the design consisted of a cooling jacket where extra methane was flowed around the combustion chamber and the rest of the igniter nozzle. Both methane circuits were controlled by the same valve, and their flow rates were controlled by their fixed relative flow areas.

Breisacher reports no significant change in the ability to ignite different methane purities, which consisted mainly in ethane, propane and nitrogen, ranging from 100 ppm each to around 3000 to 4000 ppm. Sparkplug recess was a different story as far as affecting the igniter body temperature threshold for successful ignition. The authors theorize that recessing the spark plug as little as .0038 m (.15 in) significantly affected ignition due to the walls providing additional surface area to quench the spark kernel. Minimum sparkplug power is described as 10 W for reliable ignition even at the coldest igniter body temperatures, while 17 mJ is reported as the minimum energy per spark.

A continuation of this work was conducted by Schneider, John, and Zoeckler moving from LOX/methane to LOX/$LCH_4$ to further the application of spark torch igniters as a reliable form of ignition for these thrusters. With a slight variation of the igniter to accommodate for four fuel doublets just downstream of the sparkplug, and a spark plug tip modification to obtain a

oxidizer rich core flow, another ambitious test campaign was undertaken with a total of 1402 ignition pulses total. The core mixture ratio, where the ignition occurs was extremely fuel lean at a mixture ratio of 20, with a liquid methane cooling jacket entraining the flow further downstream for an overall MR of 2. Unlike the previous test campaign, this igniter was provided with two different methane circuits from two different tanks to provide the core and cooling flow. Propellant flow was controlled with upstream (tank) pressure and cavitating venturis in each of the propellant feed lines.

Chamber pressures from 1040 to 1720 kPa were obtained with overall mixture ratios form 1.08 to 1.88 with LOX and $LCH_4$ inlet pressures around 2400 kPa and flow rates in the range of 15.26 to 12.28 g/sec. The author reports that about 5% of the pulses resulted in non-ignitions citing problems with clogging or freezing of the core fuel circuit, and with igniter hardware pre-chilling to liquid methane temperatures (~110 K). Pulsing testing was conducted as well with a variety of number of pulses generally with a 5 to 20% duty cycle. Sluggish valves that were slow or completely failed to open are blamed by the author for the non-ignition phenomena, while the end to the test campaign was attributed to the failure of the ceramic insulation in the spark plug after numerous pulsing tests were completed.

### 1.3 Problem Statement

The most common method for ignition for LOX/methane rocket engines is augmented spark ignition or torch ignition. A photochemical laser ignition presents problems of reliability and power requirements, while hypergolic ignition devices defeat the purpose the use of green propellants and may affect the restart characteristics of the engine. The interaction of a single element shear coaxial injector and the torch igniter jet stream is not a well understood one, and the design of more efficient engines, with better ignition control, and high response reliability depend on the behavior of the near field fluid dynamics.

There is a gap in knowledge for the use of shear coaxial injectors with LOX/methane considering different temperatures of methane, and different injection pressures. Also, the

geometry of the injector is a subject that has not been explored in its entirety, since most literature experiments with a generic shear coaxial injector. The differences in LOX post thickness, methane injection annulus differences, and recession of the LOX post can and will affect the near injector fluid flow field, disturbing the jet breakup further downstream and changing the flame anchoring mechanisms even with similar injection and chamber conditions. Contradictory assessments on the importance of the We, J, velocity ratio, and Oh numbers in flame stability, ignition characteristics and numerical models can be found throughout the literature, with little or no regard to these geometric constraints.

While different literature sources describe the use of shear coaxial and swirl coaxial injectors to research LOX/Methane, the ignition element of such injectors has mainly stayed in development or laboratory use stages. Most laboratory applications utilize a Gox/hydrogen torch igniter due to its wide ignition limits and ease of use, while the industry has opted for hypergolic slugs or pyrotechnics for ignition reliability reasons. The weight added to a vehicle by another propellant tank simply for ignition purposes is not an acceptable requirement, making the Gox/hydrogen torch igniter use prohibitive in a thruster application; while pyrotechnics and hypergolic slugs are indeed reliable, but can add to the overall price tag of the vehicle and of development due to handling and cleaning cost penalties.

Currently, the National Aeronautics and Space Administration (NASA) is actively involved in LOX/methane propulsion research, with engines that feature different injector technologies ranging from Pintle injector to showerhead and shear coaxial. The NASA Johnson Space Center has been especially interested in this propellant combination, and has been working on a lander test bed for their LOX methane engine design [10]. The prototype and test campaign serves as technology demonstration and proof of concept for LOX/methane engines, and it is ready for full system integration. This includes the development of an integrated igniter that will utilize the boiloff from the two main tanks as the ignition source for the main engine, and the design and testing of regenerative cooling channels with methane as the coolant. This also

produces a data gap for cold gas capabilities for the igniter and the cooling characteristics of liquid methane as well as the effects of cold gas methane at the injector.

### 1.4 Practical Relevance

The NASA Technology Roadmap clearly states that LOX/methane propulsion is one of its top priority technologies to develop since it provides a space-storable, non-toxic, clean burning alternative to more traditional propellants. Moreover, methane could be produced in situ on Mars for future space missions, while oxygen can be used in conjunction with life support systems and power generation [10]. Additional literature and more data on LOX/methane propulsion across different types of injectors will yield shorter development design cycles for the aerospace industry.

A thorough understanding of the ignition physics of a single element shear coaxial injector is critical to the design of the ignition system in order to determine the best location to initiate the flame and to optimize flame front propagation through the initial stages of the ignition process. The lessons learned through the testing and analysis of different injector geometries will help establish a more comprehensive approach to the valve timing and ignition sequence. This information can eventually be extrapolated to the ignition and pressure ramp up of larger multi-element injector systems to provide a smooth ignition without the pressure spikes characteristic of hard ignitions.

### 1.5 Project Objectives

The objectives of the study presented here focus on the igniter for the single element injector. Reliability of ignition under different propellant inlet conditions is the main driver for the relatively small thruster systems envisioned as a use for LOX/methane in literature and the ongoing investigation at the Center for Space Exploration Technology Research. Experience with augmented spark torch igniters and their operation will prove valuable in future testing campaigns both inside and outside the laboratory environment.

Testing operations for the swirl igniter chosen in this work can be divided in to three stages:

1.) Two electrode igniter.- This test series was done with the positive and negative electrodes inserted into the igniter chamber through the same ceramic insulator. The temperature of the propellants was set at room temperature or 298 K.
2.) Two thicker electrode igniter.- When the electrodes of the previous igniter failed, thicker electrode leads were used to provide the ignition spark. In this series, room temperature propellants as well as cold methane were tested for ignition reliability.
3.) Single electrode lead, grounded igniter.- Same thick electrode lead, with a grounded body, creates the spark between the lead and the body. Room temperature and cold propellants, both methane and oxygen were tested.

Different flow rates and mixture ratios were tested to find the ignition limits of the igniter under different propellant conditions to simulate the use of boiloff from the tanks in a vehicle. The establishment of reliable ignition zones is sought out as the driver of the tests. The different parameters reported will provide reliable ignition and keep out zones for the igniter design presented.

# Chapter 2

## 2.1 TECHNICAL APPROACH

The next sections will be utilized to describe the hardware that was developed to make this ignition physics project possible. These include: the development of a cryogenic delivery system, the design of a Multipurpose Optically Accessible Combustion Chamber (MOAC), and the development of a torch igniter. A small section on the Data Acquisition and Remote Control System (DARCS) and the testing facilities will also be included. All hardware was built with a certain level of flexibility for future research projects and to allow critical parts to be "hot swapped" to minimize downtime.

### *2.1.1 Cryogenic Delivery System*

The handling and delivery of cryogenics is a task that includes several challenges of which safety is probably the utmost concern. After careful examination of the literature available on cryogenic fluid storage and transportation [11], the layout in Fig. 2.1 for the cryogenic delivery system was designed. The system consists of four main modules: two propellant delivery lines, and two support lines attached to the delivery lines for initial chill-down and purging of the propellants. All the tubing is stainless steel with Swagelok fittings, and LOX compatible brass valves.

It is important to note that there are pressure relief valves distributed across the cryogenic lines where a fluid in cryogenic state can be trapped (in between two actuated valves for example). Special attention has to be given to the cleanliness of the LOX line in which any particulate along the flow can serve as an ignition source due to the oxidizer rich environment. Thomas Flynn, in his book "Cryogenic Engineering" recommends 25 micron filters to be installed before each valve since they can be a major source of impact for particulates. The Liquid methane line, however, only has one 40 micron filter after the liquid nitrogen line since the probability of particulate ignition is significantly lower.

All lines will be insulated with Aerogel cryogenic insulating material to minimize the heat flux into the lines and eventually into the cryogenic fluids, which might eventually flash into gas if the heat input is enough. Oxygen is in its liquid state at a temperature of 90 K at ambient pressure, while methane turns to liquid at 110 K. To ensure the delivery of liquid propellants at the test article, the lines are pre chilled at the begging of every test. Liquid nitrogen, which turns to gas at around 77 K, was selected as the chill-down fluid. It will flow through the delivery lines until the cryogenic temperature sensor, a Lakeshore cryogenic temperature diode, indicates that the chill-down temperature has been reached.

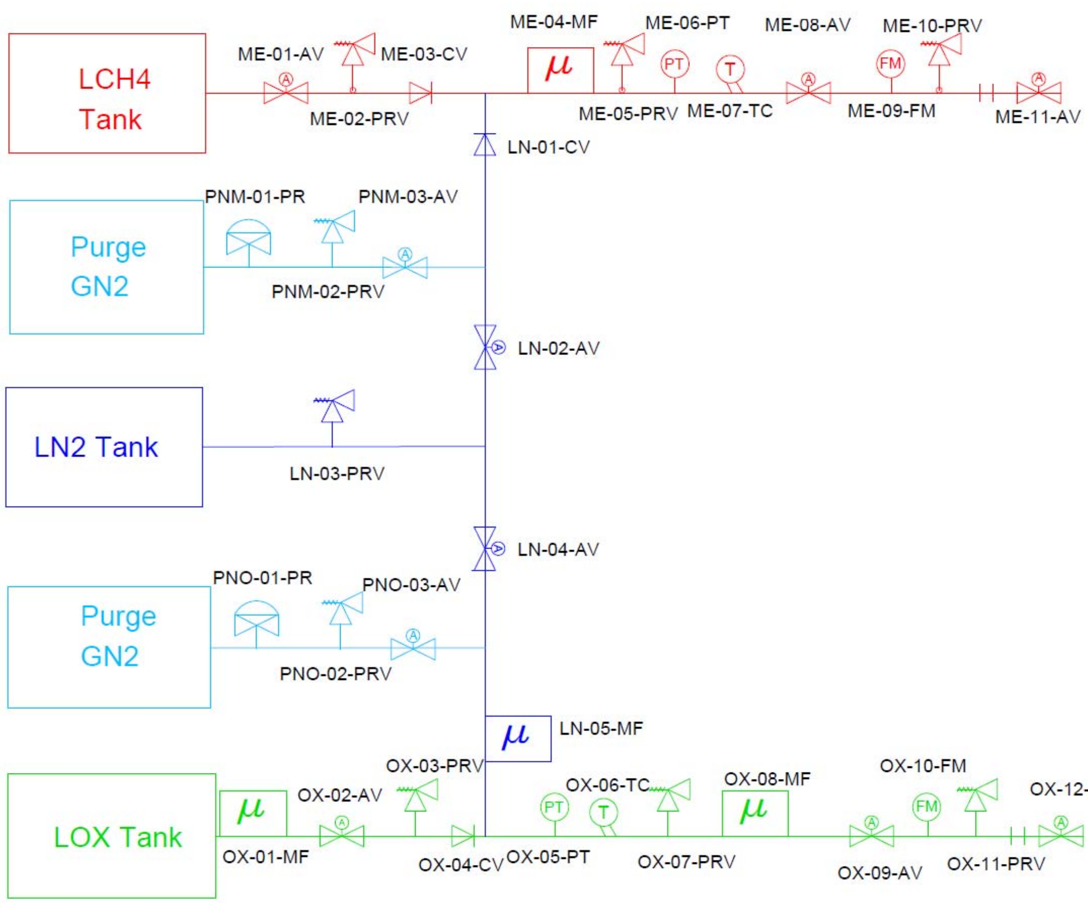


Figure 2.1. Cryogenic delivery system layout. The color code is red for Methane, green for LOX, light blue for $N_2$ purge and navy blue for $LN_2$.

The flow meter selected for the LOX delivery line is a Hoffer turbine flow meter, which has an operational range from .064-.45 liters per minute (LPM) (.017 to .12 GPM). For the gas methane line, an Omega FMA 1700 gas flow meter will be used, with a range from 0 to 250 LPM. All valves will be 120 VAC with a maximum pressure of 1551 KPa (225 psi), making them the limiting factor for pressure of the system. These valves set the Maximum Working Pressure (MWP) that the system can handle; nevertheless the pressure relief valves are set at the Maximum Allowable Working Pressure (MAWP) of 1379 KPa (200 psi) to provide an extra layer of safety.

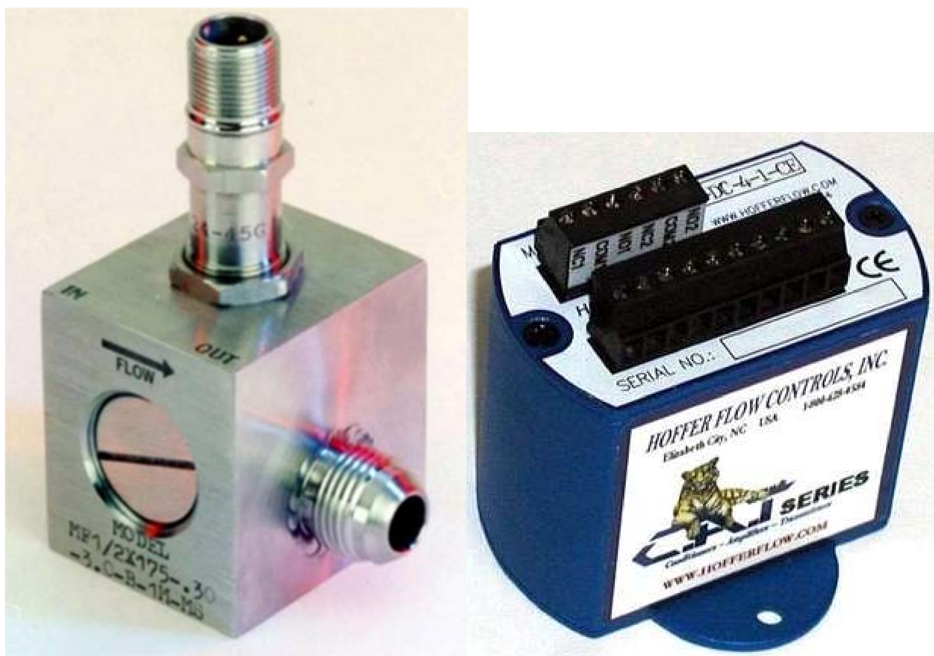


Figure 2.2. Hoffer turbine flow meter with controller


Figure 2.3 Omega FMA 1700 gas flow meters

### *2.1.2 Multipurpose Optically Accessible Chamber (MOAC)*

An optically accessible combustor was designed and built to create a combustion test rig with the flexibility to attach, test, and diagnose multiple combustion elements, injector and igniter components. The combustor can be equipped with different converging-diverging throat areas and geometries to investigate exhaust gas velocities and choked flow conditions.

The Combustor features optical access using removable windows on each side of the combustor. The ability to view combustion throughout the entirety of the combustor is required for fluid investigation. The combustor has internal rectangular combustion dimensions of 80x80x150 mm with the entire length and width visible through the side quartz windows as seen in Figure 2.4. Pressure requirements are to withstand an inner pressure of up to 20 bar during operation. The MOAC is designed to be flexible enough to simulate up to a 25 $lb_f$ thruster with modular injector and igniter systems as well as having variable converging throats and areas based on testing needs.

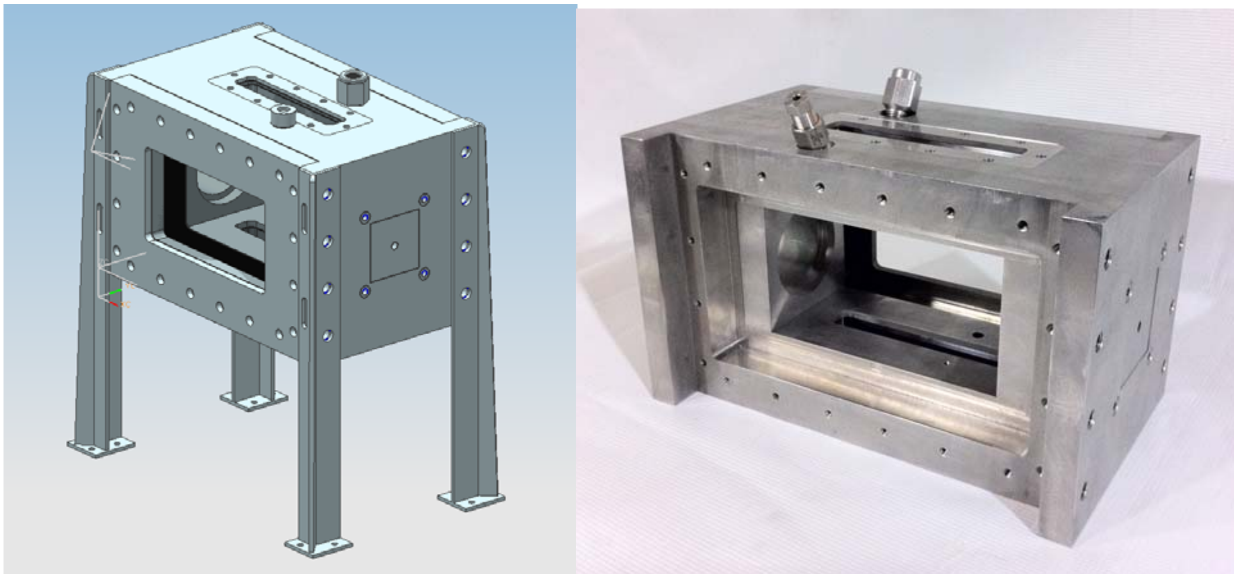

Figure 2.4 On the right, a cad model with support brackets used for testing. Left, open combustor displaying injector and converging section modularity

Since the combustor does not feature a cooling system, the mechanical design considers a maximum of 60 second operation at a pressure of 20 bar. This is deemed acceptable for the present study since only the initial seconds of ignition are of interest, with the time overdesign as a factor of safety. The modular injector and nozzle are installed from the inside to create self-sealing components, while the windows are kept in place by metal retainers and an Alumina-Silica gasket. Two pressure ports are provided, one close to the injector face plate and another one downstream close to the nozzle, any of which can be used to install the torch igniter as well. A Sensonetics high temperature pressure transducer and temperature sensor was selected to provide feedback from the chamber. It features a Silicon-on-Sapphire diaphragm that can withstand a maximum temperature of 425 C.

### *2.2.3 Torch Igniter*

The ignition source for the MOAC was designed to be an augmented spark igniter or torch igniter. The concept of an augmented spark igniter is to use an electrical discharge between two electrodes in a propellant stream to ionize, and spark the propellants in a prechamber that exhaust into the main combustion chamber. Figure 2.5 displays the design of the swirl coaxial

igniter design proposed for use in the MOAC. It consists of an oxidizer core with four tangential methane inlets creating a swirl to promote propellant mixing before they reach the spark electrodes. The swirl number for this design, is defined as “the ratio of the of the axial flux of the tangential momentum to the product of the axial momentum flux and a characteristic radius” and was calculated to be .04. It is a measure of the intensity of a swirling flow and it is used to provide flame stability when no flame anchoring method is provided. The electrodes are custom manufactured from 90% Platinum 10% Rhodium, and insulated with a ceramic thermocouple insulating tube.

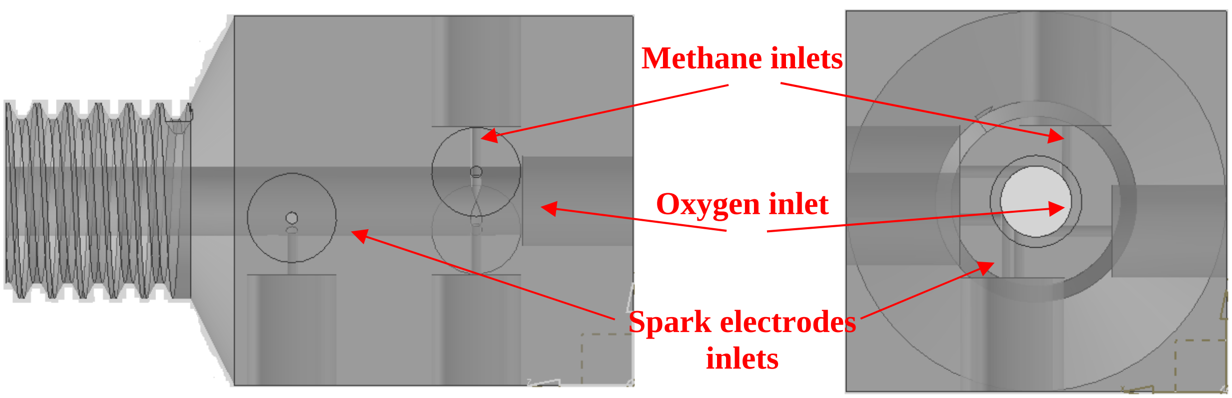


Figure 2.5 CAD representation of the igniter body

The torch igniter is integrated into the MOAC through a .635 cm (.25 in) NPT port. As stated before, there are two of these NPT ports on the combustor, one close to the injector face plate, and the other one further downstream. Figure 2.6 shows the igniter installed on the downstream pressure port in the MOAC. Behind the igniter body is a methane manifold, to evenly separate the methane into four lines that will then be injected tangentially to the oxidizer as described earlier. The spark ignition uses a DC to DC high voltage transformer providing the electrodes with 25 kV to ionize and dissociate the fluid into plasma, with a current of 0.16 mA.

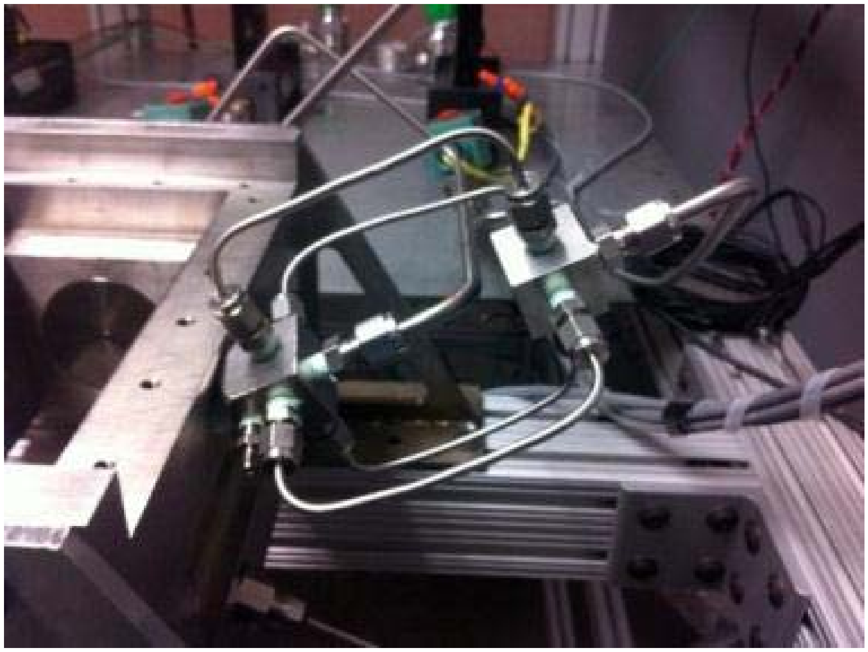

Figure 2.6 Igniter integration into the MOAC

### *2.2.4 Multipurpose Altitude Simulation System (MASS)*

This system consists of two main components: a vacuum chamber and an ejector system. The vacuum chamber is 1.52 m (5 ft) long by 48 in 1.22 m (48 in) in diameter. It has visual ports in the middle that allow for optical diagnostics to be operated such as Particle Image Velocimetry (PIV), schlieren imaging, and high speed cameras. Sixteen feed through ports are provided to grant access to any instrumentation and hardware needed for different experiments. Figure 2.7 showcases the two stage ejector system along with the vacuum chamber.

The ejector is a two stage system designed to create and maintain vacuum of 20 Torr (26 km) while operating a 15 lb LOX/$LCH_4$ thruster assuming an Isp of 368. The motive fluid for the ejector is air at 125 psig, and a compressor will deliver a total of 3828 kg/hr (8440 lb/hr); 508 kg/hr (1120 lb/hr) for the first stage, and 3320 kg/hr (7320 lb/hr) for the second stage. This provides the capability to pump 84.8 kg/hr (187 lb/hr) of Dry Air Equivalent (DAE) at 600 K, while maintaining 20 Torr pressure. The MASS has a stainless steel plate with a grid of screw holes in the fashion of an optical table in order to allow any type of instruments or experiments

to be secured. The delivery system needs to be compatible with the MASS and operate under such conditions.

Figure 2.7 MASS system coupled with the 2 stage ejector system.

### *2.2.5 Bunker Facilities and DARCS*

Due to the hazardous nature of the experiments to be performed with the hardware previously described, all operations are to be conducted inside of a ballistic proof bunker facility. The bunker walls are lined with .635 cm (¼ in) Kevlar plates and features two bulletproof windows, making this facility optimal for combustion and propulsion experimentation. The cryogenic delivery system, cryogenic propellant storage, MASS and MOAC systems will be operated inside of the bunker. Figure 2.8 displays the top view of the bunker facilities. It is worth noting that the propellant storage tanks are separated from the propulsion and combustion experiments by a Kevlar wall. The oxidizer and fuel tanks are also separated from each other by the liquid nitrogen chill-down tank and nitrogen purge tanks.

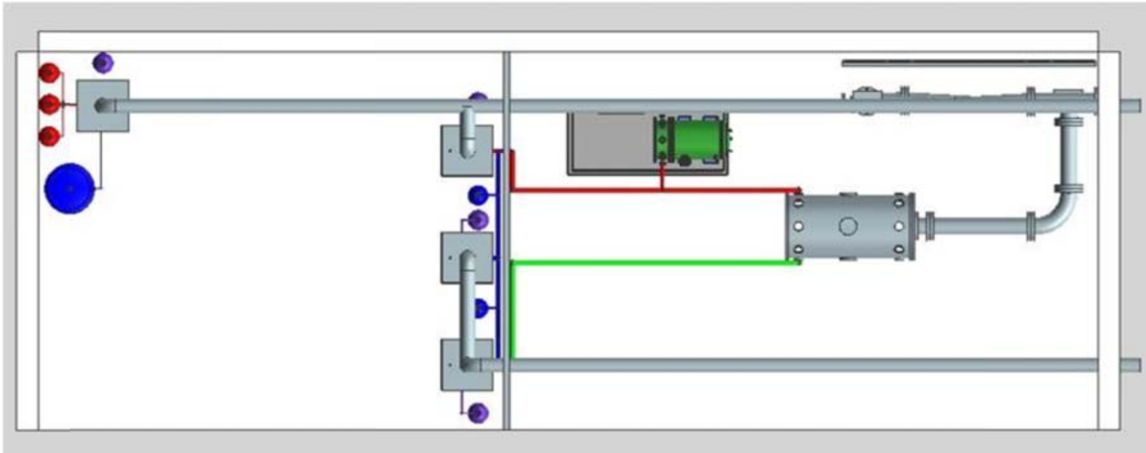

Figure 2.8 CAD design showing the top view of the bunker.

The plumbing that comes from the top of the propellant tanks is the ventilation system, designed to catch the boil off ejected from the tanks and relief valves, and safely exhaust it outside of the bunker facilities. It consists of two different circuits of lines, each connected to a 100 CFM fan, one for the methane exhaust and the other one for the oxidizer in order to avoid creating an ignitable mixture inside of the exhaust system.

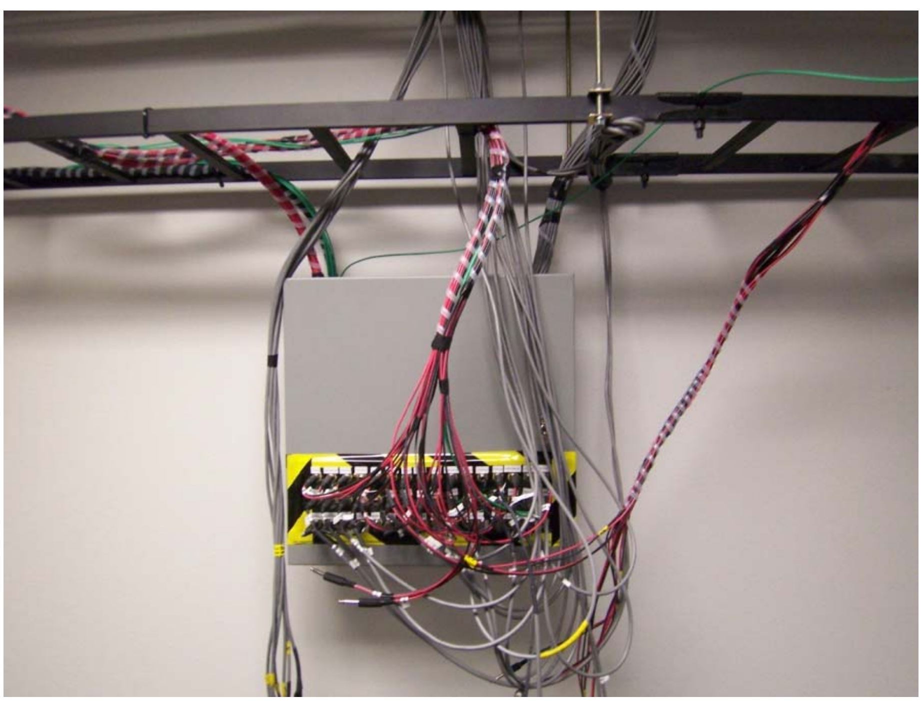

Figure 2.9 Patch panel located inside the bunker.

Power supply lines for both AC and DC components, as well as data acquisition lines are routed through an electrical cabinet with an array of audio plugs installed inside of the bunker. This patch panel adds to the modularity of the system since different plugs can be connected to the different channels, and rearranged for different experiments easily. A similar cabinet is installed inside of the control room, a room located next to the bunker to allow the instrumentation to be controlled and monitored through a computer interface, or with a set of manual switches. The cables for control, power, and data are routed through cable trays above the bunker to their respective equipment to prevent clutter, as illustrated on Figure 2.9.

The cryogenic delivery system can be operated and controlled manually through a set of switches or automatically utilizing LabView. The automation hardware selected consists of three PCI cards from National Instruments (NI) due to previous experience with NI hardware and availability of NI software (LabVIEW). A graphic user interface (GUI) was programmed to control the experiments safely from the control room and is pictured in Figure 2.10. The specific GUI in the figure is to control the Cryogenic Delivery System, and torch ignition system, but can be easily adapted to control other systems, as long as the hardware is connected in the corresponding channels.

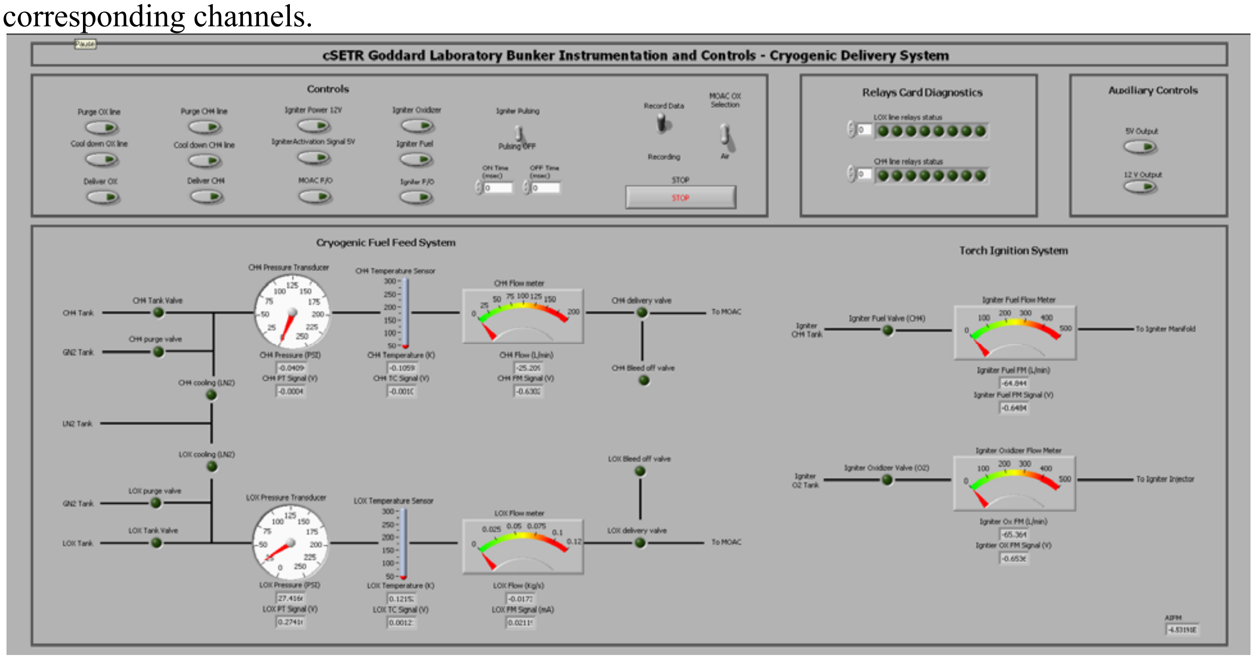


Figure 2.10 Graphic user interface for the Cryogenic Delivery and Ignition System.

The integration of all systems inside the bunker facility can be seen on Figure 2.11. The cryogenic delivery system is closer to the point of view of the picture, and is located on top of a truss section to provide ease of access to the valves, filters, relief valves, and regulators, and to provide stiffness to the ½ tubing line that it comprises. The structure behind it is the atmospheric test stand where the gox/g$CH_4$ experiments took place. Next to the atmospheric test stand is the Multipurpose Altitude Simulation System, inside of which the LOX/LCH4 were conducted. Attached in the back of the vacuum chamber and to the left of Figure 2.11 is the two stage ejector, ready to be used in the future for altitude experiments.

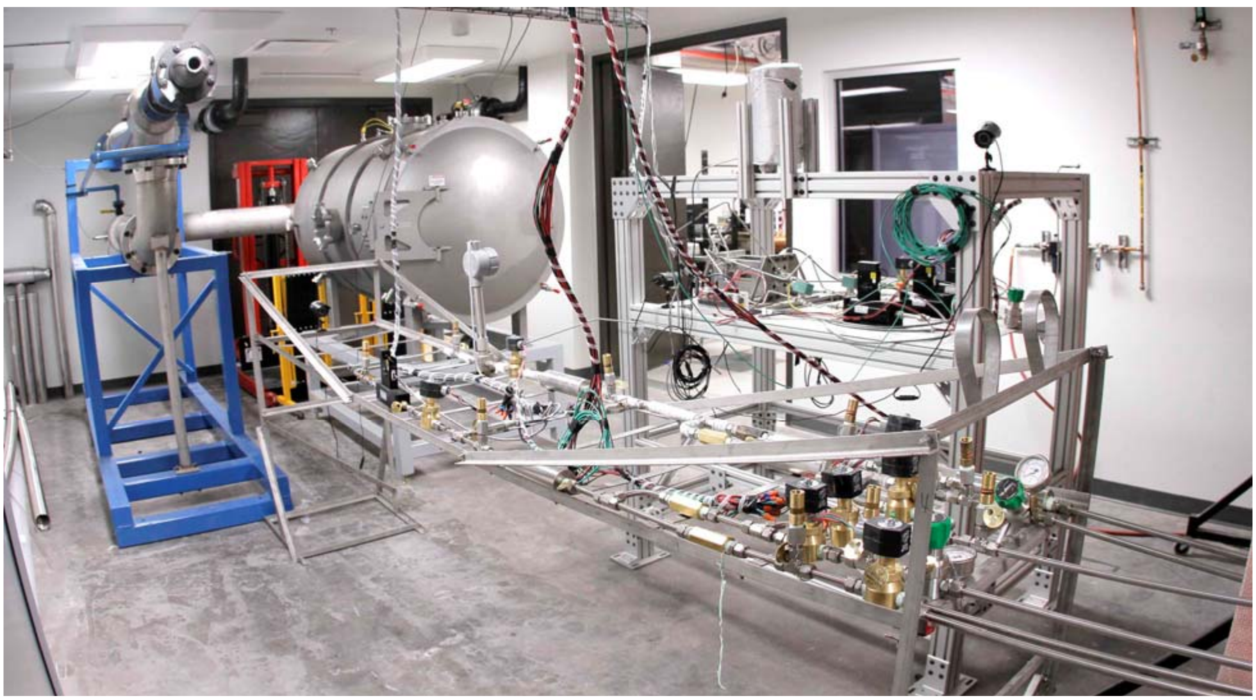

Figure 2.11 Integration of the cryogenic delivery system, MASS, and MOAC inside of the bunker.

# Chapter 3

## 3.1 HARDWARE DEVELOPMENT AND TESTING

Initial experience has been gathered from the hardware previously described to test baseline response and functionality. The operability of all newly developed hardware and software is crucial to the completion of the tests required for this study and needs to be validated. The results of these tests are presented in the following sections as well as lessons learned and proposed changes if any.

### *3.1.1 Cryogenic Delivery Lines Experience*

The lines in the cryogenic delivery system were tested for leaks with gas nitrogen. This test also qualified the correct function of the valves and the ability to control them with both, the software and manually. The temperature diode and pressure transducer readings in the GUI, as well as the controller, were a nominal 300 K, and 206.8 KPa (30 psi). The gas flow meters were installed on these lines to verify flow across the lines. Increments in pressure were then correlated to a measured flow rates to provide an estimating baseline of injection pressures. Tables 3.1 and 3.2 show the pressure to flow rate correlation obtained. The relations were taken with the injector in place exhausting into ambient conditions.

Table 3.1 Injector Pressure to Flow Rate for methane

| Line Pressure [PSI] | Methane mass flow rate [L/min] |
|---|---|
| 4 | 14 |
| 6 | 25 |
| 8 | 35 |
| 10 | 48 |
| 20 | 80 |
| 30 | 110 |
| 40 | 137 |
| 50 | 170 |
| 60 | 192 |

Table 3.2 Injector Oxygen to Flow Rate for oxygen

| Line Pressure [PSI] | Oxygen mass flow rate [L/min] |
|---|---|
| 5 | 12 |
| 10 | 20 |
| 15 | 26 |
| 20 | 32 |
| 25 | 40 |
| 30 | 46 |
| 35 | 53 |
| 40 | 60 |

A theoretical calculation of the pressure drop across the lines with cryogens present in the system was done and the model anchored with experimental data. An estimated pressure drop across the line was calculated using the major and minor loses in the pipe according to literature and component specific pressure drops, along with sample flow rates. Experiments were carried out with different tank pressures, with several pressure transducers along the line, to anchor the model to the data acquired and tweak the code to the pressure loses in the real system. With this information, pressure losses were correlated to a volumetric and ultimately a mass flow rate.

### *3.1.2 MOAC and Igniter Experience*

Upon integration of the igniter onto one of the pressure ports of the combustor, the igniter was tested to prove that it will provide a reliable and stable flame into the MOAC. It was determined that injection pressures of 8 psi for methane and 15 psi for oxygen provided a Mixture Ratio of 4 into the igniter body. These parameters provided a stable flame into the combustor while pressurizing the MOAC, with little flame detachment from the inner rim. An attempt to ignite an injector with a mixture of air and methane was made using oxygen and methane for the igniter. Although the air/methane mixture was kept at stoichiometric conditions, the injected gases blew out the igniter flame in all tests. Since the shear coaxial injector was designed for liquid oxygen coming out of the center post with gas methane around it; the air injected through the post was achieving velocities higher than those expected for LOX. This

resulted in poor mixing of the reactants and high momentum from the injector ultimately blowing out the igniter flame.

Another attempt at igniting the MOAC with air and methane was made, this time allowing a methane valve lead of 3 seconds before turning on the igniter and then opening the valve of air. This resulted in a hard ignition inside the chamber, where the propellants detonated instead of igniting in a controlled fashion. Subsequently a pressure spike in the MOAC was created, breaking the ceramic of the electrodes and led to the electrification of the delivery system with high voltage from the transformer, ruining the pressure transducer and gas flow meters. The hard ignition can be observed in Figure 3.1.

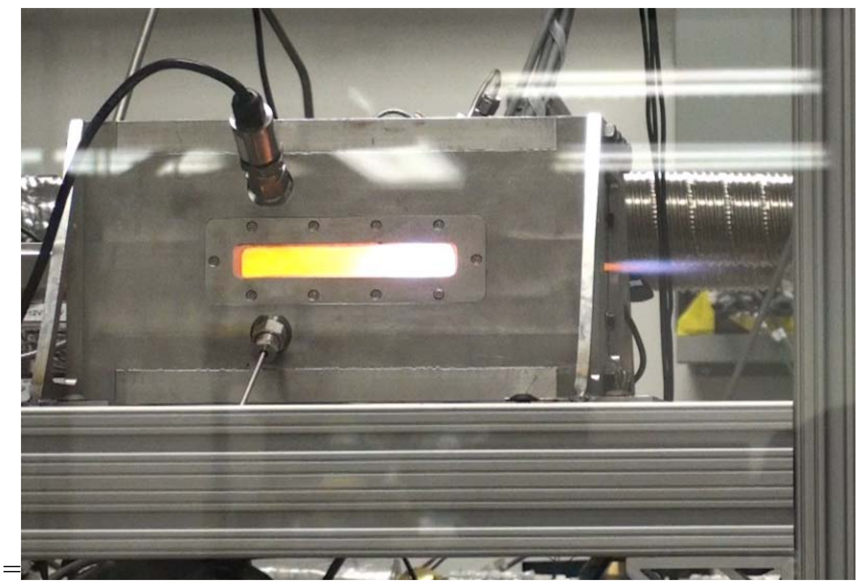

Figure 3.1 Hard Ignition of the MOAC

### *3.1.3 Previous Testing of the Torch Igniter*

An experimental procedure was developed to test the flammability limits of the torch igniter. The tests consisted of two sections: first test the operability limits with a constant mixture ratio of 4 (stoichiometric) varying the flow rate of the propellants, then by keeping a constant methane flow rate and varying the mixture ratio. This test matrix provided the flammability limits of the Ox/Methane torch igniter and established a baseline for the performance.

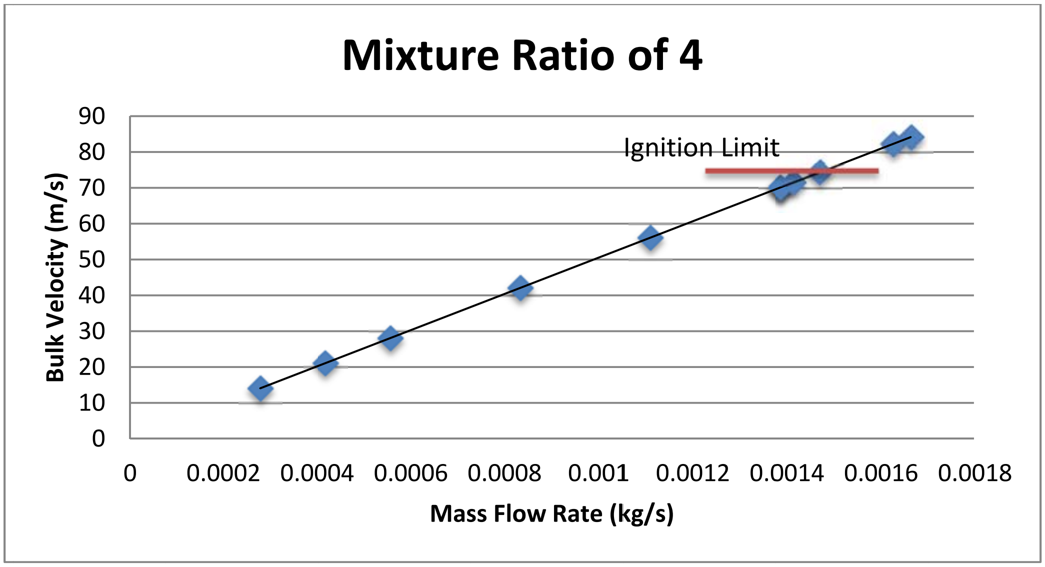


Figure 3.2 Mass Flow rate vs Bulk velocity of the torch igniter.

Figure 3.2 compares the mass flow rate to the bulk velocity of the propellants at a constant MR of 4. It clearly shows that a sustainable flame cannot be achieved with a mass flow rate of 1.4 g/s, which is estimated to have a bulk velocity of ~74 m/s through the igniter outlet. High definition video was taken of each one of the tests and the flame length was estimated with a ruler placed near the igniter flame. The flame length is compared to the flame energy with a constant MR of 4 in Figure 3.3. The slight discrepancy in flame lengths is believed to be due to the flame anchoring position with the smaller flames anchored inside of the igniter just behind the electrodes, while the longer flames are anchored at the inner rim of the igniter. The flame energy was calculated by multiplying the LHV of methane by mass flow rate injected.

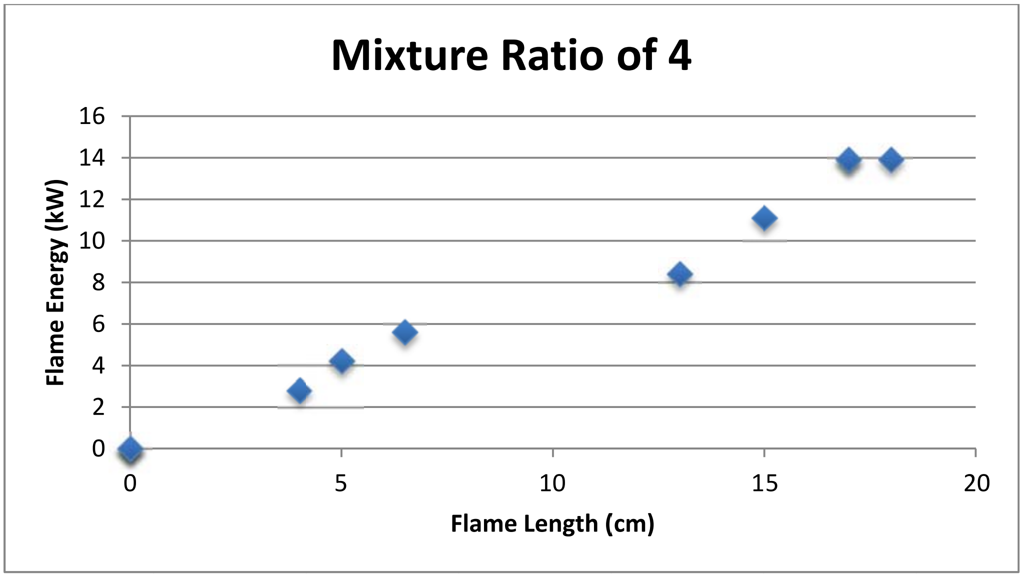


Figure 3.3 Flame length vs. Flame Energy of the torch igniter

Ignition was achieved on a range of mixture ratios from 2 to 4 as shown in Figure 3.4, which compares the mixture ratio to the flame energy. A fuel rich mixture was expected to ignite and anchor the flame successfully since the fuel is primarily creating the swirling motion by being injected tangentially into the oxidizer core stream, increasing the geometric swirl number. The reason the fuel lean mixtures did not ignite was because the swirl number declined with the majority of the momentum in the core, blowing out the flame.

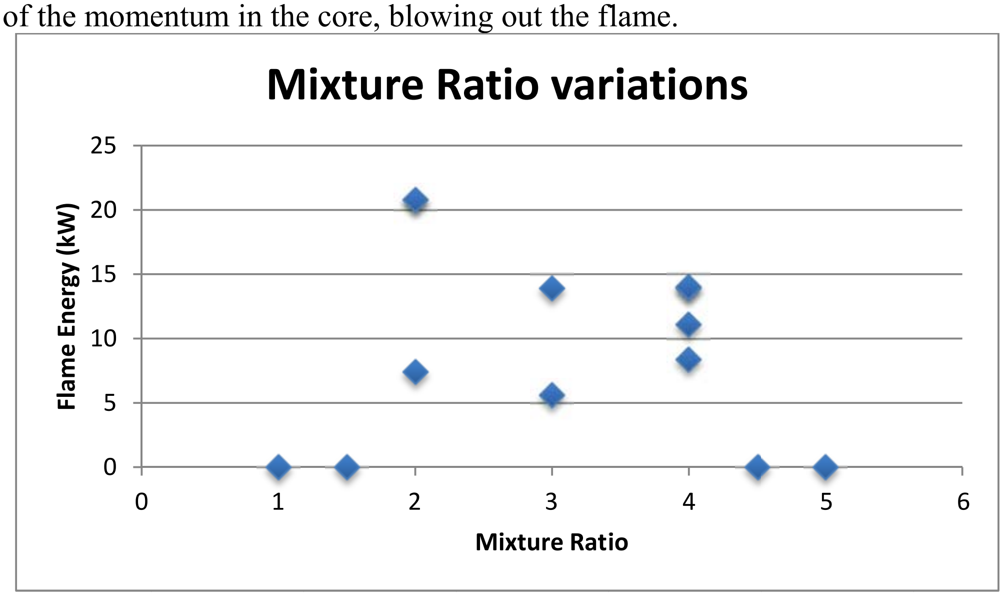


Figure 3.4 Mixture ratio vs. Flame energy of the torch igniter

## 3.2 Torch Igniter Development Campaign

### *3.2.1 Gas Oxygen and Gas Methane at Ambient Temperature*

The gas-gas testing series was done on the atmospheric test stand shown in Figure 2.11 and fastened to an aluminum plate with the methane manifold behind the combustion chamber portrayed in Figure 3.5. The oxygen line connected directly to the igniter, while the methane delivery line connected with the manifold, which separated the flow into the four tangential ports on the igniter body. Each line consisted of a pressure regulator, a mass flow meter, a solenoid valve, and a cross fitting with a thermocouple and a pressure transducer. The flow rates were set up prior to testing with the regulators, and an auto-sequence was programmed that would control both valves and the spark igniter, and record data. The file was saved as an .lvm file and later the data reduced and graphed with a Matlab program.

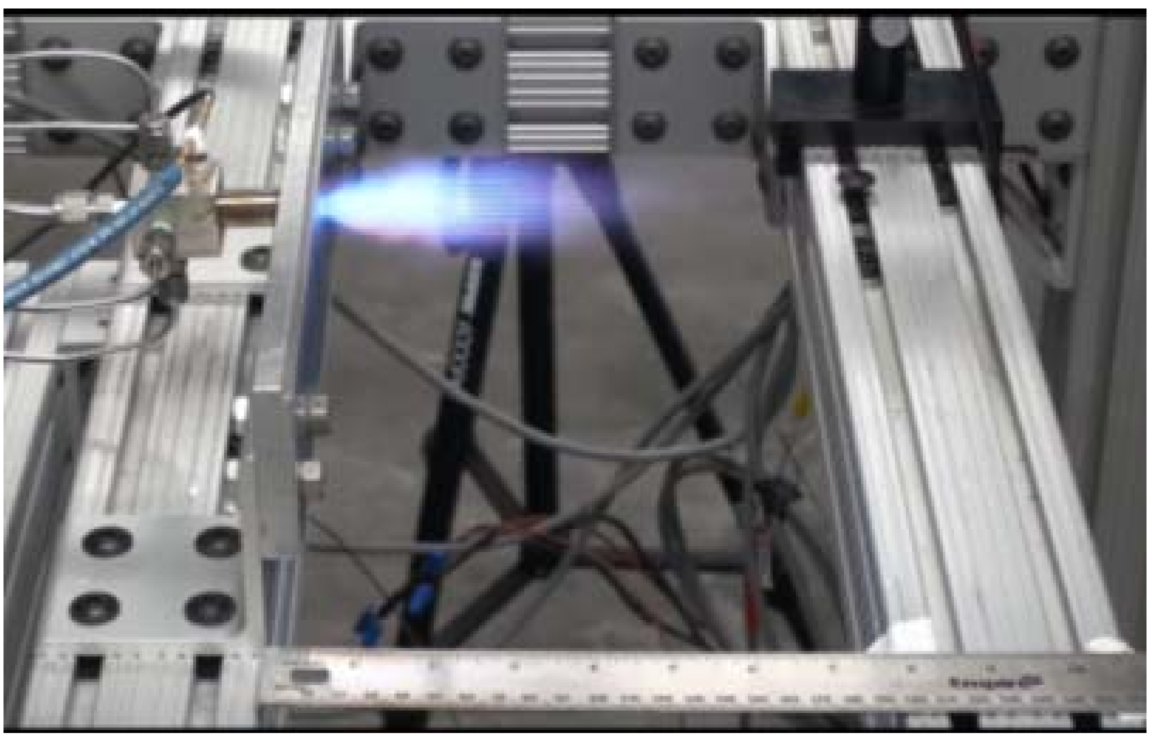

Figure 3.5 Atmospheric testing of the torch igniter

The auto-sequence opened the valves with and energized the transformer going to the electrodes, de-energizing the transformer about 5 seconds into the sequence to demonstrate a

flame stability without the spark igniter, and after 10 seconds, the valves will shut off. This was repeated 4 more times for a total of 5 ignitions per test, to provide reliability data. If there was a stable flame for 4 of the ignition trials, the data point was deemed reliable ignition. Otherwise, it was counted as an unreliable ignition.

### *3.2.2 Gas Oxygen and Cold Methane*

A heat exchanger was used to cool the methane down to around 200 K, and it will be explained later in Chapter 4. The heat exchanger used was a bath of liquid nitrogen with a coil spiraling inside. The methane would flow through the coil, and cool down in the 77 K liquid nitrogen. Allowing air inside the coil would freeze the air blocking the passage of methane through the coil, requiring a solenoid valve after the heat exchanger. However, trapping methane in the coil would also freeze the methane with similar results. Figure 3.6 is a schematic of the setup utilized for this experiment series. Nitrogen was added into the methane delivery line, to first trap nitrogen in the coil between two solenoid valves. Then liquid nitrogen would be added to the heat exchanger once it was safe to do so: the nitrogen would condense under the heat exchanger conditions but would not plug the coil.

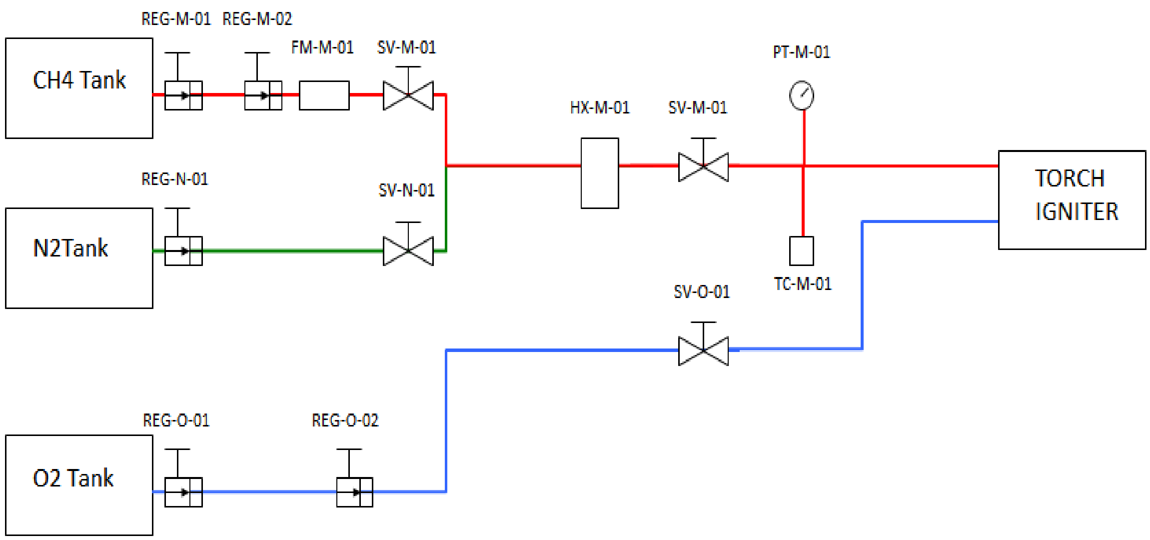


Figure 3.6.Cold Methane testing schematic

The auto-sequence again controlled all the valves and data acquisition instrumentation, flowing first nitrogen to clear the liquid nitrogen in the coil, then flowing methane through the coil into the torch igniter along with oxygen and the spark generator and run through for 10 seconds, at which point both propellant valves would shut down, and the gas nitrogen valve would actuate to eliminate all the methane in the coil, and be ready for the next ignition trial. Flowing methane into the cold nitrogen in the line without the initial nitrogen purge would freeze the methane causing blockage. This is because nitrogen is liquid at ~77 K at atmospheric pressures, while methane is liquid at ~110 K and solid at 90 K at the same pressures. Figure 3.7 shows the valve sequence for cold methane for a single trial; although this is not the entire sequence used, it repeats itself 5 times per experimental data point.

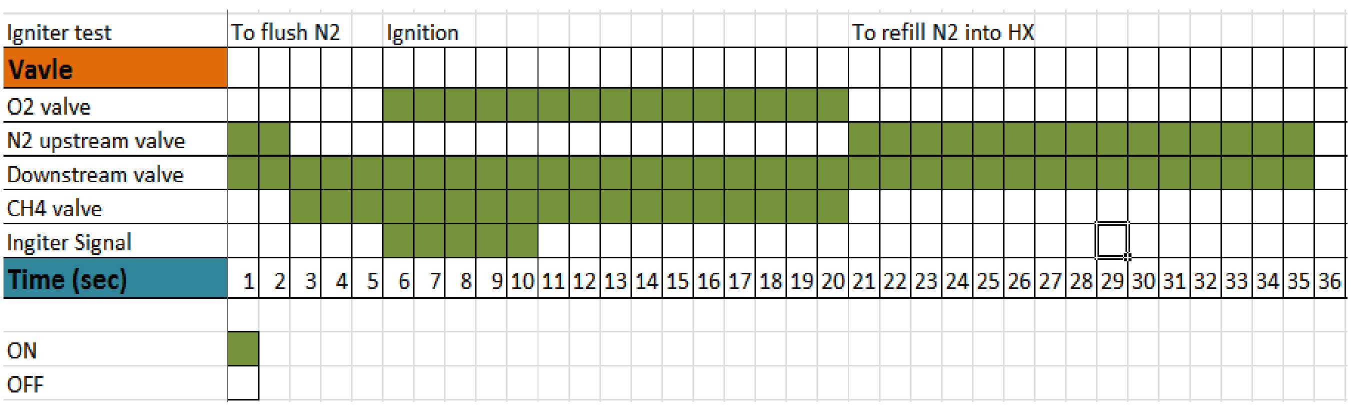


Figure 3.7. Valve Sequence for a Cold Methane Test

### *3.2.1 Liquid Oxygen and Liquid Methane*

Liquid oxygen can be purchased in pressurized tanks available commercially; liquid methane, however, is not as easily obtainable. Liquefied natural gas (LNG) can be purchased relatively simply, but it is not pure methane as it contains other hydrocarbons. Therefore a methane condensing unit was designed and built, that will use liquid nitrogen as coolant, due to its relative low cost and ease of access. A schematic of the methane condensing unit is shown in Figure 3.8.

Similar to the heat exchanger for the cold methane, this heat exchanger consisted of a tank with a long winding coil inside, except that in this case, the methane is in the tank static, while liquid nitrogen flows through the coil condensing the methane inside the tank. The condensing process took place at low pressures, since the tank was cut and welded to install the coil, and had lost its pressure rating. The level of methane condensed was measured by a strip of vertically arranged E-type thermocouples, which would read low, around 110 K, when the liquid was up to that level of the thermocouple. Once the tank was full, it was transferred by gravity and pressure difference to a lower run tank that has not been modified and could be pressurized. In the schematic, with a bright yellow color is a vacuum pump, to evacuate the production tank and run tank so as to avoid condensing oxygen and nitrogen inside the tanks along with the methane. The tanks are evacuated to a pressure of 100 Torr.

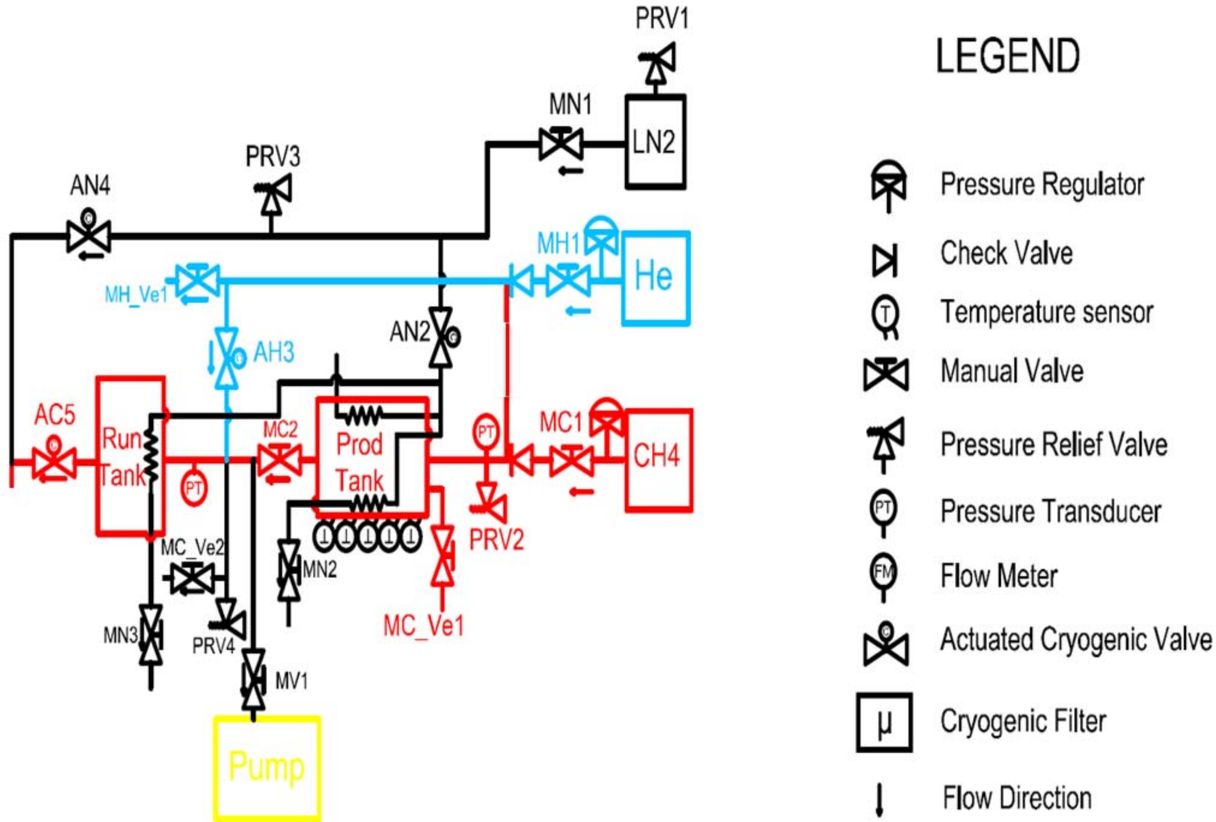


Figure3.8. Schematic of the methane condensing unit

The run tank was pressurized to deliver the liquid methane into the torch igniter at a predetermined flow rate calculated, in a similar fashion as the liquid oxygen: with the pressure drop in the line. Pressures of around 25 to 40 psig were used in these experiments for chamber pressures around 20 to 25 psig. A picture of the methane condensing unit is shown in Figure 3.9. The top tank is the condensing tank, the bottom tank is the run tank, and the solenoid valves are to control the liquid nitrogen to the condensing tank and to keep the run tank cold. There is a tee in between the condensing tank and the run tank to allow for the pressurization with helium as indicated in the schematic.

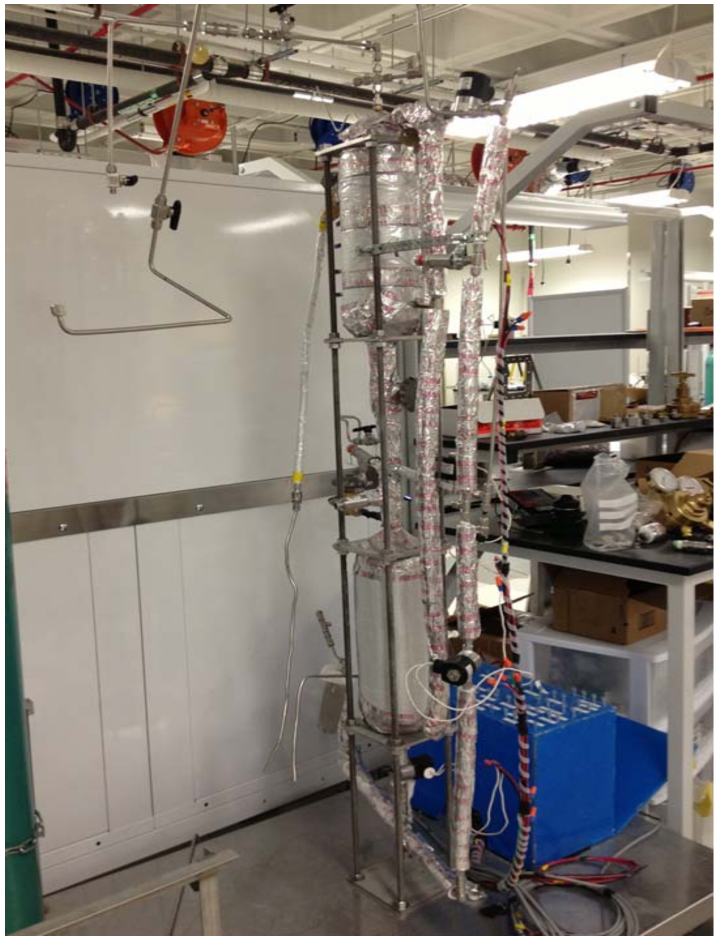

Figure3.9. Methane condensing unit

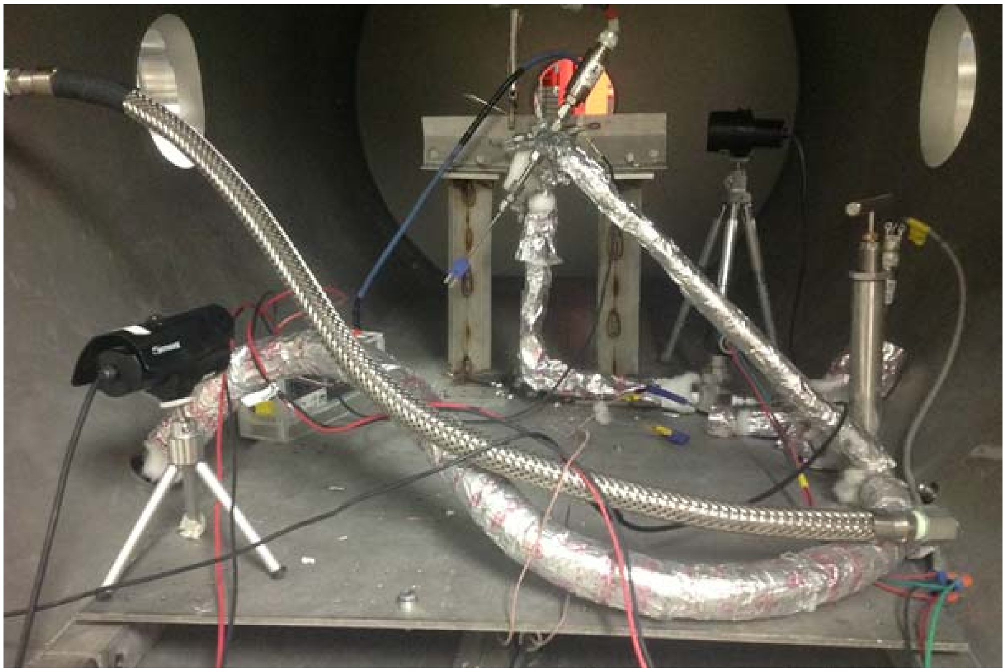

Figure 1.10. Liquid oxygen/ liquid methane torch igniter setup

As is the case for all experiments described earlier, the liquid oxygen and liquid methane test series involved a cross fitting with a pressure transducer and a thermocouple right before the point of injection to the torch igniter to closely monitor the conditions of the propellants at injection. Insulated lines were used to ensure cryogenic conditions at the entrance of the torch igniter. As seen from Figure 3.10, the test article was moved to the inside of the vacuum chamber. The vacuum chamber test stand is stainless steel, and the torch igniter was moved there for safety considerations due to the fact that liquid oxygen was used in this test series. The tests were monitored and controlled from the control room similarly to the other tests.

# Chapter 4

## 4.1 Results and Discussion Gas-Gas

### *4.1.1 Spark Ignition Method*

The first test operations were conducted with a .03 mm (.001 in) thick platinum wire as the electrodes on the spark igniters. These were implemented using 1/8" alumina thermocouple insulators with two holes, with one electrode in each hole. Using an NPT to tube Swagelok fitting, the alumina, along with the electrode protruded into the igniter body ignition chamber by about 5 mm. The assembly was covered with Resbond 919 to allow it to contain the igniter's chamber pressure, and to electrically insulate the electrodes. Platinum wire was selected due to its high melting point, and good electrical conductivity, since the electrodes extrude into the combustion chamber, albeit only the very tip of the electrodes.

After the first series of testing, described in the previous chapter, the electrode tips would melt and form bead especially in the positive electrode, making the ionization spark across them more difficult and affecting ignition. This is because although the ignitable mixture is being ionized the same, the breakdown voltage is higher since it does not have a sharp edge from which to initiate and travel through. This challenge can be easily overcome by pulling out the sparker assembly from the igniter body, and filing down the electrodes to a point again every 40 to 50 tests, but demonstrates the low reliability of the ignition method suggested. Thicker platinum wires were used for the subsequent test operations little improved performance, with the requirement to continue filing the electrodes, and the added cost of the platinum wire.

Another effort to recess the electrodes closer to the wall resulted in more difficult ignition or plain non-ignition, without much regard to the mixture ratio or flow rates in the igniter body. This evidence, along with the melted platinum wire tips, indicates that combustion was happening inside the chamber next to the electrodes, a condition not expected by the experimenter. Following this logic points to the fact that the electrode, along with the ceramic insulation was acting as a bluff body for the flame to anchor inside the combustion chamber,

instead of the flame being anchored at the exit diameter of the torch igniter, where the flame velocity and exit velocity would be equalized. The flame was anchored at the sparker assembly, kept there by low pressure recirculation zone behind the ceramic, providing the high temperature to melt and bead up the platinum, as shown in Figure 4.1. This only happened for the lower igniter flow rate tests; for the higher flow rates, the flame did anchor to the exit edge of the igniter body. Both phenomena can be seen in video 4.1

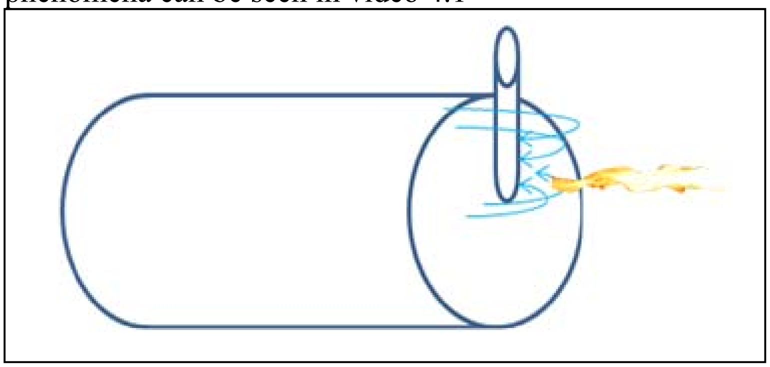

Figure 4.1- Flame attachment to the spark assembly by propellant recirculation

Video 4.1

The second iteration of spark generation utilized tungsten wire, having learned that a higher temperature material would be needed to survive the igniter's temperatures and pressures. Thin tungsten wire was not readily available from local commercial sources, and two 1.5 mm

thick tungsten rods were used as the electrodes. The same insulation technique previously described was used, with thicker alumina thermocouple insulator rods with the holes also being bigger in diameter: 1.59 mm (1/16 in). The two tungsten rods were inserted in both holes, with the tips protruding about 1 mm on the combustion chamber side, and insulated on the outer side with Resbond 919 high dielectric strength mixture. This setup provided two advantages: the electrodes being thicker and made out of tungsten would not melt, and the alumina being thicker could not protrude from the wall in the same way it did previously. Bending the tungsten rods on the outside of the chamber was a challenge since tungsten is very strong but brittle. The electrodes had to be kept insulated and separated due to high voltage arching outside of the igniter body, which was done by hot working the tungsten rods to bend them, and using Resbond to seal the alumina rod, and providing high dielectric strength.

After a failure in the Resbond ceramic during the cold methane testing, the decision to have a single electrode as the spark, and grounding the body of the igniter was made. This setup had been avoided due to the noise in the instrumentation that grounding the igniter body would provide as high voltage would affect the pressure transducers and thermocouples. A single thin ceramic tube was designed and fabricated to snuggly fit into a ¼ in NPT fitting with access to the combustion chamber. The igniter body was grounded to the high voltage transformer with a screw secured on the side close to the positive electrode. The spark gap was estimated to be 1 mm from the tip of the electrode to the wall inside the combustion chamber.

#### *4.1.2 Room Temperature Methane*

Initial testing with gas oxygen and gas methane was conducted with the tungsten dual electrode method to have a point of comparison for all subsequent testing with cold methane, liquid oxygen and liquid methane. As will be described, different mixture ratios, as well as flow rates were targeted to verify the ignitability and reliability of ignition of all mixtures in the context of the swirl igniter presented. The tests were conducted with an automated sequence, after manually setting the propellant flow rates. A typical test profile is depicted in Figure 4.2,

where the green blocks indicate "ON". The valves are all normally closed, and will open within 50 ms when energized.

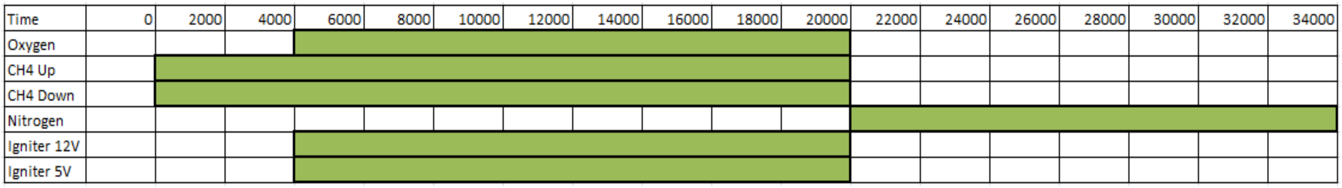


Figure 4.2- Valve sequence for gox and gas methane.

It should be noted that mass flow rate accuracies were dependent on user input of the flow rates at the time of firing. Because of this, the following data should not be considered completely accurate but used more as a basis for finding zones with a high probability of reliable and stable ignition. The flow rates vary up to from the flow set with cold gas flow, and the flow detected while firing. This is due to the increase in chamber pressure at the moment of ignition. The flow rates are accurate to +/- 2 liters/min on the flow meter.

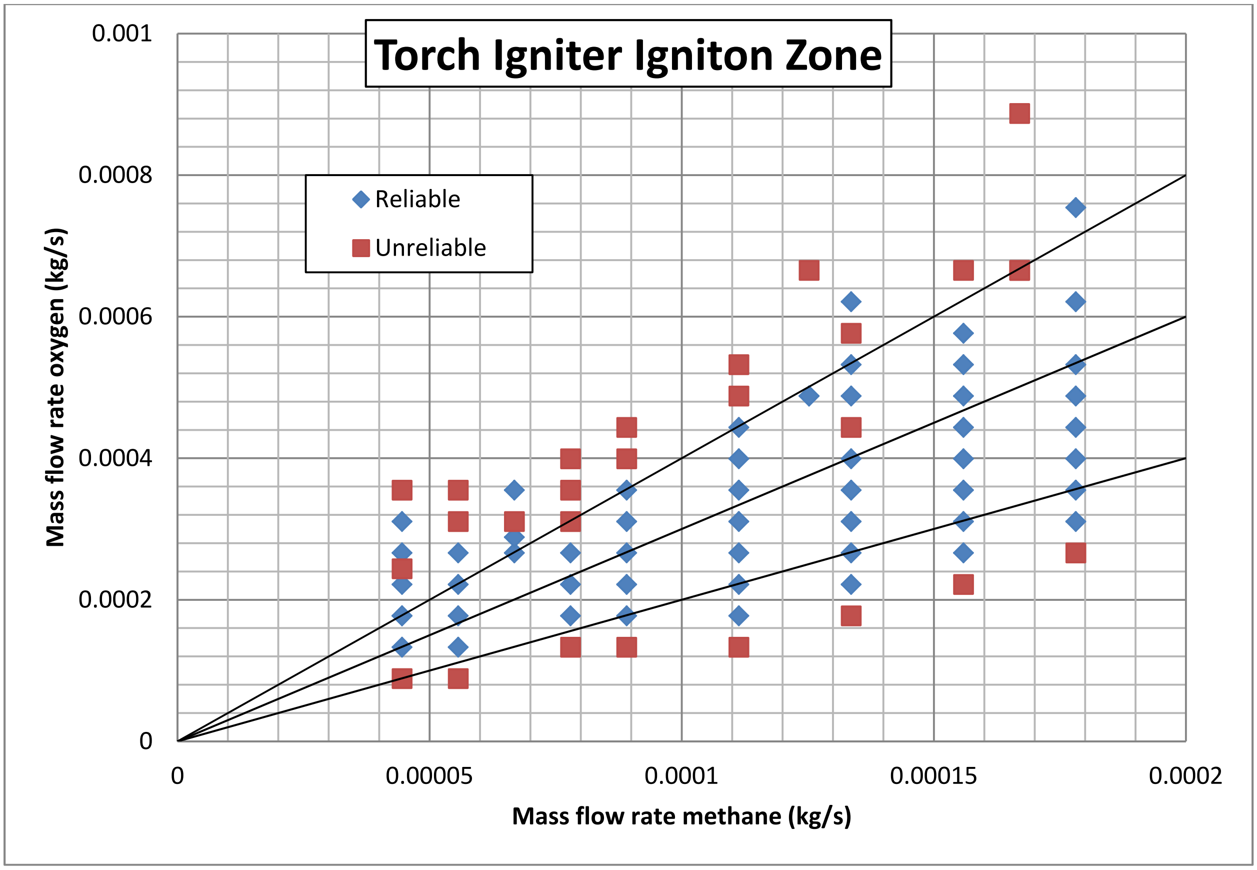


Figure 4.3- Torch Igniter Ignition zone, for Gox/methane

In this context, reliable ignition are those values that, from 5 different trials of tests conducted, it ignited 4 times or more. This is a rather rigorous data condition, and may be responsible for outliers in the data, since they may have ignited 3 times out of the 5 and were still left out of the reliable ignition criteria. Having these conditions in mind, the data in Figure 4.3 clearly points to a reliable ignition zone of all data points taken. The upper dark line drawn through the chart represents a mixture ratio of 4, the middle line a mixture ratio of 3, and finally the bottom one represents 2. Reminding the reader that stoichiometric conditions for oxygen and methane consist of a mixture ratio of 4, it is apparent that this igniter design will reliably ignite at a wide variety of mass flow rates , if only in fuel rich conditions down to mixture ratios of lower than 2. This propensity of fuel rich reliable ignition, and lack thereof in the fuel lean conditions is in no doubt due to the geometry of the igniter body. The data can be certainly extrapolated to

include higher flow rates keeping the same igniter characteristics up to a point, where bulk velocity might be too great to support combustion. At which point the velocity can be lowered by modifying the exit area to include a diffuser to slow down the exhaust gases, and maintain the flame attached to the rim of the igniter.

The maximum bulk velocity tested with reliable ignition approached 47 m/s at a mixture ratio (MR) of 4.2 as shown in Figure 4.4. Bulk velocities of between 10 and 40 m/s can be easily sustained at a variety of mixture ratios from 1.6 to up to 4.5 with a higher reliability at fuel rich conditions. Keeping in mind that these are atmospheric exit conditions, the exhaust gases are not accelerated in any way out of the igniter's combustion chamber other than the change in enthalpy of the mixture forming hot gases. It is also important to note that higher MR were ignitable, especially at lower flow rates, albeit not as reliably as with lower mixture ratios approaching the very stable MR of 3.

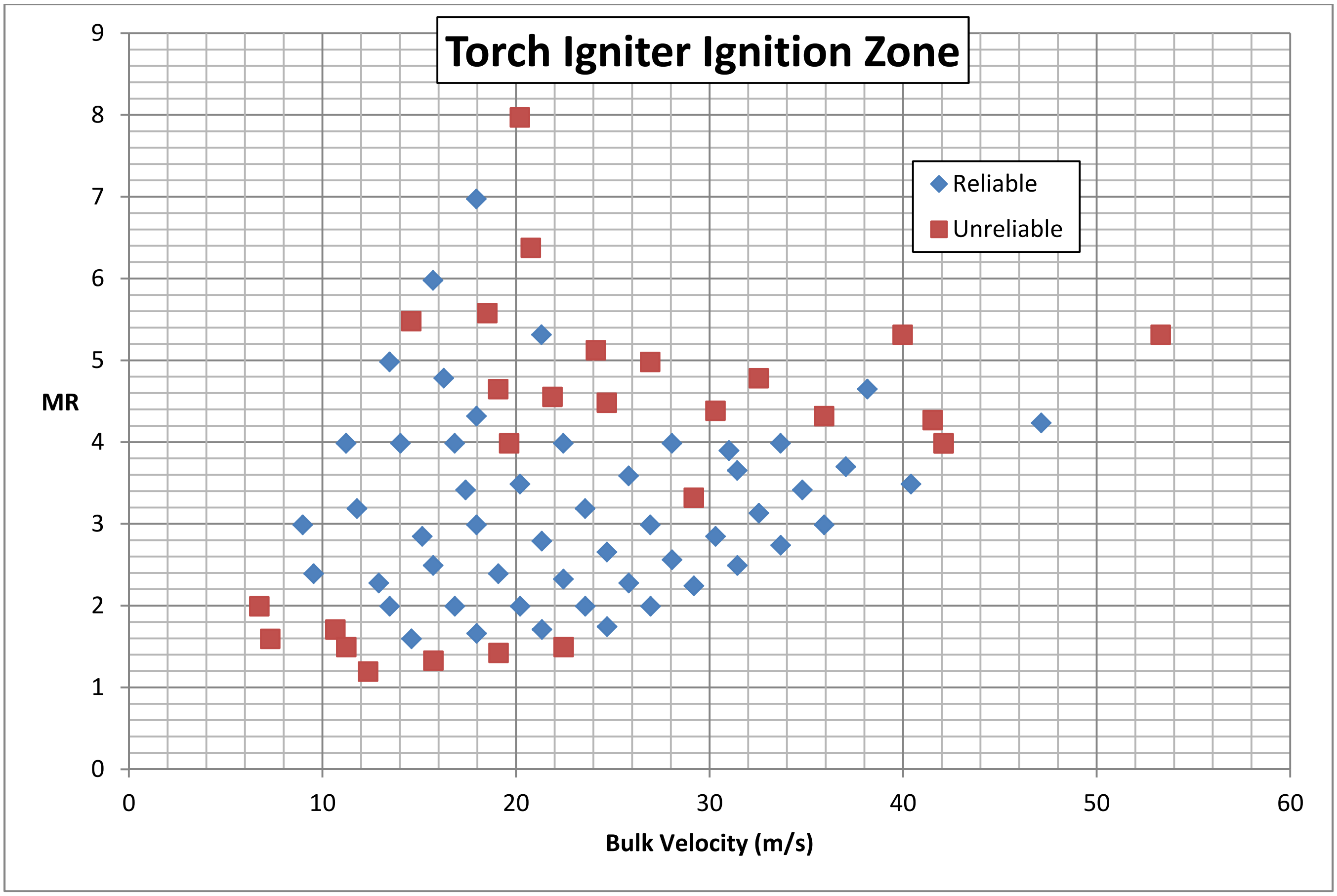


Figure4.4- Bulk velocity vs. Mixture Ratio ignition zone

The thermal response of the igniter is also of concern, especially with a long combustion chamber, made this way to clear the inclination given to it when attached to the MOAC. The idea behind the swirl given to the propellants inside of the igniter's combustion chamber is to give the igniter good thermal control and to maintain a hot core, with a cool wall. No evidence of hot spots or streaks in the igniter was found, either in the high definition video or on the hardware inspection at the end of the test campaign. The geometric swirl number is calculated with the geometry of the fuel inlets, fuel flow rate, as well as total propellant flow rate, and can influence the temperature uniformity downstream of the electrode spark, all the way to the igniter exit. Graphing the total mass flow rate against the geometric swirl number, also shows a very well defined ignition zone, which can only apply to this igniter's geometry unfortunately. It is,

however, a driver in the ignitability of the mixture and is completely dependent on the total mass flow rate when the geometry is defined.

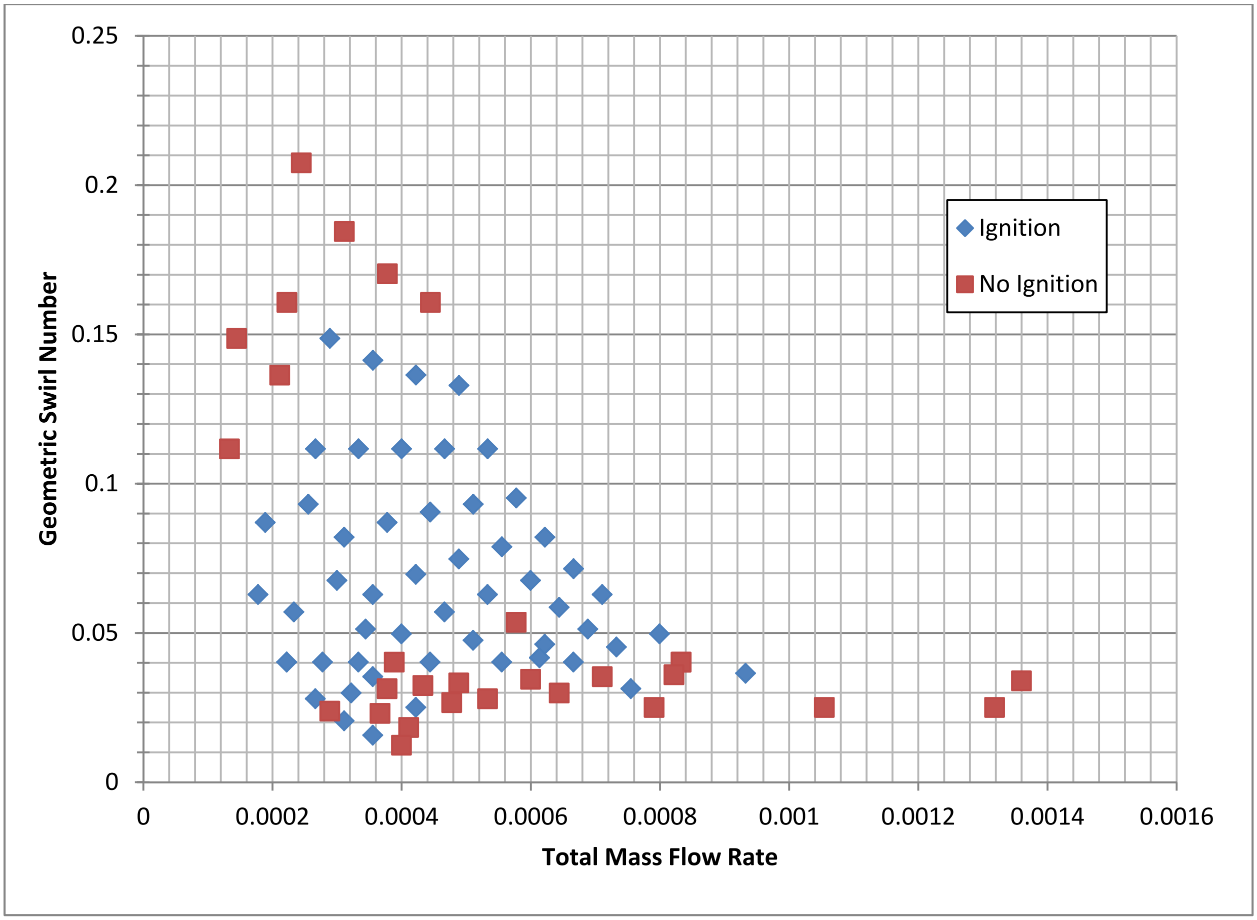


Figure 4.5- Total mass flow rate vs. Geometric Swirl Number

### *4.1.3 Cold Methane Igniter Testing*

The ignitability limits of the torch igniter presented before are for gas oxygen and gas methane at room temperature. The objectives state that the igniter has to work with the gas boil off from the LOX and $LCH_4$, which will be at a lower temperature. These conditions in the igniter will be tested and are expected to have an impact on the flame characteristics and

ignitability limits. This may be in large part due to the wide variability of the methane density with temperature, and the minimum ignition energy necessary for the flame to propagate.

A test matrix similar to the one previously described will be followed with the added variable of fuel temperature to fully characterize the igniter. Only the methane temperature will be varied for this set of tests since previous literature suggests that the temperature of the oxidizer does not change the ignition characteristics in a perceptible way. Figure 4.6 shows the heat exchangers that can be used for this purpose. The coil heat exchanger has an 0.3175 cm (1/8 in) pipe submerged in a bath of liquid nitrogen to cool the methane as it passes through the coil. The tank heat exchanger is made out of a stainless steel tank with a 0.635 cm (¼ in) pipe wrapped around it and covered with Cryogel insulation. Liquid nitrogen flows through the pipe around it to cool the system, while methane can either flow inside or be stored.

Figure 4.6- Left: coil heat exchanger. Right: tank heat exchanger

The temperature of the methane cannot be very accurately regulated using this method, but it will provide useful information with different temperatures at different flow rates. The tank heat exchanger cannot provide sufficient cooling for the flowing methane at the flow rates required for this test campaign but can provide cooling over a long period of time, such as liquid methane storage. The coil heat exchanger however, has a higher heat transfer rate and was selected for the following tests. A pressure sensor and thermocouple are installed on a tee fitting just before the igniter to monitor the inlet conditions of the methane.

A similar test matrix was followed while testing the igniter with cold methane. Figure 4.7 can be used as a direct comparison with Figure 4.3, and show that the ignitability of the propellants is lower throughout much of the test space. From this chart, it becomes obvious that there has been a swap in the ignition limits; from very fuel rich ignitability limits characteristic of the warm methane, to a tendency towards lean ignition with cold methane.

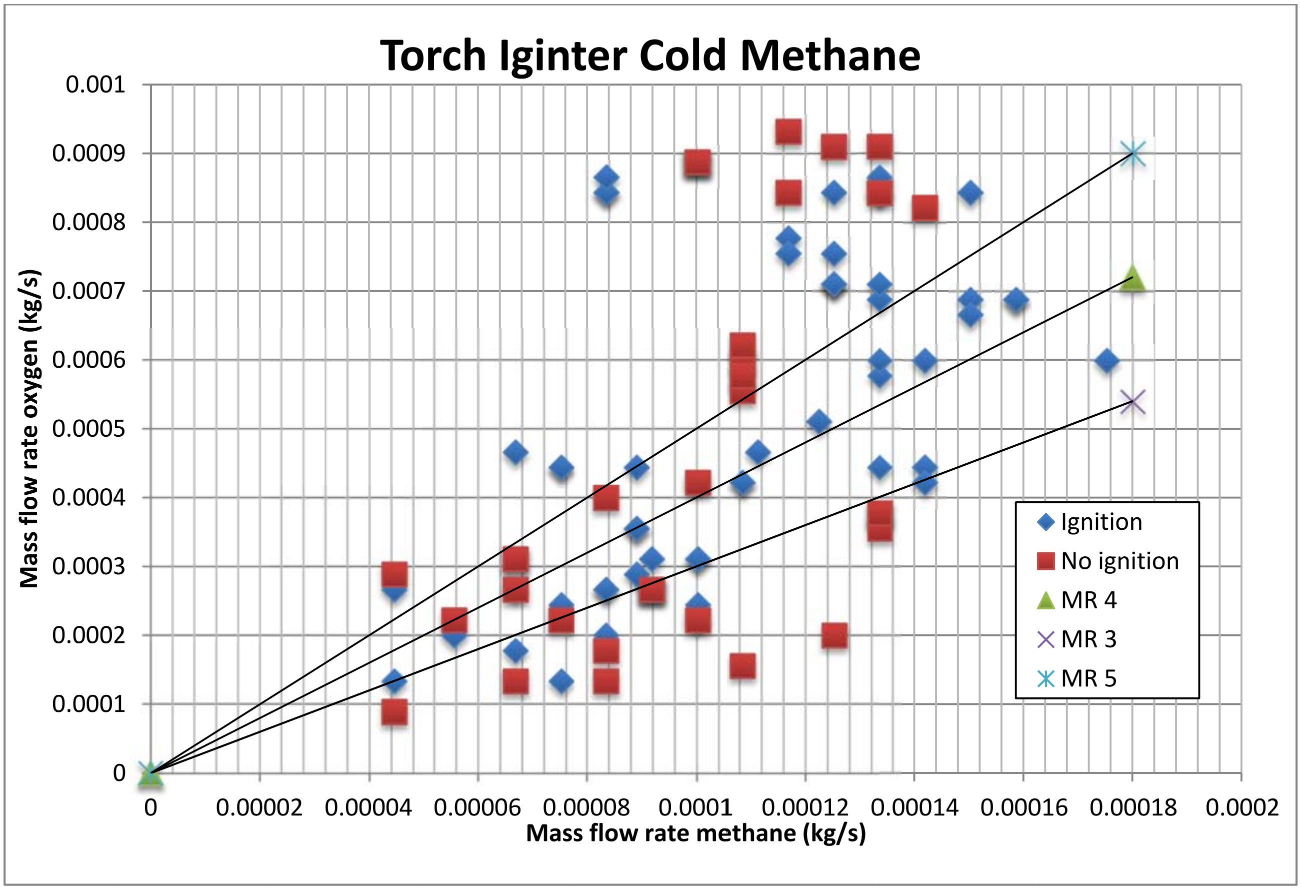


Figure 4.7 - Ignition limits of cold methane and room temperature oxygen.

As indicated before, there might are some “no ignition” points on the map that seem out of place that might be explained by the stringent ignition definition imposed on the data. The auto-sequence was designed for five ignition tests of 10 seconds each, and if the torch igniter did not light at least 4 times out of the 5, it was designated as a no ignition data point.

There is no active feedback control of the flow rate into the igniter, meaning that the flow rate was set previous to the test, and the sequence run with those regulator settings. Although the torch igniter is open to atmosphere, the chamber rises in pressure when ignited due to the expansion of the combustion gases causing a backpressure that affects the injection flow rates. Figure 4.7 reflects the propellant flow rates set at the beginning of the test, not of the actual flow rates during the test and at the moment of ignition. An average of the flow rate throughout the total burn time is shown in Figure 4.8, with mixture ratio lines for reference. It is theorized that one of the reasons why the ignition process affected more the cold methane flow rates in this set of tests, is the dramatic change in density that methane undergoes from the moment of injection to the combustion, even though the methane was never liquid.

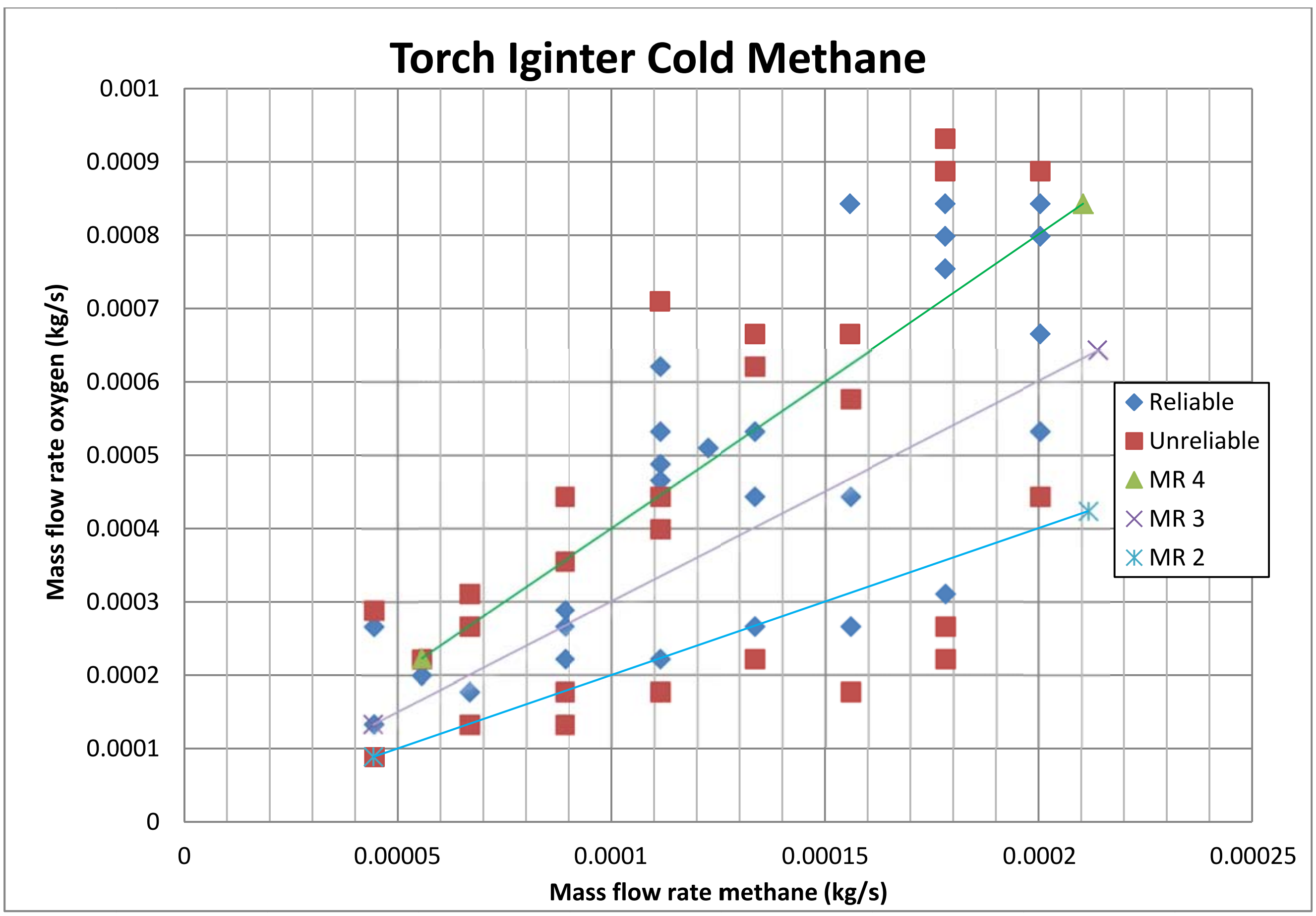


Figure 4.8- Ignition limits of oxygen and methane with measured flow rates.

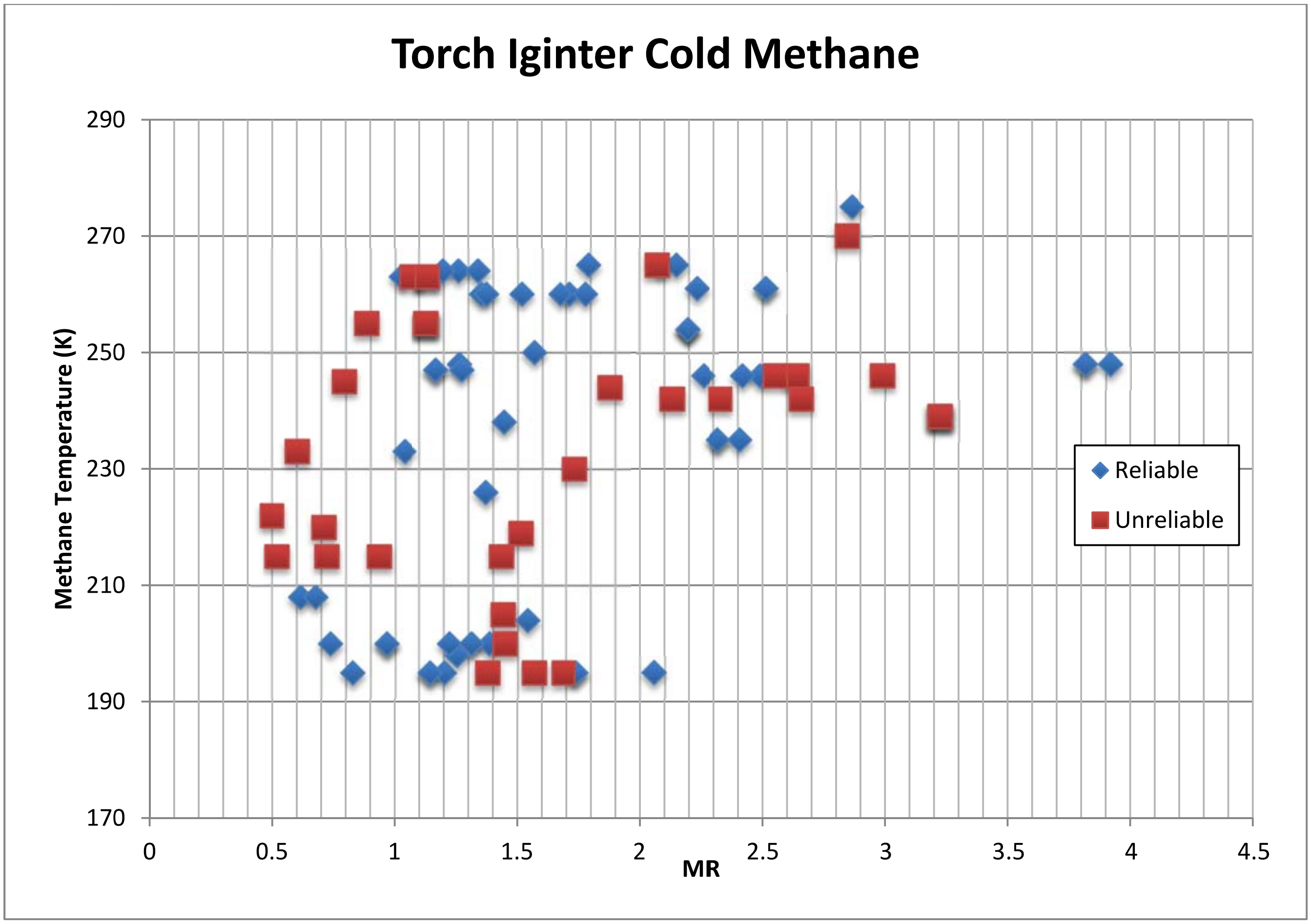


Figure 4.9- Ignition limits considering mixture ratio vs. methane temperature

A range of temperatures were achieved at the injection with the different methane flow rates. With the tee connection right before the methane manifold to the igniter, the average temperature was recorded for all tests, and plotted against mixture ratio in Figure 4.9. The methane inlet temperatures range from 270 K to 195 K, due to the variability of the coil heat exchanger fashioned for this purpose. This variability is due mainly to flow rate of methane, and level of liquid nitrogen in the cryogenic dewar. Since there is no distinct zone where the methane reliably ignites at any given mixture ration with respect to inlet temperature, it is clear that there is no correlation between the two. Although the methane temperature is a strong function of the flow rate, reliable ignition clearly depends more on the overall mass flow rate of the propellants as defined by Figure 4.8.

Comparing the same type of data from the warm oxygen and methane, to the cold methane test campaign, the fact that low mass flow rates have little ignitability in the cold methane trials stands out as a curious fact. This may have to do with the fact that the density of methane varies significantly within the temperature range used in these tests. The density of methane is about .64 $kg/m^3$ at 300 K and 100 KPa, and around 1.0 $kg/m^3$ at 190 K at the same pressure. This variation in density affects the injection velocity of methane into the igniter's chamber, rendering it slower at lower temperatures, affecting the initial mixing of the propellants, giving more momentum to the methane and keeping it near the wall longer. The drastic change in density while it warms up in the combustion chamber can possibly speed up the methane, giving it more inertia to stay close to the chamber wall, affecting the mixing with oxygen even further in a self-exacerbating process.

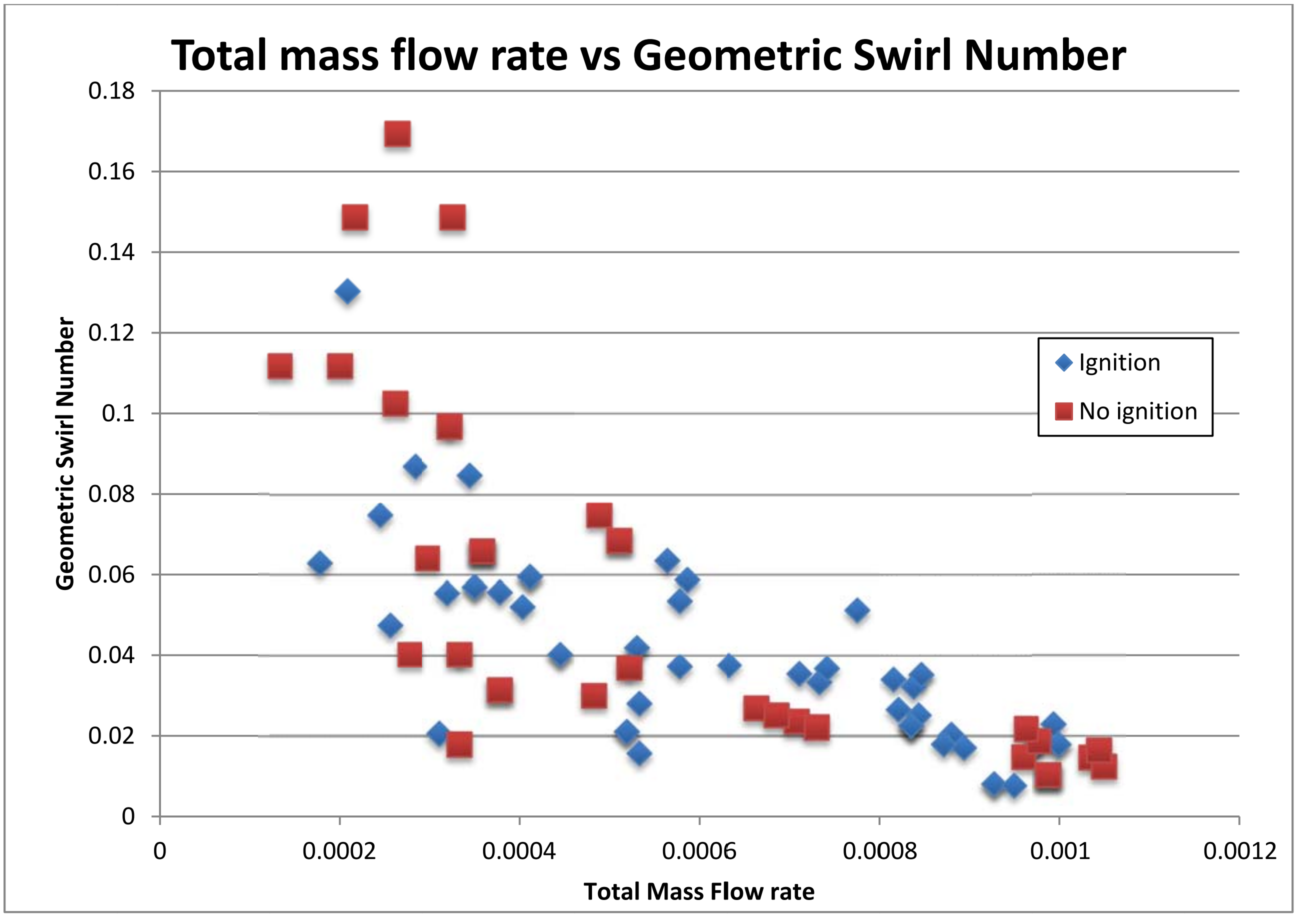


Figure 4.10- Ignition limits, comparing total mass flow rate with geometric swirl number

The geometric swirl number is a measure of the angular momentum added to a flow and can affect the flames stability limits and blowout limits. In the case of gas oxygen and cold methane, it seems that lower swirl number provides better flame stability given the total flow rates. Since the geometry of the igniter is fixed, the swirl number is a function of both, the mixture ratio, and the total flow rate. At low flow rates, it appears that a high geometric swirl number is detrimental to ignition and flame stability, while lower swirl numbers along with higher total mass flow rates allow the mixture to be more ignitable. This is expected since, in general, a higher swirl number with the current geometry means a lower mixture ratio. If this mixture ratio falls below 2.5, the mixture is not easily ignitable as shown in previous figures, such as Figure 4.8.

## 4.2 RESULTS AND DISCUSSION LIQUID-LIQUID

### *4.2.1 LOX-Methane ignition testing*

Testing of the igniter then moved to liquid oxygen to cover the wide range inlet conditions that this igniter might see in its mission duty cycle. This also presented a good testing opportunity for the cryogenic delivery system that was set up with this purpose. The testing of LOX-methane ignition was not as extensive as the previous test campaigns since the delivery system was designed for flow rates an order of magnitude higher than the ones required for the igniter. Testing was done nonetheless to verify component selection for the delivery system and correct operation, along with experience and time of operation. In order to satisfy realistic mixture ratios in which the igniter can sustain combustion, liquid oxygen volumetric flow rates would need to be impractically small for the delivery system, while the methane would need to be in the order upwards of 550 L/min. While it is possible to achieve this, it was decided to go ahead and test the liquid-liquid condition to push the limits of the igniter.

### *4.1.2 LOX-LCH$_4$ ignition testing*

Using the commercial tanks of liquid oxygen, and lowering the tank pressure to pressures along the lines of 70 and 110 psi, the proposed flow rates were achieved. Due to the constraints of flow rate metering, along with the fact that both propellants are cryogenic, there is some uncertainty in the propellant conditions and mass flow rate into the igniter. Every effort was made to ensure that both cryogens were delivered in their liquid form into the injection ports of the igniter, with a pressure transducer and a thermocouple on a cross fitting right before the igniter.

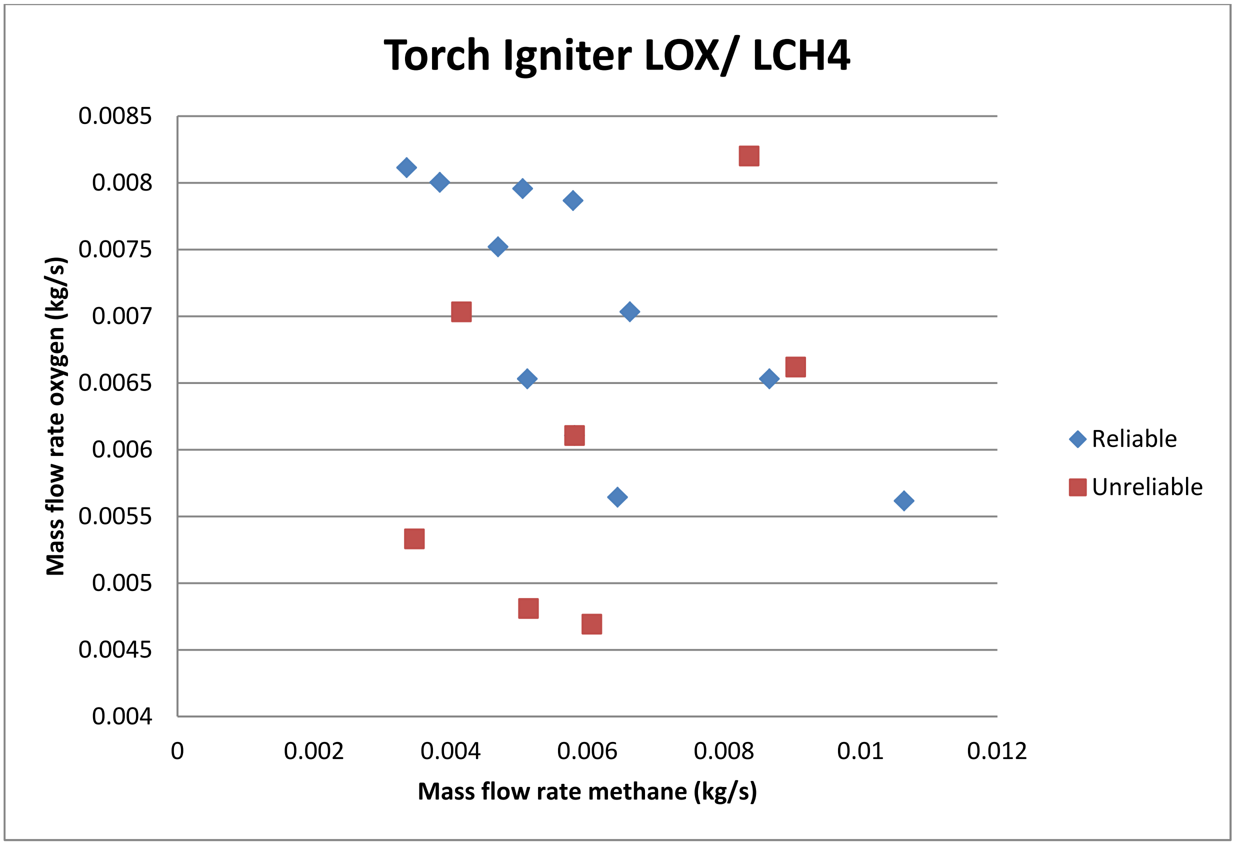


Figure 4.11- Ignition limits of LOX and Liquid methane.

The difficulty to control the mass flow rates in such small scale with only tank pressure as the control variable forced this test campaign to be smaller in overall test number, but the data was recorded. Reliable ignition was achieved in the mixture ratio regions from 2 to 6, although at the lower flow rates, the ignition was not reliable. It is possible that the liquid oxygen was only dripping out of the igniter's injection port it was up to the methane to mix with the oxygen since it has smaller ports and therefore greater velocity at the point of injection.

This testing campaign proves that the spark torch igniter designed will function properly with oxygen and methane under any propellant condition at the inlet, provided that the mixture ratio is between 2 and 5, and the total propellant mass flow rate is not above .012 kg/s. In order to accommodate greater mass flow rates, some flame anchoring techniques can be used such as a bluff body flame holder, a swirler located at the exit plane or reducing the exhaust hot gas

velocity by increasing the outlet area. The proof of concept has been established and developed, and has been determined to be robust enough for use in the MOAC.

### 4.3 FUTURE OF IGNITER WORK

There are many parameters that can be optimized for performance, reliability and ease of use. The electrode manufacturing was a problem throughout the entire testing campaign, to the point of needing to manufacture several to have them ready for use as soon as one broke. The manufacturing of the igniters evolved from two electrodes made out of platinum, to thicker electrodes made out of tungsten, to a single electrode protruding into the combustion chamber, and grounding the entire chamber to have the breakdown voltage happen directly on the chamber and not within the two wires. All these designs will work, with proper manufacturing and care taken especially around the ceramic insulation. The challenge came when trying to make the fitting to ceramic interface a sealed interface that could hold pressure.

The life of the electrode can be increased by keeping it as far away from the combustion process itself with some redesign work. The spark generator can be located in between the oxidizer inlet and the methane inlet, ionizing and making plasma out of the oxygen by itself then allowing it to reach the methane downstream and igniting away from the electrodes. This idea has been used in other igniter designs such as the once presented by Breisacher et al [10]. The idea is to keep the electrode or spark plug at a low temperature by keeping the mixture ratio low close to the igniter, and then mixing it with the rest of the methane further downstream to keep the igniter's combustion chamber at a reasonable temperature. A schematic of this igniter is depicted in Figure 4.12. This type of igniter requires more spark energy, but the authors of this study use a regular commercially available spark igniter. The flow rates they used in their study were slightly higher than the ones presented here, and the igniter they used is a regenerative cooled chamber, which is overkill for the purpose of the future studies in the laboratory.

Another improvement that can be made to the igniter presented in this work would be to include a pressure chamber close to the propellant's injection ports to allow them to build

pressure and increase the combustion time of the propellants, and allow them to fully react before injecting them into the combustion chamber. This would require a very thorough redesign of the igniter as it stands today, but it may prove helpful to achieve higher ignition reliability, in a tradeoff of higher system complexity.

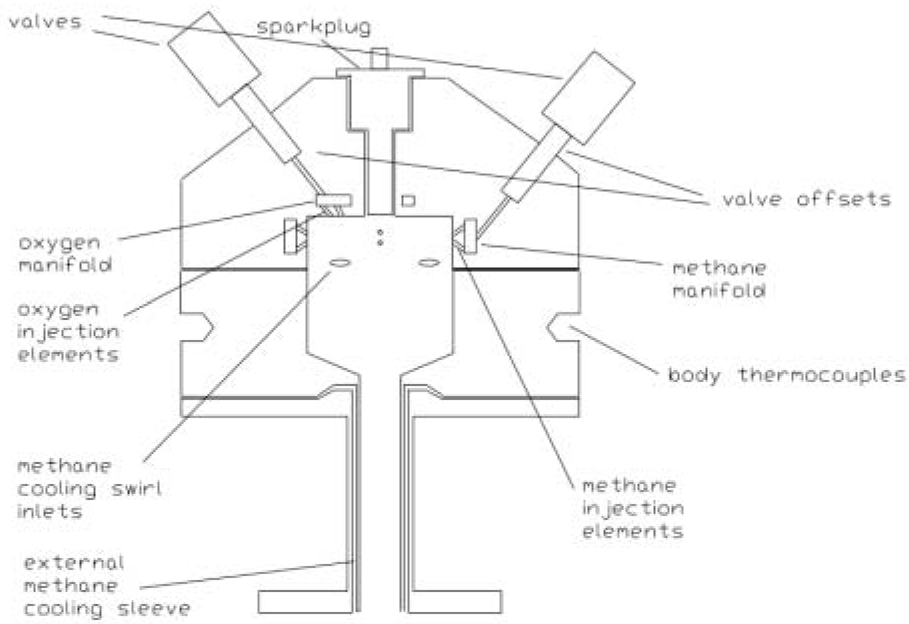


Figure4.12. Cooled igniter by Breisacher et al. [10]

# Chapter 5

## 5.1 Future Work for Injector Fluid Dynamics

The different geometries of the injector will be tested and compared to each other focusing on the breakup length of the oxidizer core. Different techniques of fluid flow visualization such as Schlerien and shadowgraph will be used for this analysis. The two geometry parameters that will be studied are the recess length and the LOX post outer radius with three different injectors, varying only one parameter per injector. Figure 4.2 shows a description of the injector parameters to be varied, while Table 4.1 describes the different injector parameter modifications.

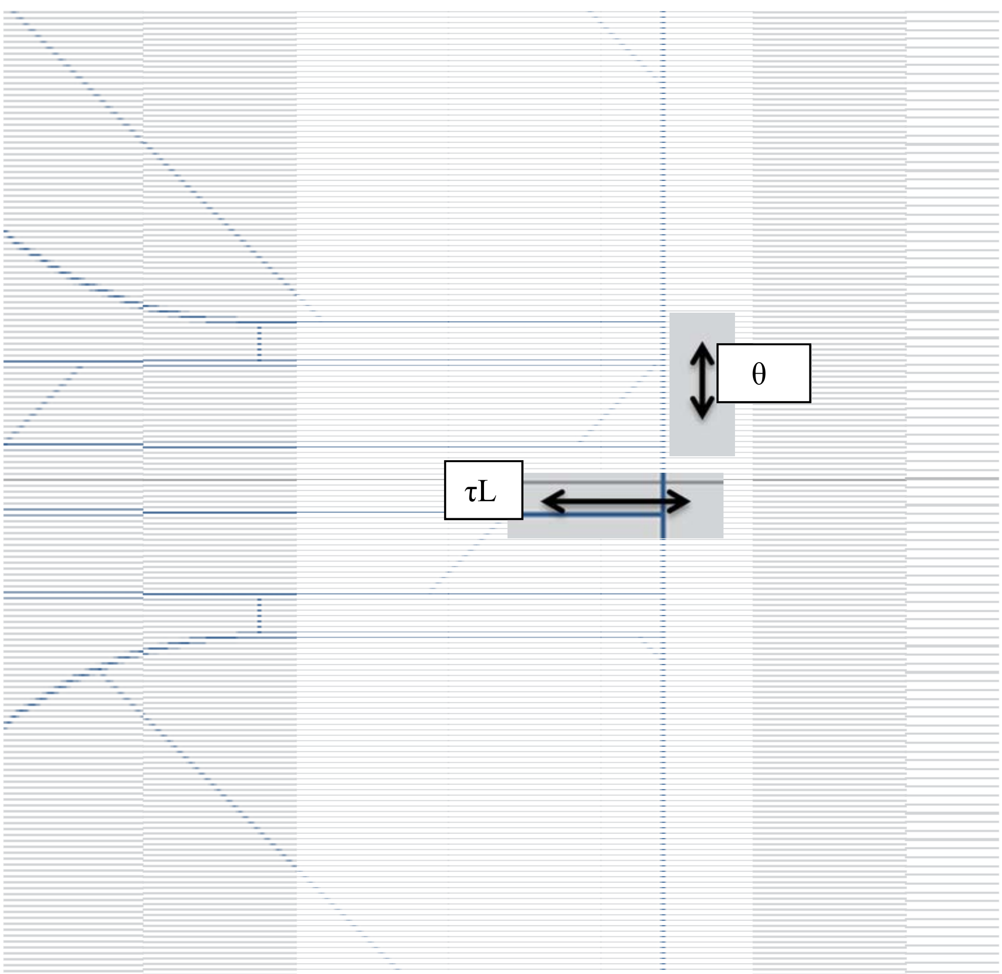


Figure 5.1 Illustration of Injector Parameters [15]

Table 4.1 Injector Geometry Parameters

| Injector | $\tau_\theta$ (mm) | $\tau_L$ (mm) |
|---|---|---|
| Base | 0 | 1.42 |
| Thick Post | 5 | 1.42 |
| Recessed | 0 | 2.26 |

As referenced in Chapter 1, most authors that have studied the shear coaxial injector propellant atomization reference the velocity ratio, Reynolds number, and Weber number as the main drivers for liquid core breakup. Figure 5.2 portrays the expected parameters with different flow rates ranging from .6 Kg/s to .3 Kg/s in the base injector. The Reynolds number of the liquid core is expected to range from 6.9e5 at the low mixture ratio and low flow rate condition to 1.6e6 at the higher end of the spectrum. These are liquid velocities of the oxidizer core ranging from 59 to 139 m/s as pictured in Figure 5.3 It is emphasized that these are proposed flow rates and that others can be chosen.

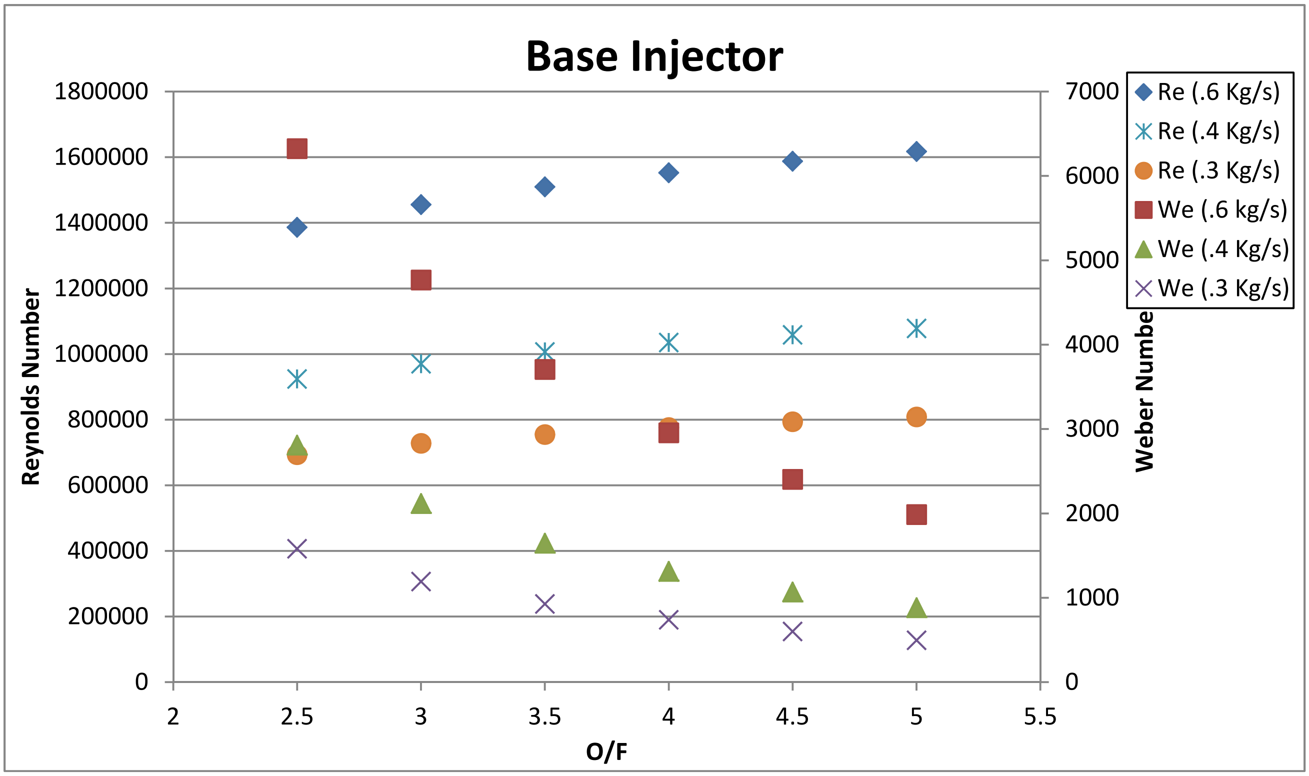


Figure5.2. Base Injector Calculated parameters

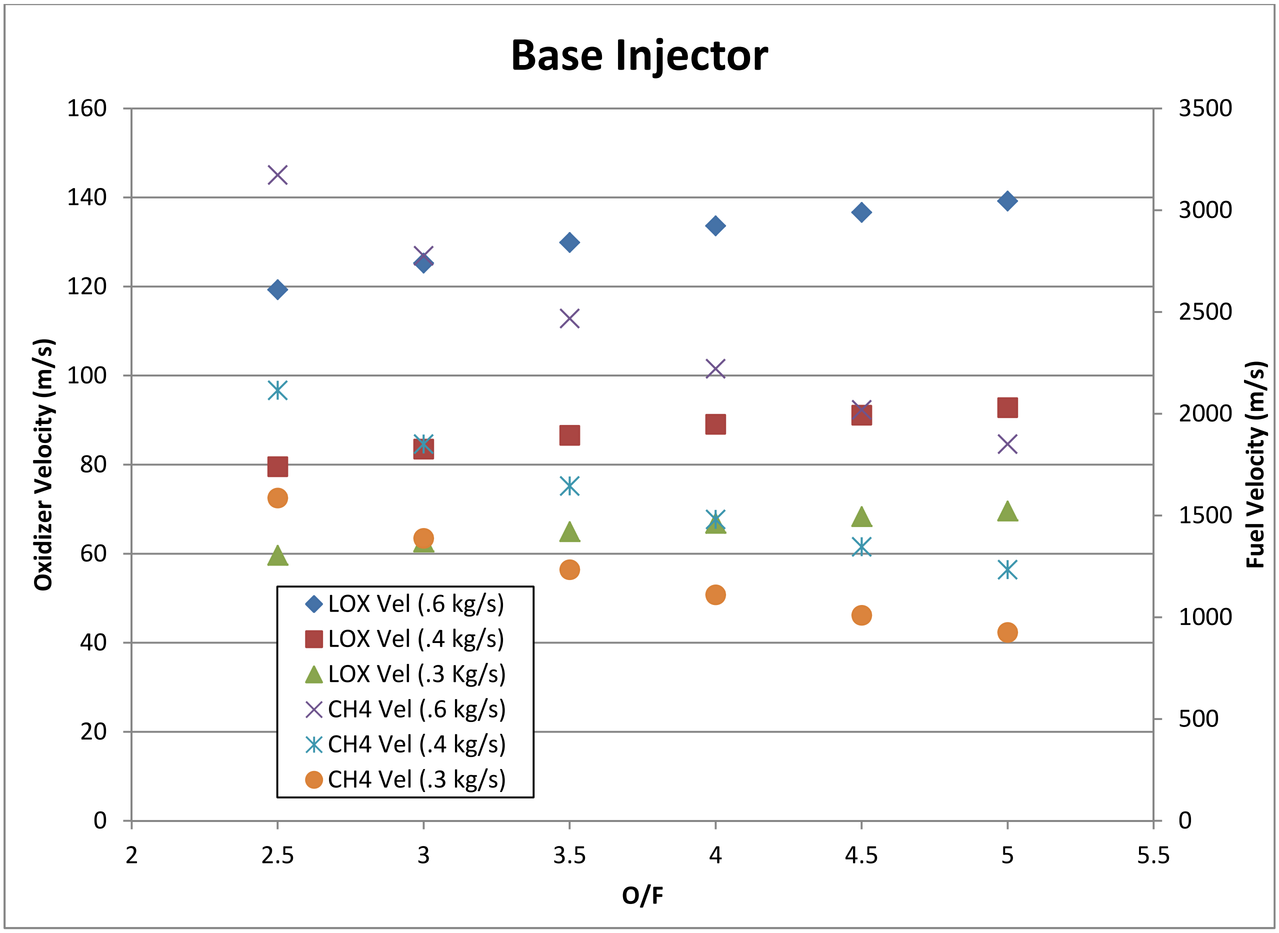


Figure5.3. Propellant Injection Velocities for the base injector

According to N. Chigier and R. D. Reitz in their "Regimes of Jet Breakup and Breakup Mechanisms" these parameters will most likely be in the super-pulsating region of the liquid disintegration in coaxial flow, which states that the breakup length will be close to the injector face, and spray pulsation will begin. Atomization is said to be a "pulsating, unsteady process, even if the emerging liquid and the atomizing gas are initially oscillation and vibration free" [17].

The Reynolds number for most of these conditions is too high compared to most of the literature, since the actual injection port is 2 mm in diameter. This situation can be alleviated by opening up the injection port, even if this is done only at the exit of the LOX post by a slight tapered angle to reduce the exit velocity. This can be done in further experimentation, although it

will change the geometric parameters such as the LOX post thickness, but can also be of use to compare their performance against all the other parameters.

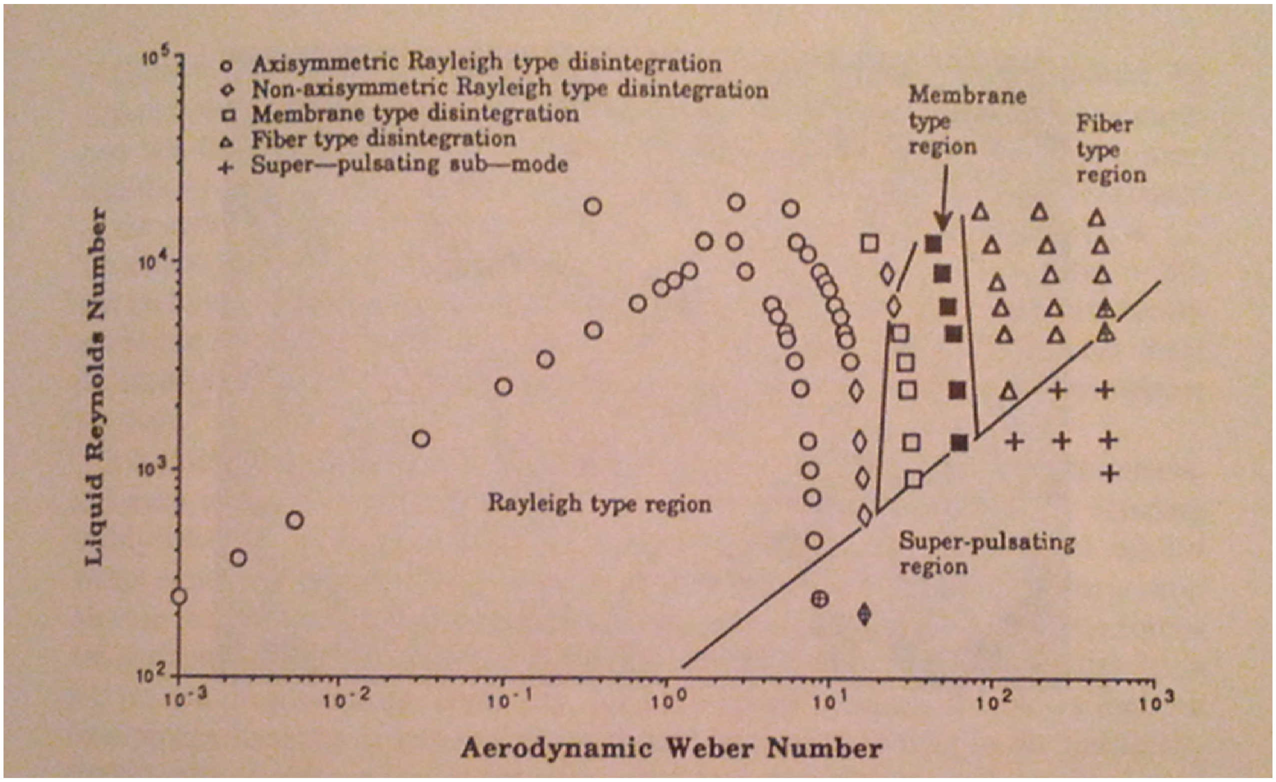


Figure5.4. Modes of liquid disintegration in a coaxial flow. (Taken from [17])

### 5.2 Hot Fire Testing

The injectors will be hot fire tested with the torch igniter. A high speed intensifier camera will be used to determine the flame front propagation from the igniter flame as the source to the injector. The tests will include data from the injection pressure and compared to the nominal chamber pressure to characterize the pressure drop of the injector. The important parameters to explore for the hot fire tests are the We, J, and Oh numbers, previously described. The differences in cold flow analysis to the hot fire testing will be analyzed and compared to provide deeper understanding of how hot fire testing affects the injection, droplet atomization and evaporation.

The results from the hot fire tests will be compared with previous literature focusing on the initial spray atomization, LOX core break up length, flame stabilization location and mechanism, and ignition transients. Added to the volume of literature available to the scientific community are the effects of the geometry changes in the performance of the injection characteristics. This work will also present these findings in a methodological way with more controlled parameters, specifically in regards to the dimensions observed, experience with hardware and sharing the lessons learned.

# Chapter 6

## 6.1 CONCLUSIONS

The stage is set for the study of shear coaxial injector with any type of propellant in a visually accessible combustion chamber. The Multipurpose Optically Accessible Combustion Chamber (MOAC) has been designed to be fully modular to be able to quickly exchange injectors, igniters, and throat section, in the pursuit of faster research cycles. The methane condensing unit was designed and built and valuable experience was gained for future design iterations. The Multipurpose Altitude Simulation System is available as a valuable second layer of experimental safety and a veritable test stand that is versatile enough to be used in an academic environment. Valuable chill in conditions and experience has been accomplished for the cryogenic delivery system that will provide a data point in the design of future experiments. When the technology is mature enough and the learning curve for LOX/Methane has been breached, an entire second phase of research can be undertaken at altitude conditions with the support of the two stage ejector.

A comprehensive literature review of the state of the academic and industrial knowledge of lox-hydrocarbon, specifically LOX/$LCH_4$, is provided as a frame for the importance and relevance of this particular work, as well as the Center for Space Exploration Technology Research's (cSETR) role in this field of study. Evidenced by the review of the different articles presented, is the need for a more thorough understanding of the ignition physics of LOX/Methane and the more systematic and academic study of this particular propellant combination. Different, and often contradictory conclusions have been reached from a variety of studies that would be better served by an academic approach.

An augmented spark torch igniter was designed for use on the MOAC for the study of LOX/Methane ignition physics on shear coaxial injectors. The torch igniter is part of a series of incremental steps to demonstrate the ability of designing a regenerative cooled Liquid oxygen, liquid methane rocket engine with an igniter capable of operating with the gases from the

propellant boiloff. The challenge is to design an igniter versatile enough to reliably function under a variety of propellant inlet conditions, from liquid to cool gas.

The torch igniter presented in this work has been extensively tested as a development phase in the laboratory. It has been demonstrated to reliably ignite and sustain combustion in a battery of different test campaigns that include gas-gas operation, warm oxygen and cool methane, and liquid oxygen and liquid methane. The ignition and sustained combustion limits with respect to mixture ratio and propellant flow rates was established in a methodical testing procedure that encompassed more than two hundred test article ignitions. The data is presented in an "ignition, no ignition" fashion that is very stringent and exclusive, in an attempt to find a truly reliable ignition parameters global map.

Suggestions are provided for the direction of iterative design for the torch igniter in future tests and to improve reliability and ease of use. These recommendations include: spark electrode configuration arrangements, stability and thermal management ideas that show promise, and combustion chamber geometry configuration changes that would improve the life of the electrodes while providing better flame anchoring and control.

A glimpse of the future of injector testing is also presented to convey an indication of the exciting future work that awaits this project, and the promise that it entails. This consist of the design parameters on a shear coaxial injector that can be modified and their effects studied, such as momentum flux ratio, Reynolds number, Weber number and chamber pressure among others.

## References


[1] Mark D. Klem "Liquid oxygen/ liquid methane propulsion and cryogenic advanced development." International Astronautical Congress

[2] Todd Neill, Donald Judd, Eric Veith, Donald Rousar. "Practical uses of liquid methane in rocket engine applications" Aerojet, USA Carta Astronautica 65, 2009

[2] Robinson, Philip J., Veith, Eric M., "100-Lbf $LO_2/LCH_4$ reaction control engine technology development for future space vehicles" Aerojet Sacramento, CA, USA

[3] Mark D. Klem, Timothy D. Smith, Mary F. Wadel, Michael L. Meyer, James M. Free, Harry A. Cikanek III "Liquid Oxygen/Liquid methane propulsion and cryogenic advanced development". NASA Glenn Research Center, Cleveland Ohio, USA.

[4] Delphine Salgues, Geraldine Mouis, Seong-Young Lee, D. M. Kalitan, Sibtosh Pal, and Robert Santoro "Shear and swirl coaxial injector studies of $LOX/GCH_4$ rocket combustion using non-intrusive laser diagnostics" Propulsion Engineering Research Center, Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park PA 16802

[5] Chiara Manfletti, Joachim Sender, Michael Oschwald. "Theoretical and experimental discourse on laser ignition in liquid rocket engines" Institute of Space Propulsion, German Aerospace Center (DLR) Lampoldshausen, Germany. 2009.

[6] Sirignano William A. Mehring, Carsten, editors, *Liquid Rocket Thrust Chambers: Aspects of Modeling, Analysis, and Design*, 2004. "Distortion and disintegration of liquid streams" University of California, Irvine, California.

[7] Hurlbert, Eric A., Moreland, Robert J. and Candel, Sebastian, editors, *Liquid Rocket Thrust Chambers: Aspects of Modeling, Analysis and Design*, 2004. "Propellant Ignition and Flame Propagation".

[8] Oschwald, M., Cuoco F., Yang, B., De Rosa, M., Haidn "Combustion of $LOX/H_2$- and $LOX/CH_4$-sprays" Instiure of Space Propulsion DLR Lampoldshausen, German Aerospace Center, 74239 Lampoldshausen, Germany.

[9] Zong, Nan, and Yang Vigor "Near-fiel flow and flame dynamics of LOX/methane shear coaxial injector under supercritical conditions" Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, 104 Research Building East, University Park, PA 16802, USA.

[10] Breisacher, Kevin and Ajmani Kumud. "LOX/Methane Main Engine Igniter Tests and Modeling" 44$^{th}$ AIAA Joint Propulsion Conference & Exhibit. 21-23 July, 2006.

[10] Hart, Jeremy and Mitchel, Jennifer "Morpheus Lander Testing Campaing" NASA Johnson Space Center, 2101 NASA Parkway/EG6 Houston, Texas 77058.

[11] Flynn T. M. "Cryogenic Engineering" Second Edition, 2005

[12] Aerojet TechSystems Company "Ignition characterization of LOX/Hydrocarbon propellants" Final Report, Contract NAS 9-16639. Prepared for: NASA Lyndon B. Johnson Space Center 1985.

[13] Betancourt, Jesus “Instrumentation, control and torch ignition systems development for LOX/methane propulsion research” The University of Texas at El Paso, Thesis, 2012

[14] Pineda, Francisco “Cryogenic system development for LOX/hydrocarbon propulsion research” The University of Texas at El Paso, Thesis, 2012

[15] Navarro, Christopher “Development of a high pressure optically accessible combustor and shear coaxial injector” The University of Texas at El Paso, Thesis, 2012

[16] Sanchez, Luis “Combustion characteristics of a swirl torch ignition system for propulsion research” The University of Texas at El Paso, Thesis, 2012

[17] N. Chigier and R. D. Reitz, “Regimes of Jet Breakup and Breakup Mechanisms” Chapter 4 in “Recent Advances in SprayCombustion: Spray Atomization and Drop Burning Phenomena Volume I” Pages 109-135.

# Vita

Jesus Roberto Flores received both a Bachelor and a Master of Science degree in Mechanical Engineering from The University of Texas at El Paso in 2008 and 2009 respectively. He continued his studies at The University of Texas at El Paso and in 2010 was admitted to the doctoral program in Environmental Science and Engineering, Energy Science and Engineering track.

Dr. Flores is a research associate at the Center for Space Exploration Technology Research. He also completed an internship with NASA White Sands Test Facility and with Blue Origin. Dr. Flores was the recipient of a Patricia and Jonathan Rogers Scholarship.

Dr. Flores' research, which he presented at meetings of the American Institute of Aeronautics and Astronautics (AIAA) Joint Propulsion Conference and the International Test and Evaluation Association (ITEA) Conference, focuses on the ignition and injector physics of LOX-Methane combustion chambers for low thrust rocket engines, and the dynamic response of low thrust rocket test stands.

Dr. Flores' dissertation *Effects of Injector Geometry on the Flow Field and Ignition Physics of LOX/Methane in a Visually Accessible Combustion Chamber,* was supervised by Dr. Ahsan Choudhuri.

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