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Development and Testing of Oxygen/Methane Torch Igniter Technologies for Propulsion Systems

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DEVELOPMENT AND TESTING OF OXYGEN/METHANE TORCH IGNITER TECHNOLOGIES FOR PROPULSION SYSTEMS

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Dedication

I wish to dedicate this dissertation to my family and girlfriend for their support throughout my doctoral effort.

DEVELOPMENT AND TESTING OF OXYGEN/METHANE TORCH IGNITER TECHNOLOGIES FOR PROPULSION SYSTEMS

A DISSERTATION

by

LUIS EDUARDO SANCHEZ

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Executive Summary

The development and testing of an oxygen/methane torch ignition system as well as the evaluation process of the system are presented with the purpose of characterizing the properties and performance of methane as a fuel in a propulsion system. The experimental approach to this dissertation entails the development and testing of a swirl torch igniter under conditions that may be seen when feeding propellant from the main storage tanks: combinations of gaseous and liquid oxygen and methane. The experimental goal of this dissertation is to display the range of operability of the igniter technology presented leading to stable and consistent ignition. The interest on liquid oxygen/Methane as a propellant combination for rocket engine propulsion has been boosted due to recent developments in commercial space exploration, along with a desire to decrease the cost of space exploration technologies. Torch igniter requirements were met in this test campaign however issues with oxidizer condition were observed in the second phase of the torch igniter test campaign. The torch igniter design modification mitigated the issues encountered in the previous design iterations of the torch igniter. A total of 310 test runs were conducted in the torch igniter developmental test campaign. Steady state ignition was achieved in 276 out of 310 tests. Gas/gas propellants had a 100% ignition rate while liquid/liquid propellants had a 66% ignition rate. The propellant quality was plotted with the saturation curve to quantify the condition of the propellant that was fed to both successful and unsuccessful test runs. The objectives of this dissertation were successfully met as the swirl torch igniter was proven to resist and operate reliably in a rigorous duty cycle test. The igniter demonstrated the capability of recycling within seconds if the occasion required it.

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Chapter 1

1.1 Introduction

The interest on oxygen/methane as a propellant combination for rocket engine propulsion has been boosted due to recent developments in private space exploration, along with a desire to decrease the cost of space exploration technologies. Private space companies like Space Exploration Technologies (SpaceX) and Blue Origin, to name a few, have chosen liquid oxygen/methane as the propellant combination for their new engines that are currently being developed. Hydrogen has been historically used as fuel in rocket engine. There are many advantages of using methane as a fuel over hydrogen. Methane has higher density than hydrogen thus requiring smaller storage vessels [1]. Additionally, the storage temperature of liquid oxygen and liquid methane is similar (40 °F difference) in comparison to the drastic temperature difference between liquid hydrogen and liquid oxygen (130 °F difference). The possibility of resourcing methane in-situ can significantly decrease the weight requirements of a space vehicle for long-term missions in space. Even though the combination of liquid oxygen and liquid hydrogen produces a higher specific impulse (390s) than liquid oxygen and liquid methane (320s) the possibility of resourcing and the storability of methane for deep space explorations are viable reasons for developing oxygen/methane propulsion systems [2]. Table 1.1 presents the comparison of rocket fuel properties currently used in propulsion systems.

Table 1.1: Comparison of rocket fuel properties currently used in propulsion systems [2]

	Density (lbm/ft^3)	ISP sea level (s)	Boiling Point (F)
Hydrogen	4	390	-422
RP-1	51	300	350-500
Methane	25	320	-253

Ignition has been identified as the highest risk for Liquid Oxygen/Methane rocket engines. A reliable ignition sources for oxygen/methane propulsion system is required to successfully ignite the propellants in the combustion chamber. Historically, hypergolic propellant based igniter systems have proven to be significantly more difficult to handle due to extreme propellant toxicity and corrosiveness as well as their harmful environmental effects during testing and operation [3]. An oxygen/methane ignition system with a robust duty cycle capability and a reliable ignition performance is essential to replace hypergolic based ignition systems in current propulsion systems.

The development and testing of a swirl torch ignition system developed by the Center for Space Exploration Technology Research (cSETR) at the University of Texas at El Paso is detailed in this dissertation. The igniter system developed uses methane as fuel, a significantly less toxic fuel and a candidate for in-situ resourcing in deep space exploration missions. The igniter system can also operate over a wide range of propellant quality, spanning from gas/gas, two-phase, and liquid/liquid conditions. This project uses GOX/LOX/GCH_4/LCH_4 as propellants to measure the performance of this igniter design over the full range of operating conditions. The compactness of the igniter system design provides flexibility on placement of the igniter within the main engine and vehicle design. The igniter design is meant to be adaptable so it can be

operated from the main engine tanks, without the need of a secondary or independent tank system. The inclusion of replaceable inline-orifices within the igniter system provides the capability to adapt the igniter to suit a wide range of main tank upstream pressures, mass flow rate, and main engine chamber pressures. This feature is desirable as it can significantly reduce the number of required feed system components thus reducing overall system weight. Not only with this igniter be implemented in the cSETR-developed engines but also will be capable of functioning with different rocket engines.

1.2 Literature Review

Currently, different ignition methods are utilized in propulsion systems ranging from pyrophoric igniters to oxygen/methane igniters. A literature review of existing ignition technologies was compiled to identify the improvement needed in current ignition system. The literature review covers current ignition systems utilized as well as emerging technologies utilizing oxygen/methane as propellants.

1.2.1 Analysis of Hypergolic Igniters

Hypergolic igniters have been in used since the beginning of the American space program. The most critical factor in rocket propulsion is a smooth ignition [3]. To initiate a smooth ignition, a hypergolic cartridge igniter of a mixture of 15 per cent triethylaluminum and 85 per cent triethylboron, called TEA/TEB [12]. TEA/TEB chemicals are highly toxic and ignite spontaneously on contact with air, increasing the complexity when storing and handling this type of igniters. The control of the mixture percentage of TEA/TEB is critical to the assurance of reliability for engine ignition and this guarantee a successful operation of the propulsion system.

Ignition within a rocket engine combustion chamber occurs in an event scaled in milliseconds. Ignition delay is fundamental in rocket engine ignition. An ignition delay is important in an ignition process and it has to be timed close to perfection to prevent overpressure event due to extended ignition process inside a combustion chamber. Average ignition delay of

TEA/TEB was obtained by small destructive testing and a statistically analysis of number of hypergolic cartridges utilized [3].

Over 200 samples of TEA/TEB were obtained from various vendors and examined for this study of ignition delay. Mass spectrometric analysis as well as gas chromatographic analysis of the hypergolic mixture resulted in a decomposition in which the products were apparent but the original quality of the material was not certain. Impurities in the original components were easily detected prior to each destructive test for qualitative purposes but no evident impacts were observed in the ignition delay of TEA/TEB.

The results from this study presented hypergolic igniter that show consistently acceptable ignition delays. Even though TEA/TEB will ignite practically at any condition as long as there is air in its operating environment, the handling difficulty and the toxicity has led efforts to explore new igniter technologies.

1.2.2 LOX/Methane Main Engine Glow Plug Igniter Test and Modeling

A propose switch from hypergolic propellants to oxygen/methane propellants for in space propulsion systems require the development of highly reliable igniters. Due to this necessity an ignition test program at NASA Glenn Research Center was created to evaluate an ignition system and analyzed its potential as a redundant ignition system. An in-house torch igniter and automotive glow plugs were used in this experimental effort. Figure 1.1 present the glow plug igniter schematic. The igniter was a three-piece design consisting of a head end, chamber section and a fuel coolant sleeve [4]. At the top of igniter, are the glow plug and the propellant valves. Instrumentation upstream of the valves were placed to obtain data for propellant inlet conditions during testing. Igniter body temperatures were measured by two thermocouples located at the mid-section of the igniter body. Additional methane cooling was provided at the exterior wall of the exit sleeve of the glow plug igniter.

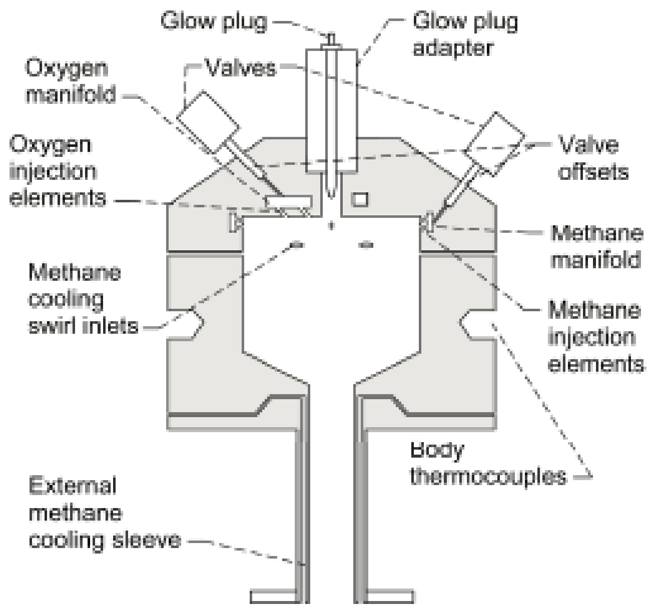

Figure 1.1 Glow plug igniter schematic

All glow plug igniter tests were conducted at an altitude simulation chamber capable of simulating 95,000 feet or 10 torr. Propellants were pressurized by a regulated feed system up to pressures of 400 psia. The test campaign utilized both warm and cold gas propellants at the inlet of the igniter. This attempt was to characterize the performance of the glow plug igniter at warm and gas inlet conditions feed to the igniter. The glow plug igniter was tested at different body temperatures to determine any potential effects in performance. A liquid nitrogen cool loop was used for test that required cold hardware but warm propellants. In the cases where testing required cold gas propellants, the hardware was chilled with propellants prior to a hot fire test with the addition of the cooling loop. In figure 1.2, a hot fire test with cold hardware configuration can be observed.

Figure 1.2 Ignition test at reduced igniter body temperature

Preliminary studies of this glow plug igniter demonstrated that the technology is capable of ignition over a range of mixture ratios of three to twelve with warm and cold propellants feed to the igniter. The igniter body temperature was tested down to -218 °F. Even though the glow plug igniter showed promising results in performance the glow plug element took a significant amount of time to reach the temperature required for ignition in the chamber of the igniter. It took the glow plug 7 to 11 seconds to reach the necessary temperature to ignite the propellants [4]. This can be an issue if implemented to a propulsion system that requires rapid and reliable ignition at any given time.

1.2.3 LOX/Methane Main Engine Igniter Tests and Modeling

NASA Glenn Research Center has led the development of oxygen/methane igniter technologies in the recent years. Previous studies conducted at Glenn Research Center have

focused on testing their igniters at liquid conditions and varying the igniter body temperature. This study was conducted to anchor experimental data to igniter modeling. The data obtained from de test conducted will provide the necessary data to develop CFD models of torch igniters. A total of 750-ignition test were performed in this test campaign. Fuel purity was explored during testing, fuel with low and high concentrations of ethane, propane, and nitrogen were tested with no significant change in igniter performances or detriment to the ignition process [5]. Figure 1.3 presents a hot fire test of the torch igniter investigated in this study.

Figure 1.3 LOX/CH4 igniter hot fire test

The igniter body temperature was tested to determine if there was a point in which ignition was not sustainable. An ignition boundary was obtained with a cold igniter body at altitude testing. Figure 1.4 presents a plot of the ignition limits observed at different igniter body temperatures. Oxygen tank pressures of 60, 80 and 120 psi were tested while determining the ignitability limit at low body temperatures. As the pressure of the oxygen increased the limit of

the temperature body increased. The study authors attributed this relationship observed due to increased heat loss to the walls of the igniter as igniter chamber pressure increased [5].

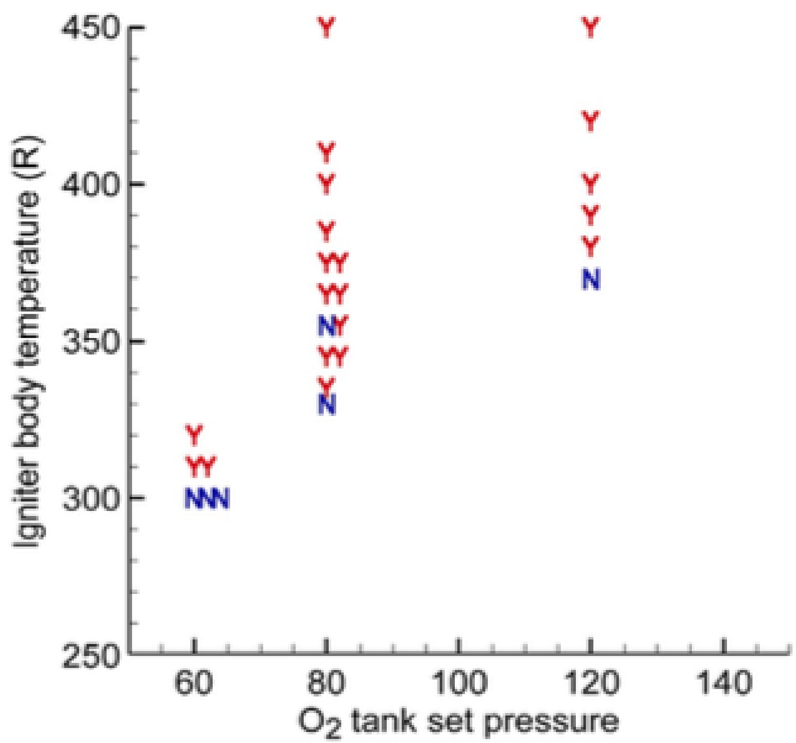

Figure 1.4 Igniter body temperatures per Oxygen tank pressure tested

The National Combustor Code (NCC) was used to perform the igniter simulations of the Glenn Research Center main engine igniter. This computational combustor code is capable of solving time dependent Navier-Stoke equations with chemical reactions. The study authors claim the experimental results obtained from testing can be further explained and understood by looking at CFD simulations. The simulations conducted were focused in two different test scenarios, warm and cold igniter body. Flight ignition systems may use igniter body heaters thus it is important to test and model a condition in which the igniter body is at low body temperatures to obtain an approximation of how much the igniter body will need to be heated if its required and how it would perform under this conditions [5]. The simulation results can be observed in figures 1.5 and 1.6 for warm and cold igniter body. The simulation of a successful

warm ignition observed hot gas all across the body of the igniter as expected when compared to the experimental data obtained. The result of the simulation with a cold igniter body showed that the ignition kernel does not propagate to the igniter walls as a successful warm simulation. Warmer gas can be observed to flow around the walls of the igniter body due to the cold walls from cooling. Approximately 750-ignition test were conducted and the data from this tests were utilized to anchor 4 simulation of warm and cold igniter body.

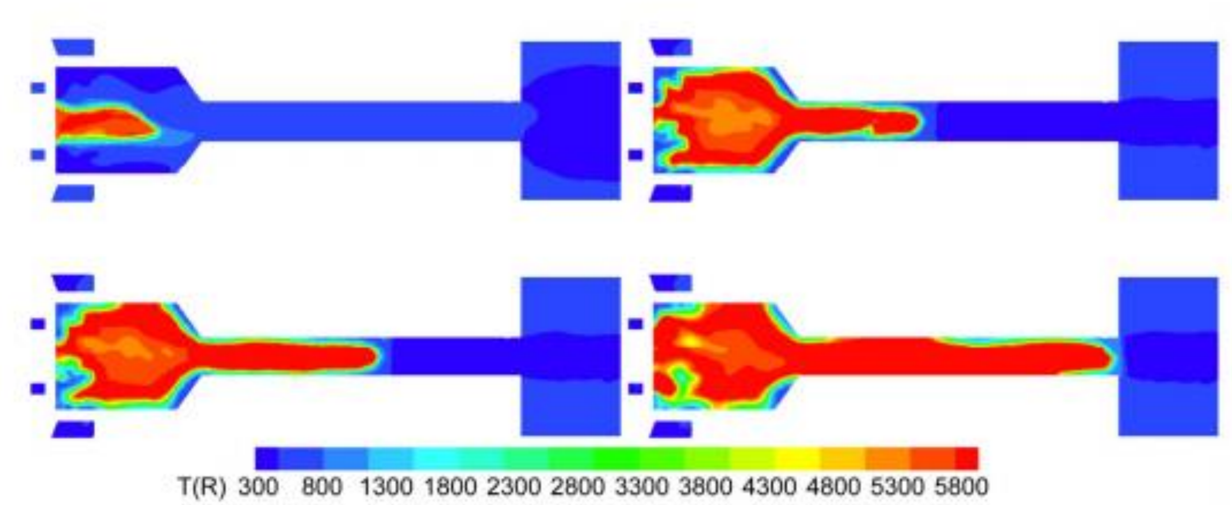

Figure 1.5 Simulation of a successful test with a warm igniter body

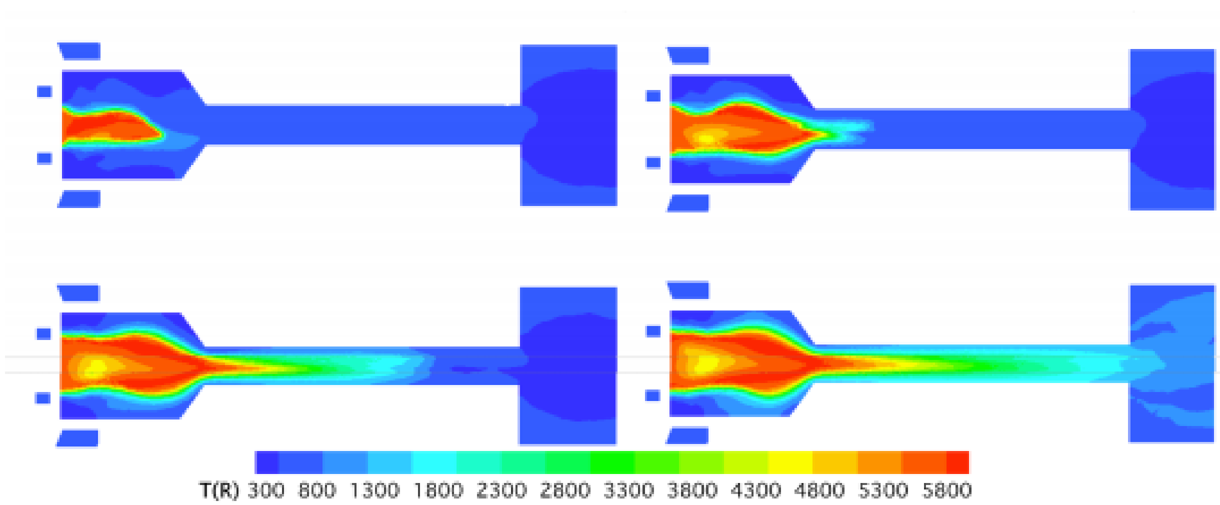

Figure 1.6 simulation of a successful test with a cold igniter body

1.2.4 Design, Fabrication, and Test of a LOX/LCH4 RCS Igniter at NASA

A workhorse liquid oxygen-liquid methane rocket igniter was developed at NASA Glenn Research Center with the purpose of evaluating the ignition processes. The workhorse igniter was design with a bluff body tipped sparkplug. A cross section of the workhorse igniter can be observed in figure 1.7. The bluff body spark plug exciter was capable of delivering 200 sparks per second at 20 kV [6]. The igniter was feed from three different lines, two for fuel and one for oxidizer. Liquid oxygen was injected by the bluff body of the spark plug were the spark arcs across to the inside wall of the igniter. One fuel line fed fuel by the tip of the spark plug; at this location a design overall mixture ratio of 2 was set. The other fuel line was injected downstream of the spark plug bluff body to supply a film cooling to the igniter combustion chamber. The secondary fuel injection point was design to be at a mixture ratio of 20 to maintain a flame temperature compatible with the hardware [6]. Propellant mas flow rate was meter by cavitating venturies upstream of the inlet valves. All tests were conducted at a simulated altitude of 98,425 ft. Liquid nitrogen was continuously cycled to maintain propellant tank temperatures to sub cooled liquid conditions prior to test. Gaseous feed systems were used to pressurize the run tanks up to 400 psia.

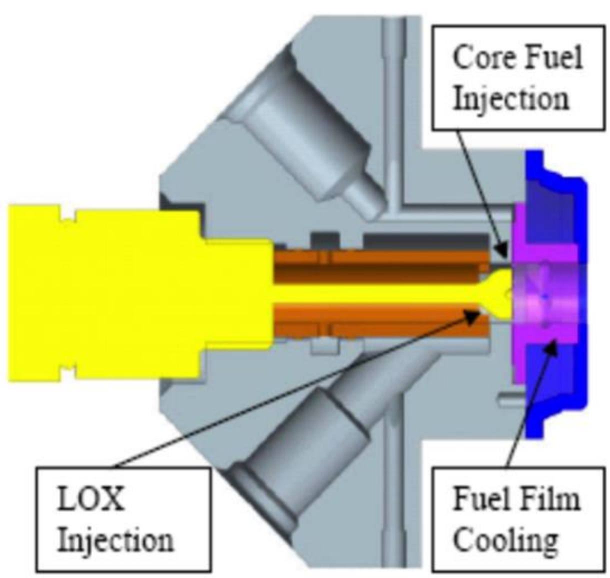

Figure 1.7 Cross section of the workhorse igniter

The test campaign was design to evaluate the performance of the igniter under variations of mixture ratio. The igniter body was tested at two different temperatures of 70 and -250 °F. The test sequence was controlled by a PCL in which the fuel valves has a 0.2 second lead over the oxidizer valve. The spark plug was energized at the same time the oxidizer valve was opened with duration of 0.25 seconds [6].

The durability of the spark plug was of main concern during the test campaign as it was important to obtain a duty cycle of the igniter. Understanding the duty cycle of the igniter could gage the lifetime of the spark plug and other components of the igniter. The igniter successfully ignited over the range of propellant conditions specified in the test matrix of this test campaign. Single ignition pulses of 0.5 seconds burns were performed throughout testing.

The fuel condition was monitored to determine whether the fuel remained in the liquid condition as it was fed to the igniter. Three points were of main focused for this investigation, tank condition, inlet of the venturi and inlet of the valves. In figure 1.8, the fuel condition at the three location of interest is presented from selected data. The saturation curve for methane is included to assist in the determination of the fuel condition during tests. The data shows that methane remained in liquid conditions at the tanks and cavitating venturies and started to flash as it was passing by the igniter valves. Methane was injected in a cold gaseous condition as it is expected when the hardware is at ambient conditions [6].

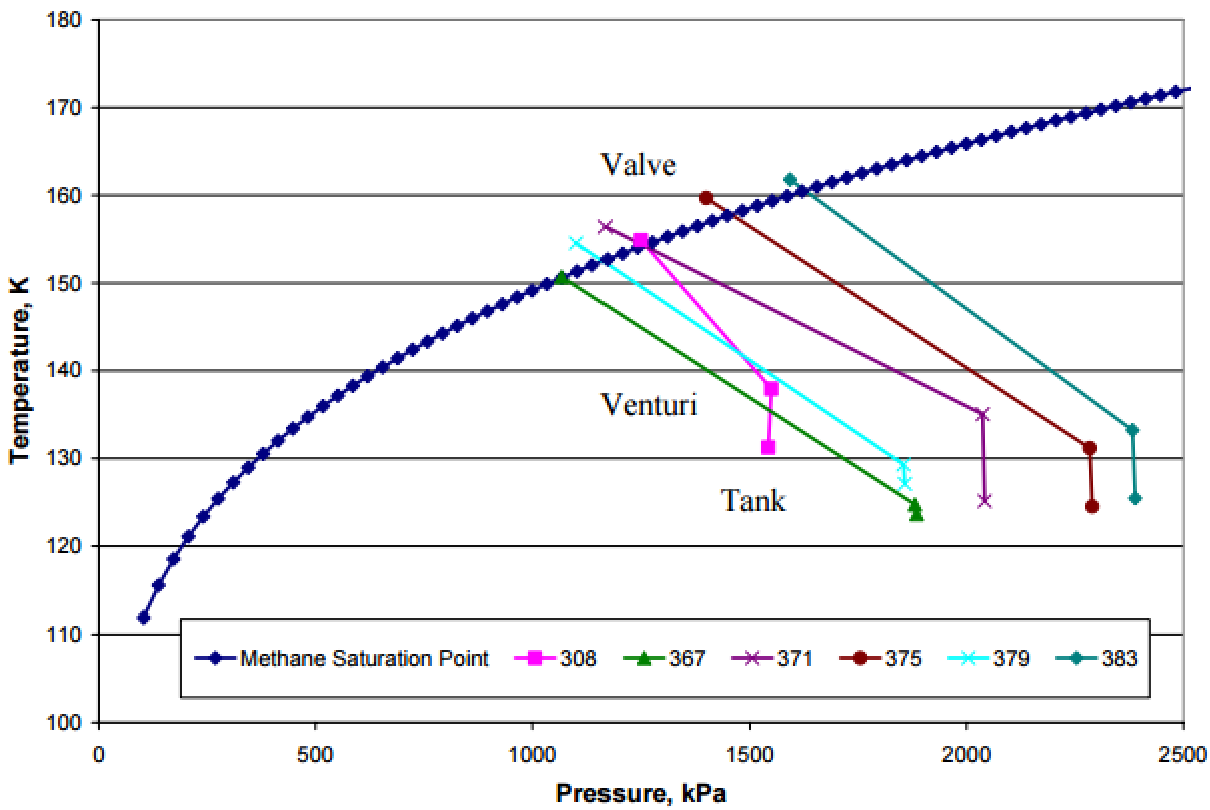

Figure 1.8 Selected data of methane condition at tank, venturi and valve.

A total of 1402 hot fire test of the torch igniter were successfully conducted. The test demonstrated ignitability over a range of mixture ratios of 1- 1.88. The igniter chamber pressure ranged between 150 to 250 psia. Igniter body temperature was also tested with mixed results. Approximately 5 percent of the total test attempted resulted in non-ignition. The durability of the ceramic in the spark plug was compromised during cold body testing. The test campaign was halted due to the failure of the ceramic in the spark plug and no further attempts to continue testing were made. Figure 1.9 presents the spark plug damaged during testing and it can be observed that the ceramic in the bluff body was significantly damaged.

Figure 1.9 Damaged spark plug

1.2.5 Development of a Rocket Engine Igniter Using the Catalytic Decomposition of Hydrogen Peroxide

This study describes the study of developing an igniter technology using hydrogen peroxide decomposition as a propellant. The authors of the paper claim that igniters based on catalytic decomposition of Hydrogen Peroxide requires less components thus reducing the complexity of the system. A hydrogen peroxide based igniter eliminates the need of electronic components for a spark plug based ignition system.

The decomposition of hydrogen peroxide produces a gas of approximately 1400 °F, which is above the auto ignition of liquid oxygen/liquid hydrogen propulsion systems [7]. The temperature achieved from decomposition will not require active cooling. The study claims that an ignition system with hydrogen peroxide decomposition can make a lighter, safer and more reliable that current systems.

A silver mesh was selected as the catalyst for the decomposition of hydrogen peroxide. The igniter injector plate and body was made out of 304 Stainless Steel. The igniter feed systems was designed for a maximum operating pressure of 1800 psi. Pressure and temperature sensors were located at mass flow measurement points and isolation valves in the systems.

The test campaign for this hydrogen peroxide based igniter was done under cold weather conditions that had an effect on testing that resulted in cold hydrogen peroxide prior to initial testing. Initial cold body starts were unsuccessful, temperature of the hydrogen peroxide reached -370 °F and liquid hydrogen peroxide was flowing out of the igniter. To mitigate this problem, short pulses were done to pre-heat the catalyst prior to a test. The pre-heating pulses were done for 0.2 seconds at intervals of 5 seconds. Following the preheating procedures, four hot fire tests of 8 seconds of total duration were conducted. The hot fire test resulted in a chamber pressure of 130 psia in average with a temperature of 1080 °F [7]. Figure 1.10, present a hydrogen peroxide hot fire test conducted in this study. Even though an ignition system with decomposition of hydrogen peroxide reduces the number of components needed the fact that there is preheating process needed significantly decreases the reliability of this ignition system.

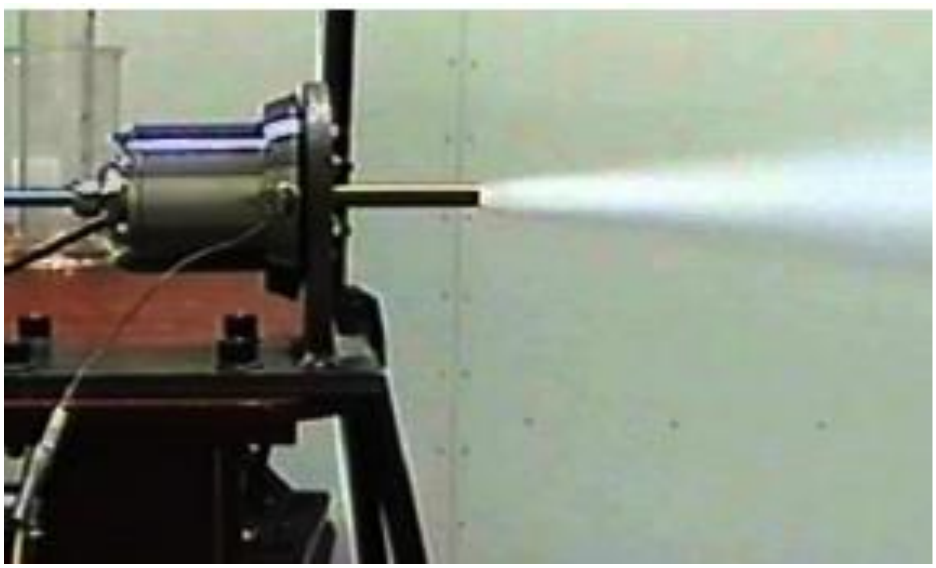

Figure 1.10 Hydrogen Peroxide igniter hot fire test

1.2.6 Jet Engine Ignition System Utilizing Pyrophoric Fuel

There are currently several jet engine patents that cover the invention of pyrophoric fuel as the engine ignition system. Pyrophoric fuel, in this case Aluminum Triethyl, ignites spontaneously on contact with air at ambient temperatures or lower [8]. In a jet engine, high-

speed flow is constantly seen during operations. Initial ignition can be difficult due to the high-speed flow of the combustible fuel through a jet engine. Re ignition in a jet engine can be difficult to achieve due the previous high speed flows mentioned and flame blow out are can occur thus the need of a reliable ignition source to the combustible fuel. Pyrophoric fuel will instantaneously ignite at all operating conditions as long as air is present in the combustion chamber of the jet engine.

Air breathing engines currently use spark plug systems as well as pyrophoric fuels. The application of pyrophoric fuel as an ignition source is intended only for ignition of a combustible mixture in which air is present, in this case all air breathing jet engines [8]. In Figure 1.11, a test of the pyrophoric fuel in an air breathing engines is being conducted.

Figure 1.11 Hypergolic ignition in a jet engine

1.2 Problem Statement

Despite the fact that the collected literature review described the development efforts for oxygen/methane ignition technologies, this technology remains to be fully explored. The problem to address is the scarcity of experimental knowledge of the effect of propellant quality and repeatability on ignition systems. Current igniter technologies have limited the operating conditions to cryogenic or gag/gas propellants without exploring a broader range operability with oxygen/methane. A reliable ignition system is the most critical component in an oxygen/methane propulsion system. In oxygen/methane propulsion systems, the ignition system can be fed from the main engine storage tanks thus eliminating the necessity of adding an additional fluid system. By supplying the ignition system from the main tanks, the propellant quality can vary significantly based on how often the system is operated. For this reason, it is critical to explore the capability of an ignition system in a wide range of propellant inlet conditions.

Hypergolic igniters are capable of reliably igniting propellants in a rocket engine combustion chamber but its repeatability is questionable. Hypergolic based igniters can corrode and damage the hardware to a point in which re-ignition might not be achievable. Hypergolic ignition systems can also increase the overall price tag due to the complexity of handling and preparation of the propellant due to its toxicity and corrosiveness.

A reliable and robust ignition system is essential to meet the reusability of today's propulsion systems. It is important to provide the capability of multiple engine re ignitions eliminating the concern of compromising the hardware if re ignition is required. Re ignition of propulsion systems requires an ignition system capable to ignite the propellants regardless of the condition in which they are delivered to the igniter combustion chamber. The torch ignition performance using oxygen/methane as propellants has yet to be characterized at a wide range of operability conditions. Previous efforts focused on analyzing an ignition system with liquid propellants or gaseous propellant only but not optimizing both in a same test campaign and more importantly maintaining a constant hardware configuration.

1.4 Practical Relevance

Private space companies have selected oxygen/methane propulsion systems for their next generation orbital vehicles. This study is relevant to current development efforts in oxygen/methane propulsion systems, as it will provide literature for performance and capabilities of oxygen/methane ignition systems.

A complete analysis of the performance of the torch ignition system is vital to determine operability limits before is utilized in a full-scale propulsion system. The lessons learned through the testing and analysis of the ignition system under different propellant conditions will help the development of a reliable and robust ignition sources for upcoming oxygen/methane propulsion systems.

1.5 Project Objectives

The objectives of this dissertation are focused on the ignition capability and performance of a swirl torch ignition system developed at the Center for Space Exploration and Technology Research. The experimental effort for this study was focused testing the robustness of the ignition system as well as to provide a direct comparison to current oxygen/methane ignition technologies. The experimental results obtained will prove valuable for future testing of oxygen/methane propulsion systems that are currently under development at the cSETR.

Test campaign for the swirl torch igniter detailed in this work was divided in to two test phases:

1) Gas/gas conditions: The goal of this test phase is to analyze the performance of the torch igniter with propellants set at room temperature. The test matrix for this phase is detailed in chapter 4.
2) Liquid/liquid conditions: the goal of this test phase is to analyze the performance of the torch igniter with propellant at two phase and liquid conditions.

The igniter objectives form the two test phases are the following:

1) Demonstrate igniter reliability for gas/gas and liquid conditions, 3 seconds steady state burns at chamber pressures between 100-150 psia and a propellant mixture ratio between 1-3

2) Demonstrate a robust duty cycle capability of the torch igniter system. The test campaign will allow for inspections and analysis of any negative effects of repeated cycles of steady state burns.

Chapter 2

2.1 Technical Approach

The igniter system studied in this document has been through 3 different design upgrades. Igniter design iterations as well as the main outcomes observed are detailed in this chapter with the intent of proving a developmental background of the igniter technology. This chapter will cover the test facility at the University of Texas at El Paso in which the test campaign for the torch ignition system was conducted. Propellant feed system, test hardware and instrumentation utilized in the test campaign was determined and set to meet the test requirements of the torch ignition systems which are explained in chapter 3.

2.1.1 Torch Igniter

The torch ignition system uses an internal swirl injection where the mixing of the propellants is governed by the momentum of colliding streams. Oxidizer flows through an axial inlet and is impacted by four tangential fuel inlets that create a swirl that mixes the propellants prior to ignition. Swirl injection also provides some film cooling, as the fuel is directed towards the walls of the combustion chamber [9][10]. This configuration has remained constant throughout four igniter design iterations. These design iterations were geared towards improving the igniter performance, while creating a more optimal, and reliable oxygen/methane propulsion system component.

2.2 Torch Igniter Background

The torch igniter technology studied has undergone different iterations. These design iterations had the purpose of addressing issues encountered during testing and more importantly improving the reliability of igniting the propellants at any given propellant quality.

2.2.1 First iteration of the Torch Igniter

The first iteration of the swirl torch igniter was designed with two separate manifolds, one for oxygen and the other for methane. The manifolds were made out of a stainless steel 304 blocks and were united through some NPT to Swagelok fittings and Swagelok tubing. The oxygen injection diameter was selected to be of 0.185 inches while the methane injection point's diameter was of 0.0625 inches [10]. Figure 2.1 shows the CAD models, and Figure 2.2 presents the complete hardware assembly.

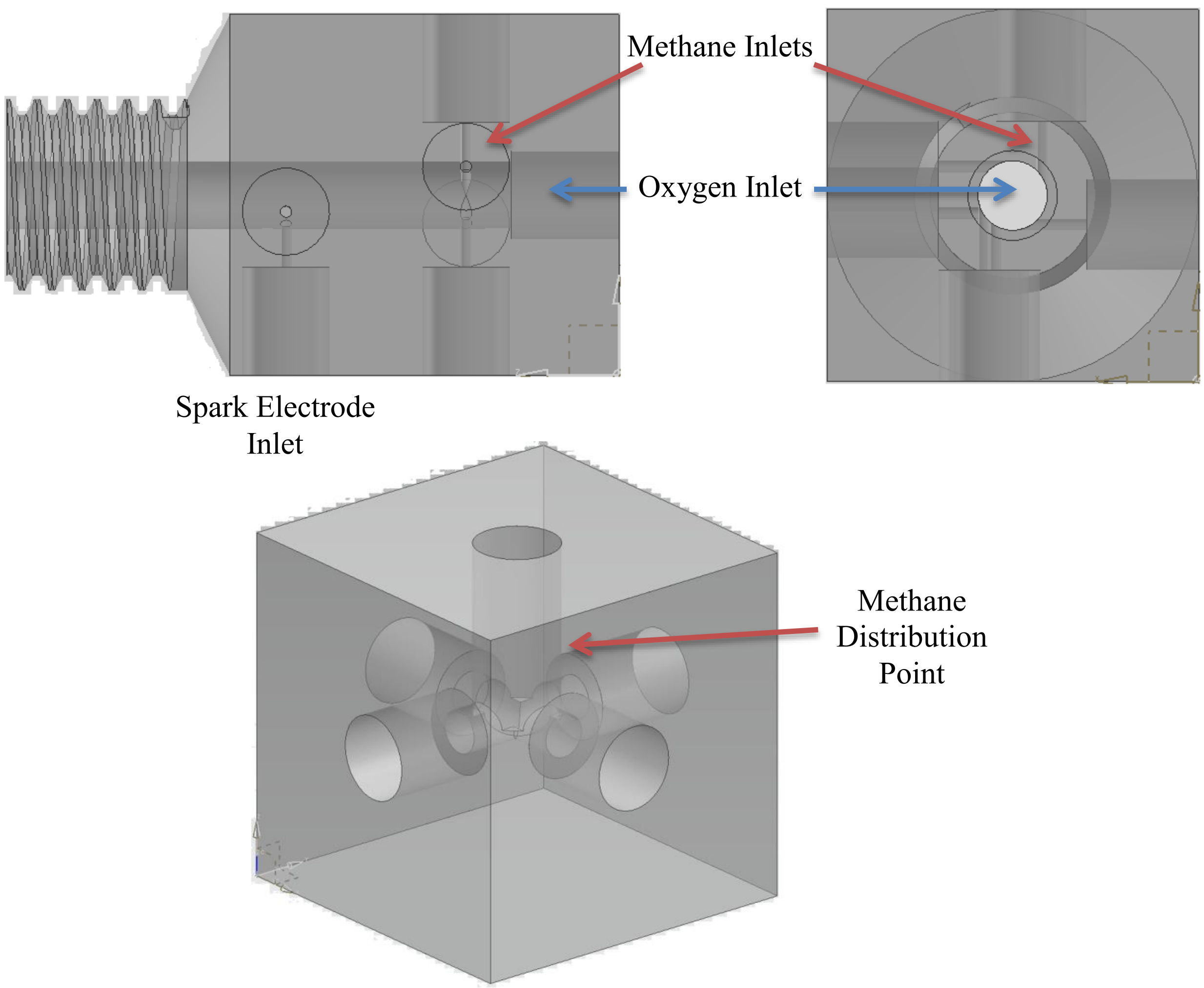

Figure 2.1 CAD model of First Iteration of Swirl Torch Igniter

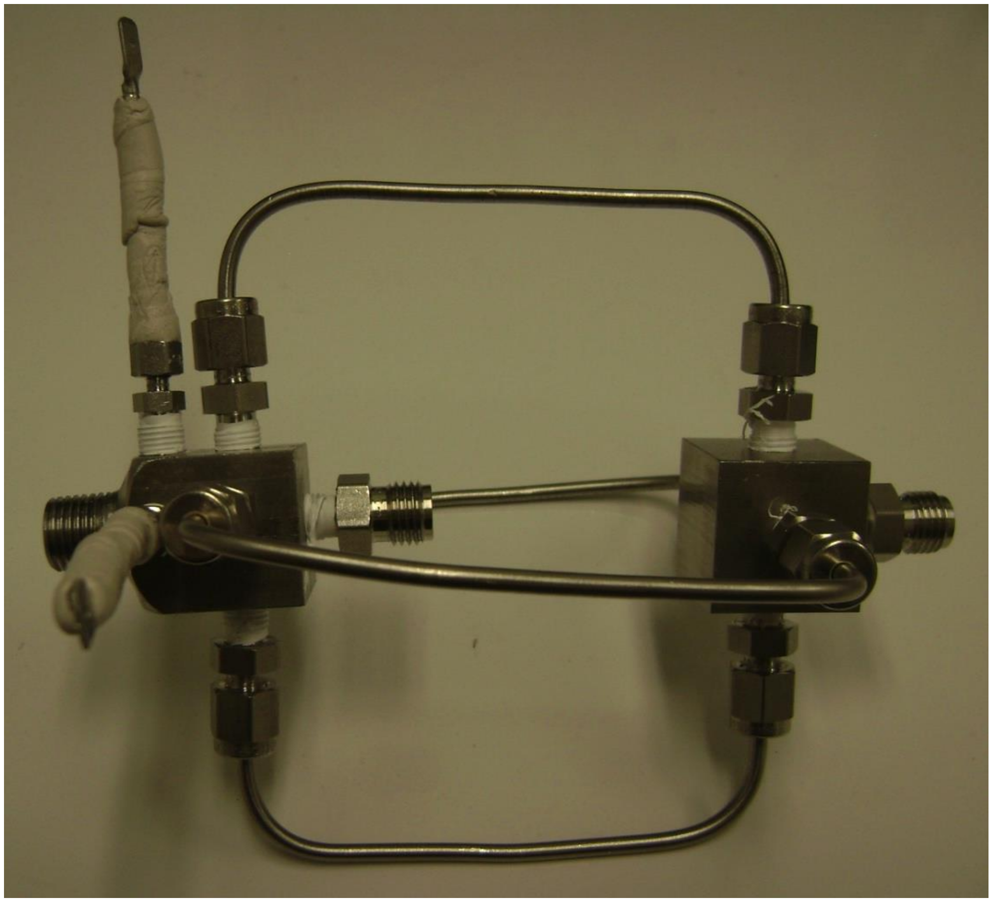

Figure 2.2 Assembly of First Iteration of Swirl Torch Igniter

The sparking system has gone through several iterations due to problems undergone while testing. The original sparking system contained two 90%platinum and 10% rhodium wire that were placed inside a fitting that went from a 1/16 Swagelok tube fitting to a 1/16 NPT male fitting. Each component was set using a high temperature epoxy. These were placed to tangentially and to a certain distance as seen in Figure 13, the gap between the wires created a spark when voltage was given to each lead. The lead would discharge with the metal interior of the igniter creating an arc that would ignite the atomized propellants. The problem with this iteration was that after several tests done the wires integrity was compromised and it would stop sparking. Issues observed with this in-house sparker was destruction of the ceramic due to high

transient pressures. The sparker this caused inconsistencies with arcing and reduced capability to ignite the propellant stream [11].

The test camping of the first iteration of the torch igniter was set with a proof of concept approach. The torch igniter was tested at low flow rate and an initial reliability map was compiled as it can be observed in Figure 2.3.

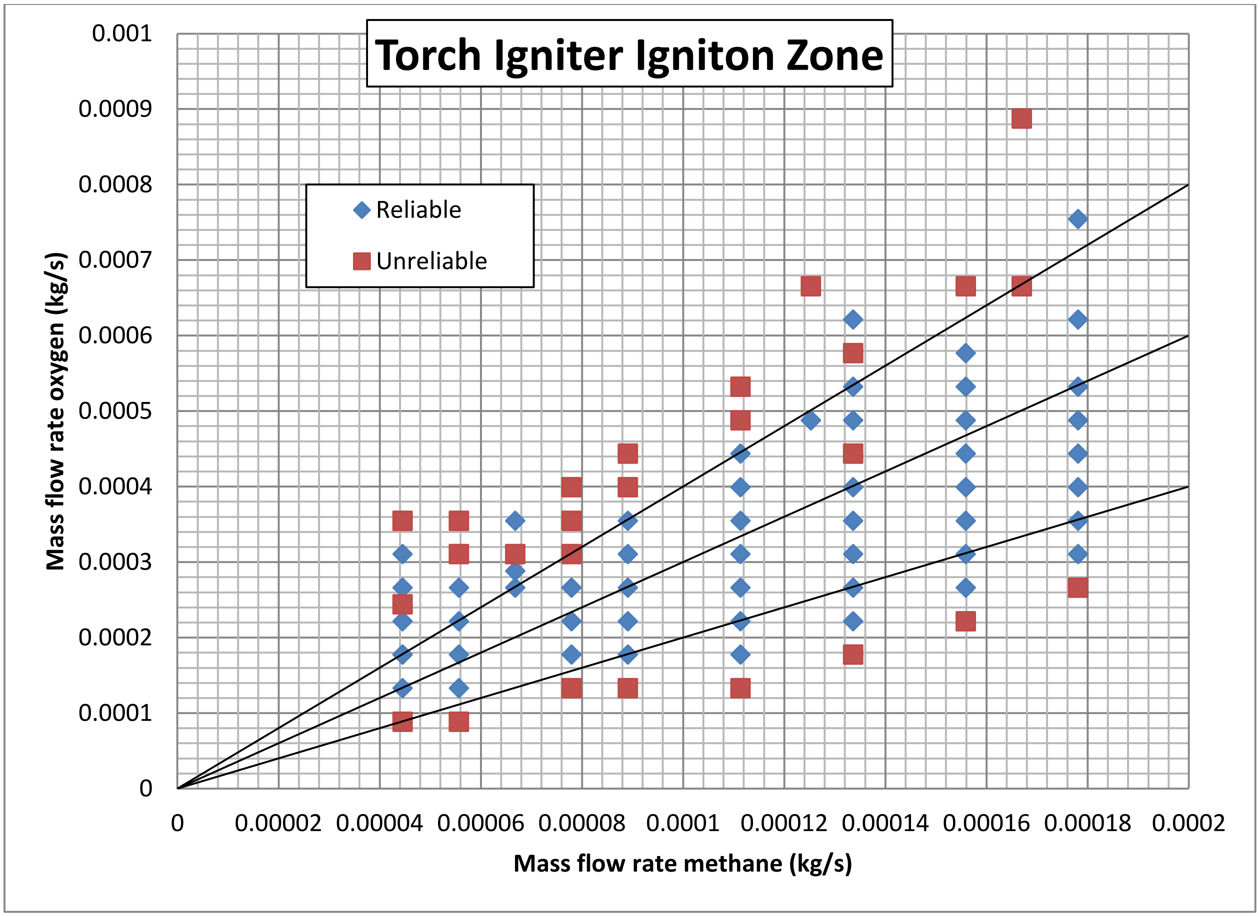

Figure 2.3 Ignitability map of the first iteration of the torch igniter

The proof of concept of the torch igniter was tested at inlet pressures of 10 to 60 psia for both gaseous oxygen and methane. The igniter was tested at low pressure to understand the mixing of the propellant under a swirl injection method. For this torch igniter design, there was no pressure measurement considered for testing. The outcomes of this test effort successfully

proved the concept of the torch igniter injection design. The next design effort was focused in improving the test capabilities of the torch igniter.

2.2.2 Second iteration of the Torch Igniter

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

The past iteration contained to separate manifolds for the oxygen and the methane. In this iteration the manifold was put into a single body, given it better aesthetics, more compact, and giving a lower probability of leaking. The tubing instead of being on Swagelok fittings was instead laser-welded to the body, thus eliminating the threaded fittings for the tubing. The interface between the delivery lines and the igniter were a 1/8 NPT thread. The injection distance between the oxygen and the methane was changed from ¼ to a 1 inch; this is the distance from where the oxygen enters the swirl torch igniter and meets the tangential inlets of the methane. Figure 2.4 shows the CAD model of the second iteration of the swirl torch igniter.

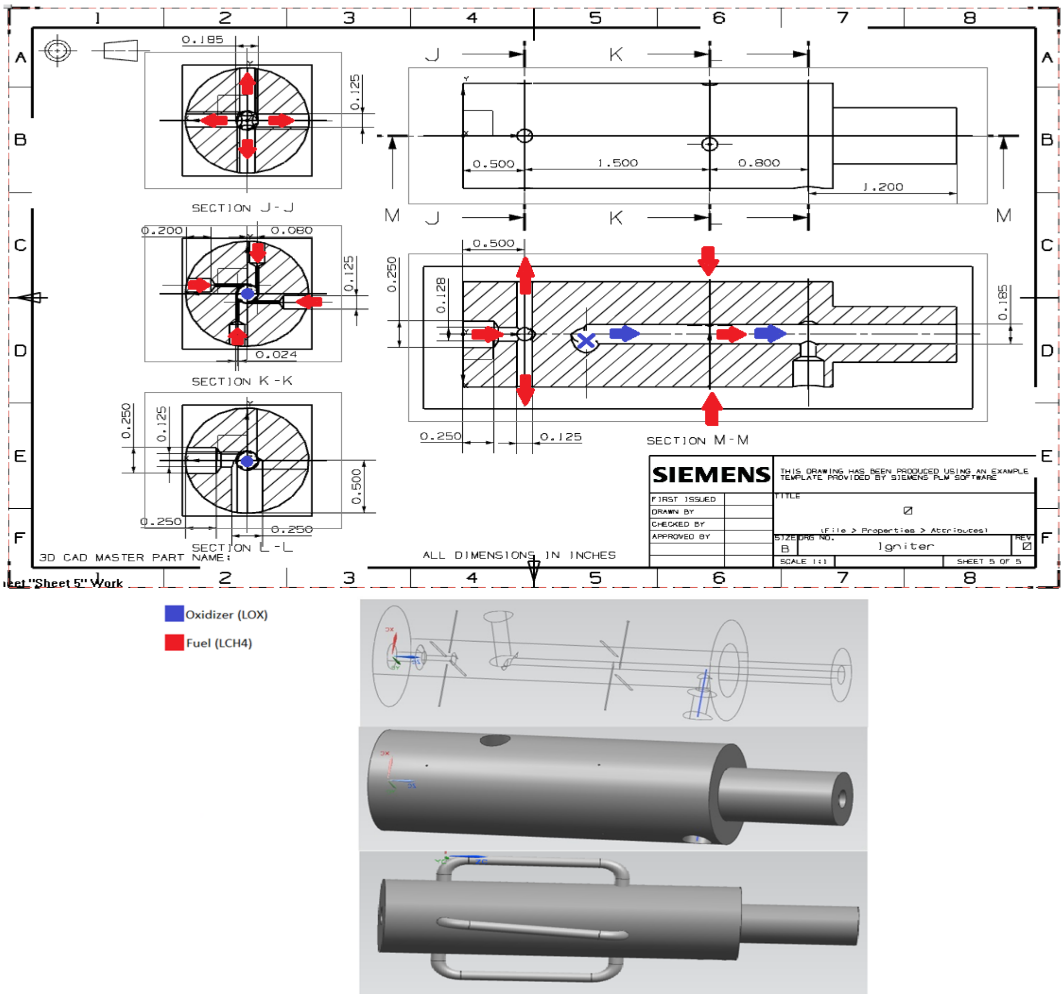

Figure 2.4 CAD model and Drawing of Second Generation

The diameters of both the fitting and the ceramics were increased to provide better electrical insulation and decreased the stress experienced. The ceramic was modified to have two diameters to prevent a blow out in case of an overpressure in the igniter, the bottom part having a larger diameter. A tungsten lead was still used for this sparking system. Figure 2.5 shows a CAD model of the sparking system.

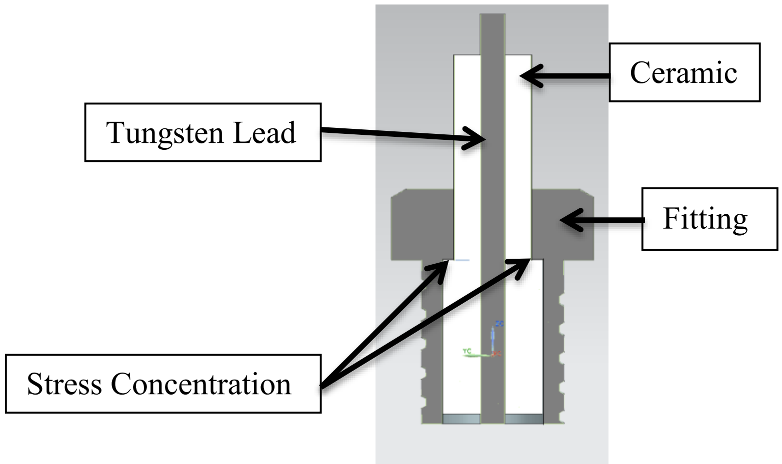

Figure 2.5 Cross-Section of Sparker

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

There were three test phases done for the second design iteration of the troch igniter. All of the test phases were intended to test the troch igniter design under liquid conditions for both oxygen and methane. Hardware damaged resulted in all three phases of the test campaign in this design iteration. The test sequence was not properly set and the torch igniter sustained combustion for more than six seconds thus permanently damaging the torch igniter. The torch igniter was manufactured again with the intention of continuing testing and tuning the test sequences to prevent hardware damages. The troch igniter was again damaged during testing due to an error in the console program that froze upon testing without the capacity of de energizing the valves in the test article. The outcomes from this torch igniter iteration yield the need to improve the configuration of the troch igniter and the improvement of the spark plug system used for this test campaign. Figure 2.6 presents a frame of hardware damage during a hot fire test.

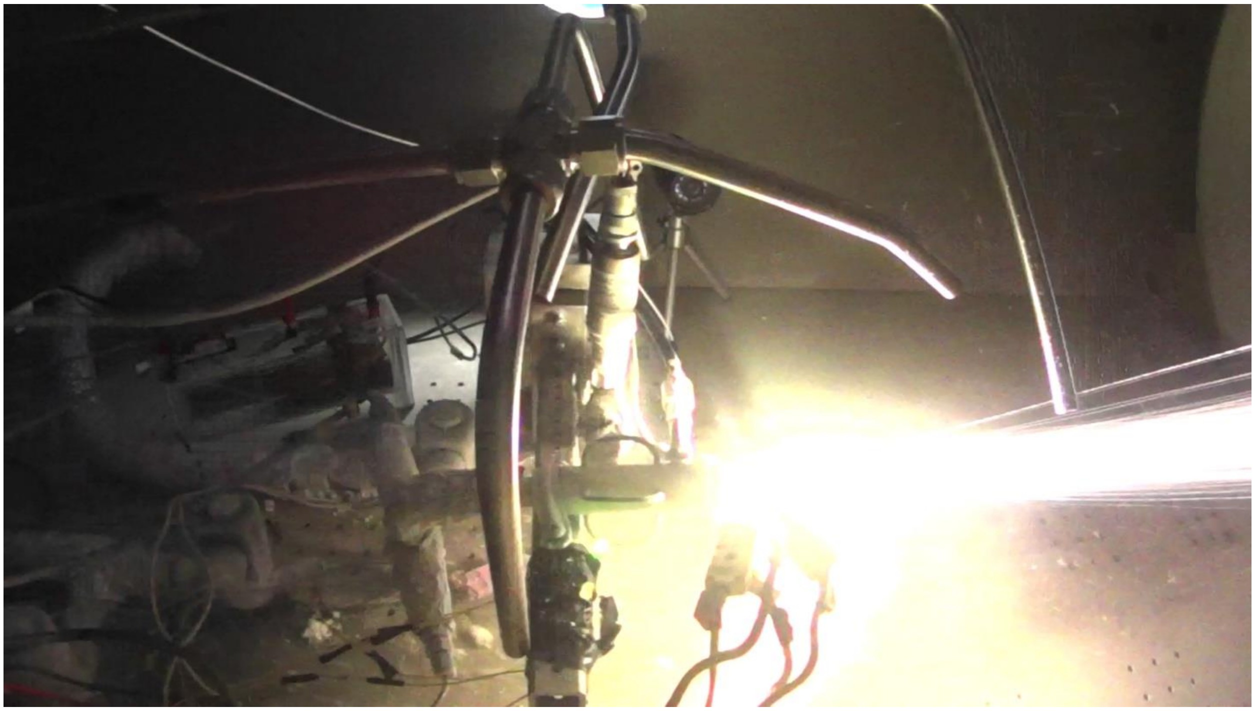

Figure 2.6 Test failure of the second iteration of the troch igniter with liquid propellants

2.2.3 Third iteration of the Torch Igniter

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

In this third iteration of the swirl torch igniter both the methane and oxygen inlets were selected to be axial, unlike in the previous iteration that had the methane inlet axial and the oxygen inlet perpendicular to the body. The methane manifold was changed from having an inlet split into 4 Swagelok tubing and then injected tangentially, to having a ring manifold as seen in Figure 2.7. A manifold of the same material as the igniter body was welded to the swirl torch igniter body.

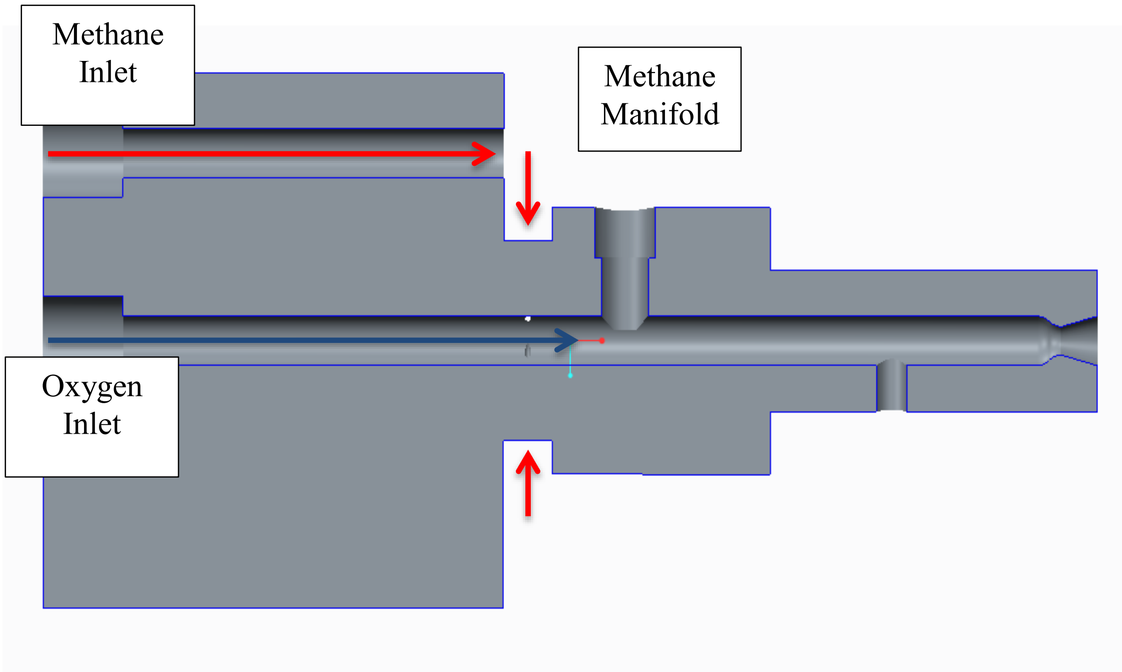

Figure 2.7 Swirl Torch Igniter Cross-Sectional View

A torch igniter subsonic ratio of 3 was selected for the swirl torch igniter. This ratio gives a throat radius of 0.053 inches and throat area of 0.009 squared inches. This throat was added to give an increase in the chamber pressure, which will increase the igniter performance.

A conical nozzle with a 15-degree half angle was selected for the swirl torch igniter, since it is the simplest to manufacture and has optimum expansion at sea level. It had a supersonic expansion ratio of 3, which gave an exit radius of 0.092 inches and an exit area of 0.027 squared inches.

The sparker was changed from previous iterations. Instead of manufacturing the in-house designed sparker an already manufactured spark plug was selected. This spark plug is much smaller in diameter than previous sparkers used, having only a threaded section of ¼-32. Being this small it allowed moving the spark plug closer to the methane injection ports, allowing the spark plug to get more film cooling from the methane.

The test campaign for his torch igniter design iteration was conducted with gaseous propellants at ambient temperature. The objectives of the testing conducted were focused in analyzing the performance of the new spark plug system implemented and to determine the robustness of it. Previous spark plugs utilized were brittle and had no resistance to the combustion chamber pressure of the igniter once the propellants were ignited.

The results obtained from testing were promising as the robustness of the spark plug was significantly improved and more than five test were successfully ignited without compromising the spark plug. The tests were conducted at the stoichiometric ratio that produced the highest product temperature for oxygen/methane combustion. Testing at stoichiometric temperatures was done with the intent of testing the spark plug at high temperatures and analyzing the robustness of the spark plug. Table # presents the data collected from testing of the third design iteration. An igniter chamber pressure of an average of 100 psia was achieved with a mixture ratio of four.

Table 2.1 Data from third iteration torch igniter

	Test # 1	Test # 2	Test # 3
Oxygen Mass Flow lb/s	0.029	0.029	0.029
Methane Mass Flow lb/s	0.0072	0.0072	0.0072
Chamber Pressure psia	102	102	102
Oxygen Injection Pressure psia	108	108	108
Methane Injection Pressure psia	109	108	108
MR	4	4	4

Needle valves were utilized to regulate the flow of the gaseous propellants to the torch igniter. As previously mentioned, five tests were conducted with two tests resulting in failures. The chamber pressure port was overheated during the last two tests as it can be observed in figure 2.8. The pressure sensor was compromised due to combustion occurring at the chamber pressure port resulting in no data acquired. The orifice size of the chamber pressure port was large enough that it allowed combustion from the igniter combustion chamber to travel to the pressure sensor and thus damaging it. The test campaign for this torch igniter design iteration has immediately stopped and a remediation plan was put in to action. The design modification needed to address the issue of combustion occurring in the pressure port as well as eliminating the unnecessary body mass of the torch igniter.

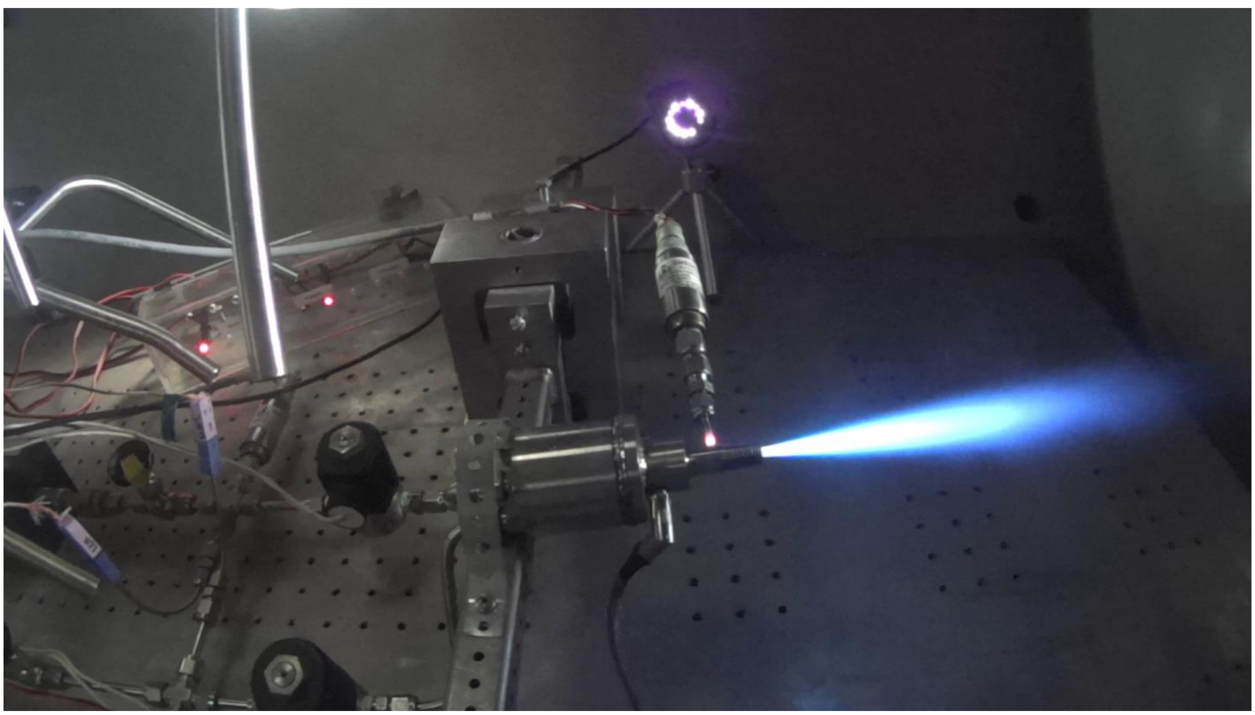

Figure 2.8 Hot-fire test of the third iteration of the torch igniter

2.3 Current Torch Igniter Design

This configuration has remained constant throughout three igniter design iterations. Some of the enhancements of this design iteration are the inclusion of replaceable inlet orifices, a

chamber pressure orifice, and reduction in component weight. The final modification of the igniter design was optimization of the igniter dimensions for significant reduction in system weight, while maintaining structural integrity. A spark plug was again implemented in the current torch igniter design as the ignition source replacing previous in-house sparkers used in prior iterations. The improvements to the igniter have been tested under varying inlet pressures and propellant states: gaseous oxygen of varying temperatures below/at ambient with a combination of gaseous methane and liquid methane as well as liquid oxygen with a combination of gaseous methane of varying temperatures below/at ambient and liquid methane.

2.3.1 Igniter

The four iteration design of the torch igniter was significantly reduced in mass and weight. Removing the unnecessary mass was done with the intention of elimination any thermal mass in preparations for cold and cryogenic propellant testing. The material selected for the torch igniter was Inconel 718. This Inconel alloy has higher resistance to temperatures than Inconel 625 that was previously used for the third iteration of the igniter. A drawing of the new igniter design is shown in figure 2.9.

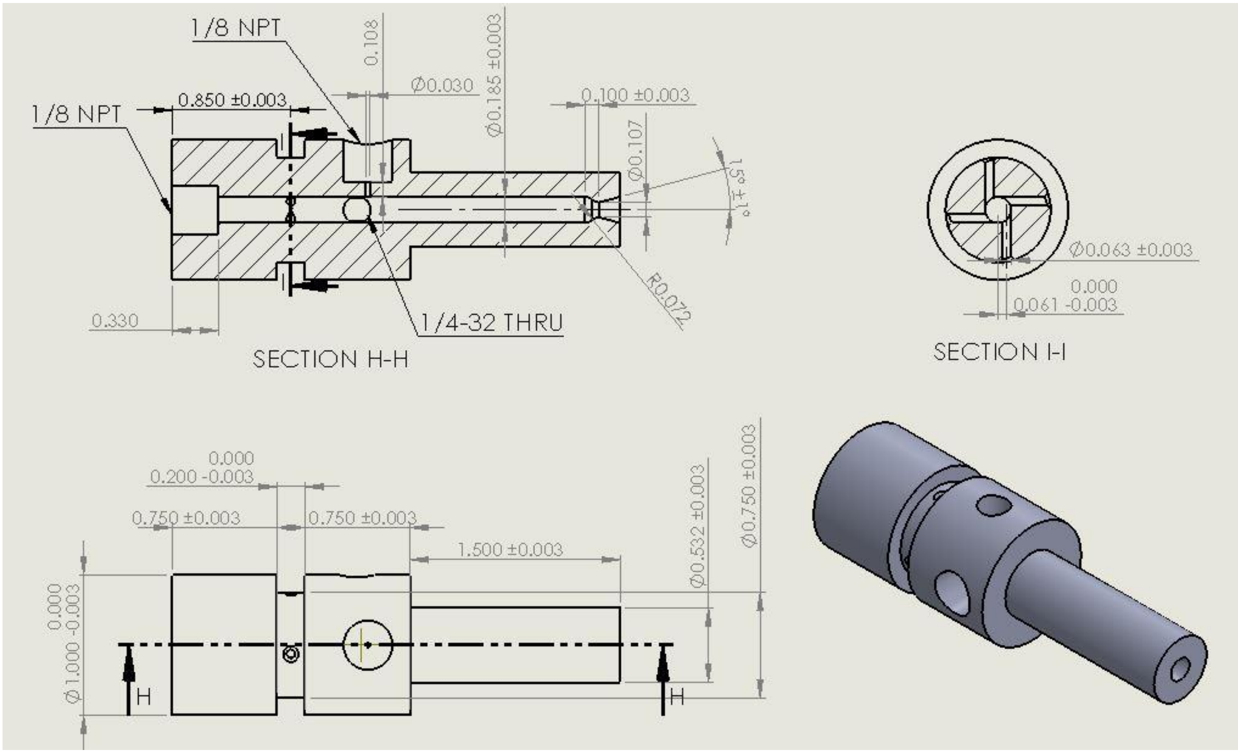

Figure 2.9 third design iteration of the torch igniter

The igniter body mass was significantly reduced in comparison with the third design iteration of the troch igniter. A fuel manifold of Inconel 718 with a welded male ¼ inch Swagelok fitting was laser welded to the igniter body. This new igniter body configuration was done with the purpose of having a compact design that will proving flexibility upon integration to a propulsion system. The compact design can be welded to any location in an engine combustion chamber.

2.3.2 Spark Plug

A spark plug was again chosen as the ignition source for the torch igniter due to the cost, size, and repeatability shown from testing of the third design iteration of the igniter. This spark plug was not compromised from previous testing and was more resistance to the combustion products than any previous spark plug used in any design iteration of the troch igniter. The spark plug has a ¼ - 32 fitting that is tangentially inserted into the igniter. The metallic inner walls of the sparker are used as the ground electrode of the spark plug as the main ground electrode is

removed to utilize space. The electrical discharge across the walls of the sparker and the center electrode is created using a transformer that facilitates a stepping in voltage from 5 V to 16 kV. The result is the ionization of a fraction of the propellant stream, causing it to combust nearby the propellants' mixture causing flame propagation.

2.3.3 Igniter Instrumentation Improvements

The main focuses of the design improvements for this igniter iteration were to eliminate the previously seen issues and provide vital temperature data of the igniter body. The previous pressure port of the torch igniter was a four inches in length tube of 1/8 inch in diameter that was welded to the combustion chamber of the torch igniter. This configuration allowed combustion products to over heat the tube and eventually damaging the pressure sensor. The modifications done in the chamber pressure port for the new igniter design where to eliminate the use of tubing welded into the igniter body and add a 1/16-inch NPT fitting. This modification of the igniter chamber pressure port will allow the use of different orifices throughout the test campaign. The NPT fitting on the torch igniter body was not manufactured all the way through, 100/1000 inch to the igniter chamber material left and an orifice with a diameter of 30/1000 inch. The orifice was manufactured as a secondary precaution to prevent combustion occurring at the pressure port.

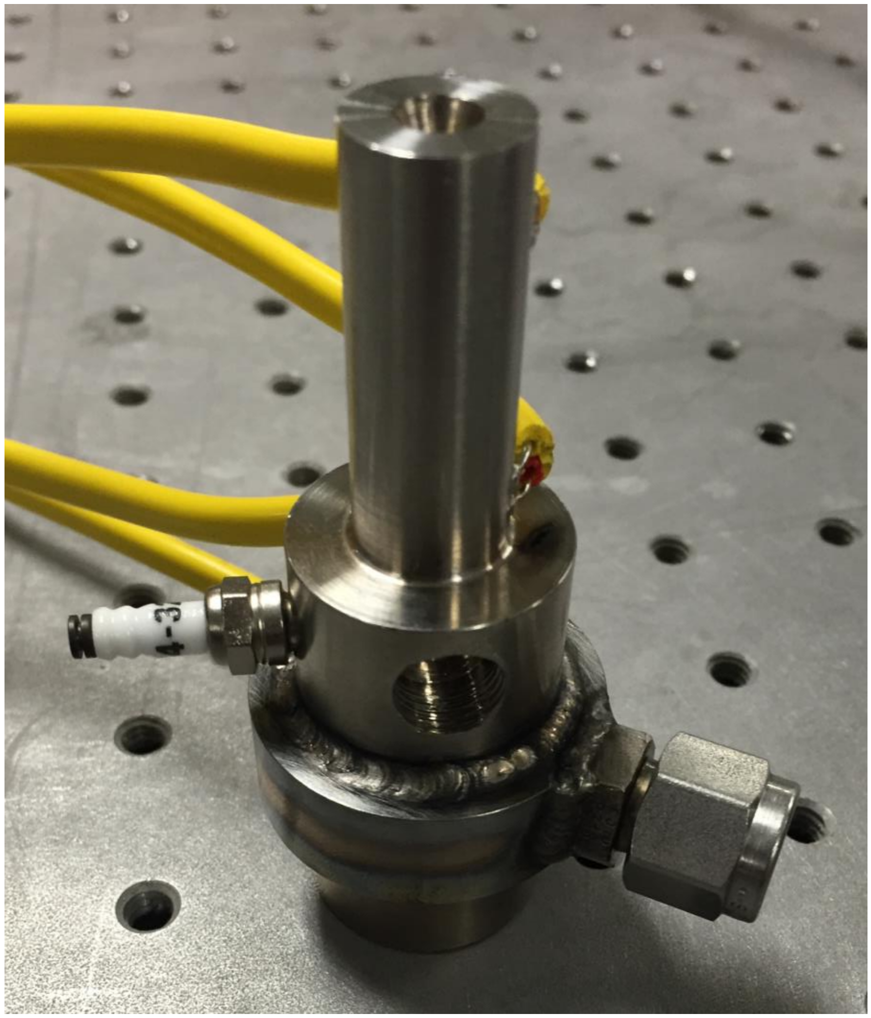

Figure 2.10 fourth design iteration of the torch ignition system

K type thermocouples were added to this igniter iteration. Previous design iterations did not had any temperature measurement on the igniter and thus no temperature data for the steady state hot fire tests was obtained. In figure 2.10, the k type thermocouples can be observed. It is critical to have temperature data on the torch igniter during and after a hot fire test. Four k type thermocouples were welded to the igniter body at different locations. The locations of the thermocouples were by the igniter throat, combustion chamber, spark plug port where ignition occurs and by the oxidizer inlet. It is expected to see higher temperatures at the throat and the spark plug of the torch igniter. Even though test will be limited to a few seconds, the effect of continuous ignition in the torch igniter can stack the temperatures to a limit. The temperature

date collected will provide essential information to determine the duty cycle of the torch igniter and more importantly how often and long can you test the torch igniter without compromising any hardware or instrumentation.

2.4 Test Facility

The test campaign was conducted in the multi-purpose altitude simulation system (MASS) inside the bunker at the Goddard Propulsion Laboratory. The test setup, hardware and test operations conducted for the torch igniter fourth design iteration is discussed in this section.

2.4.1 Test Bunker

All torch igniter test campaigns were conducted inside a ballistic proof test bunker at the University of Texas at El Paso. The test bunker is lined with ¼ inch Kevlar walls and bullet proof windows. This was an optimal test bunker for secure testing of the torch igniter. Figure # shows the layout of the bunker and where the systems used for testing of the torch igniter are located.

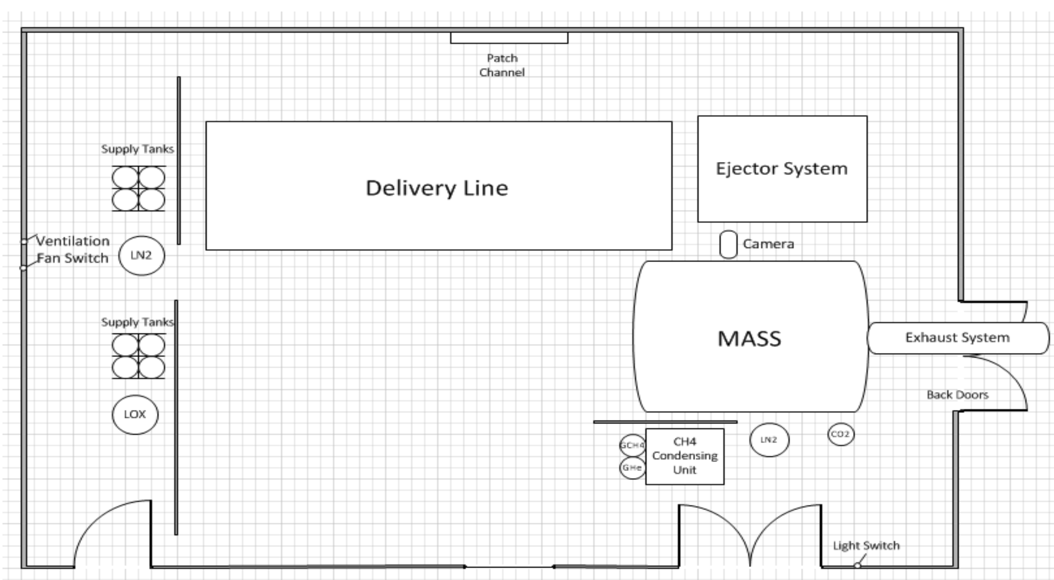

Figure 2.11 Test bunker layout

The delivery lines, the MASS, supply tanks and a mobile methane-condensing unit are located inside the test bunker. An ejector system is located as well inside the test bunker but is not currently being operated. The ejector system will provide the capability of testing in the MASS at higher altitudes in future testing of the torch igniter. The test bunker has the capability of delivering liquid nitrogen, gaseous nitrogen, liquid oxygen, gaseous oxygen, liquid methane and gaseous methane. A ventilation system is constantly running as well as an exhaust system in case a leak or ventilation from the test bunker is needed. Camera surveillance is available to monitor the systems during testing.

Figure # and # present the propellant feed systems for the gaseous test phase of the torch igniter. The propellant delivery lines are of ¼ and ½ inch stainless steel 304L for both oxygen and methane systems. A support structure was built for the delivery lines and fluid components. The delivery lines are limited to a maximum allowable pressure of 225 psia. This limit is due to the MWAP of the solenoid valves in the test bunker. Pressure and temperature sensors are located in the delivery lines of the propellants to monitor the condition of the propellant for each test conducted.

Figure 2.12 Cryogenic/gaseous oxygen delivery line in the test bunker

The propellant feed system for oxygen and methane was separated from each other for safety purposes. The oxygen storage and run tanks were located on the west part of the test bunker and surrounded with mobile Kevlar walls for additional safety. Liquid oxygen dewars were ordered when needed and limited the time stored inside the test bunker. The mobile methane-condensing unit was located next to the MASS as it required closed monitoring during and after condensing procedures. A mobile Kevlar wall separated the methane-condensing unit from the test article. Methane condensing unit was limited to half capacity of the tank per test day and incase more was needed the recycling time was minimal.

A test procedure for the hot fire test of the torch igniter was developed. This was with the intention of having a secure and result oriented test campaign of the torch igniter. The test operations were simplified and clear for a three student to conduct the igniter hot fire tests. The test procedure calls for a test console operator and two hardware configuration operators. The procedure was developed in such way that a lab personnel not familiarly confident with the test bunker was able to conduct the steps to conduct a hot fire test of the troch igniter. The test procedure detailed the systems utilized during testing and more importantly the emergency procedures contingencies in case of an emergency. Test goals and a test matrix are presented in the procedure for a result-oriented operation. Having a result-oriented procedure eliminates any unneeded tests and control the efficiency of testing.

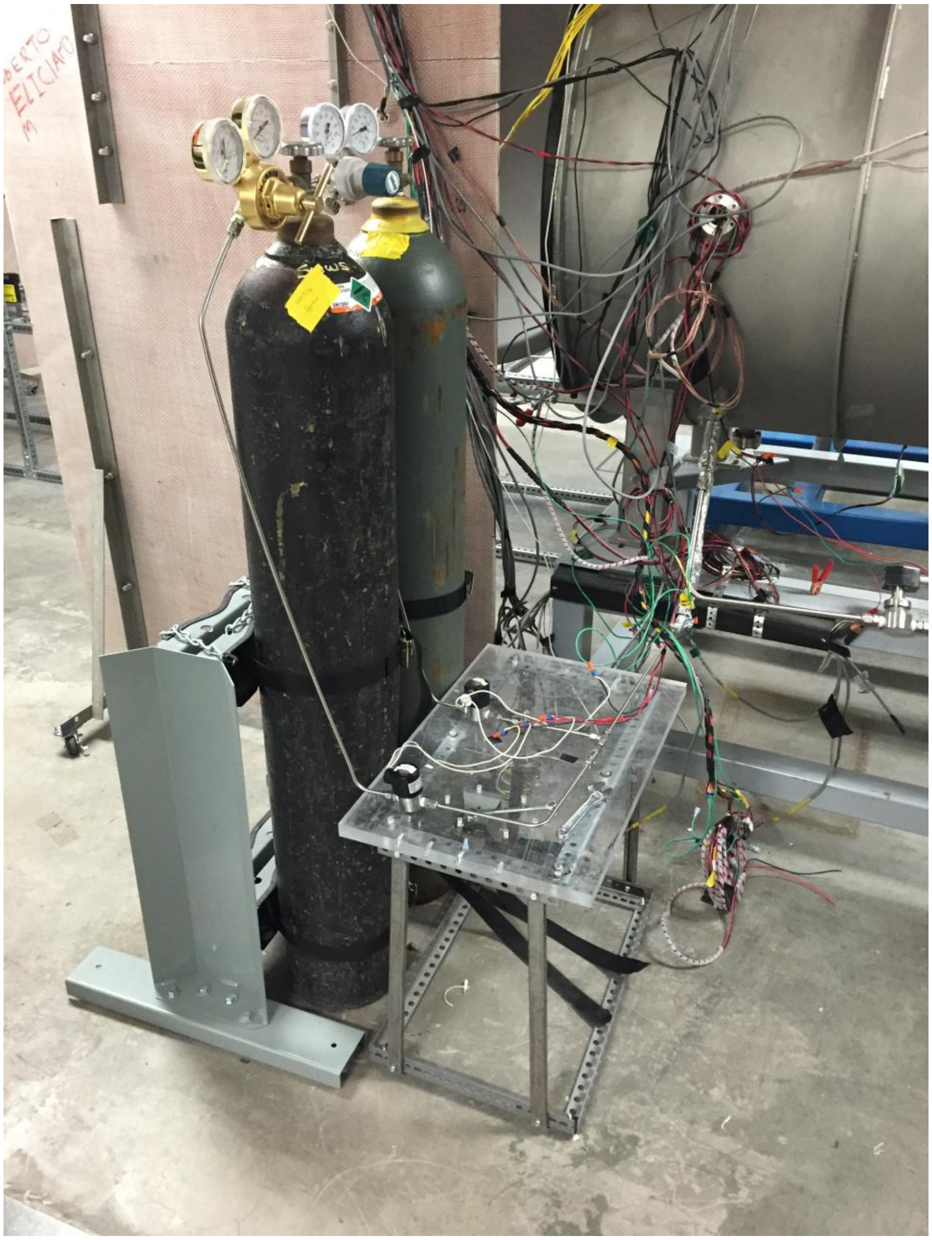

Figure 2.13 Gaseous methane feed system for the first phase of testing

2.4.2 Piping and Instrumentation Document

The piping and instrumentation document (PI&D) is shown in figure 2.14. Oxygen, methane, nitrogen and carbon dioxide fluids were used through the test campaign of the torch igniter. The fluid components used in the system are labeled and identified in the PI&D. Solenoid valves, check valves, orifices, pressure transducers and thermocouples were the main

test components and instrumentation used throughout the hot fire tests of the torch igniter. Carbon dioxide was used inside the MASS in case an uncontrolled fire needed to be extinguished without compromising tests personnel. As previously mentioned, pressure and thermocouples were installed in the delivery lines to monitor the propellant quality for each test phase of the torch igniter.

Since one of the main test requirements for the torch igniter is to test under different inlet conditions, it is important to have the necessary instrumentation in the test article to determine the propellant quality being tested. A pressure transducer and a thermocouple were installed upstream of the main igniter isolation valves of the torch igniter. The pressure and temperature data will give the density of the propellants throughout the test campaign. This data is essential, as it will give the condition in which the propellants are entering the combustion chamber of the torch igniter.

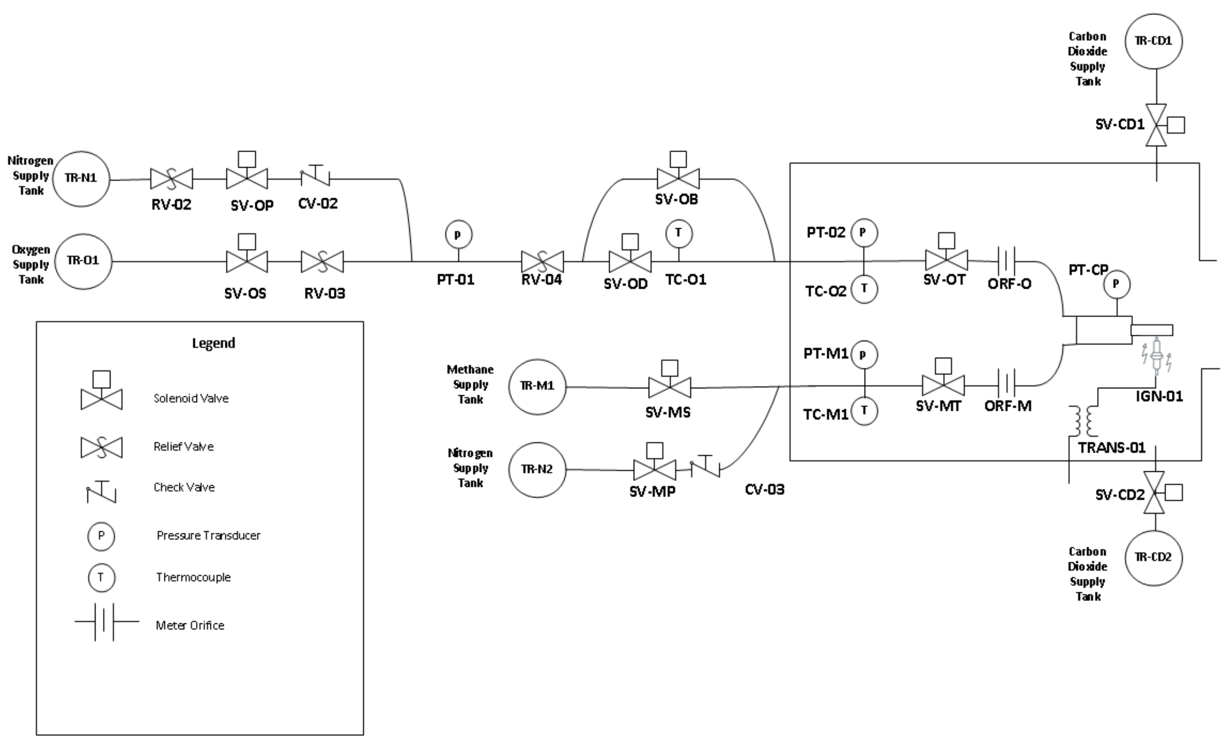

Figure 2.14 Piping and instrumentation document of the torch igniter

2.4.3 Multipurpose Altitude Simulation System (MASS)

The torch igniter was placed on a test stand designed for these experiments. A mounting structure was used to support the torch igniter body. The igniter body was clamped and bolted to the mounting plate at a height of three inches from the base. The multipurpose Altitude Simulation System (MASS) has three optical windows, 16 feed through ports and exhaust port. The MASS has a diameter of 48 inches and 70 inches in length. The optical windows provide access to any optical diagnostic if needed as well as surveillance cameras. Pressure transducer, thermocouple and spark transformer cabling was routed from the test bunker instrumentation panel to the MASS feedthrough ports. The test hardware installed inside the MASS can be observed in figure 2.15. Additional to a wireless camera positioned at the exhaust of the torch igniter, CCTV cameras were placed inside the test cell to monitor the test article closely form the control room monitors.

Attached to the MASS is a class 150 flange that has a duct reducer (10” to 8”) welded, to which two galvanized steel ducts are attached as well as a 90 degree elbow to serve as an exhaust system as shown in Figure 6. To prevent any propellant accumulation inside the MASS, a ventilation system was mated to the exhaust duct. The ventilation system is a necessary precaution that can prevent an accumulation of gaseous methane inside the test bunker. Additionally, an oxygen sensor is located next to the oxygen delivery system. This sensor has the purpose of detecting an oxygen deficient environment or an excess of oxygen caused from a leak in the delivery system.

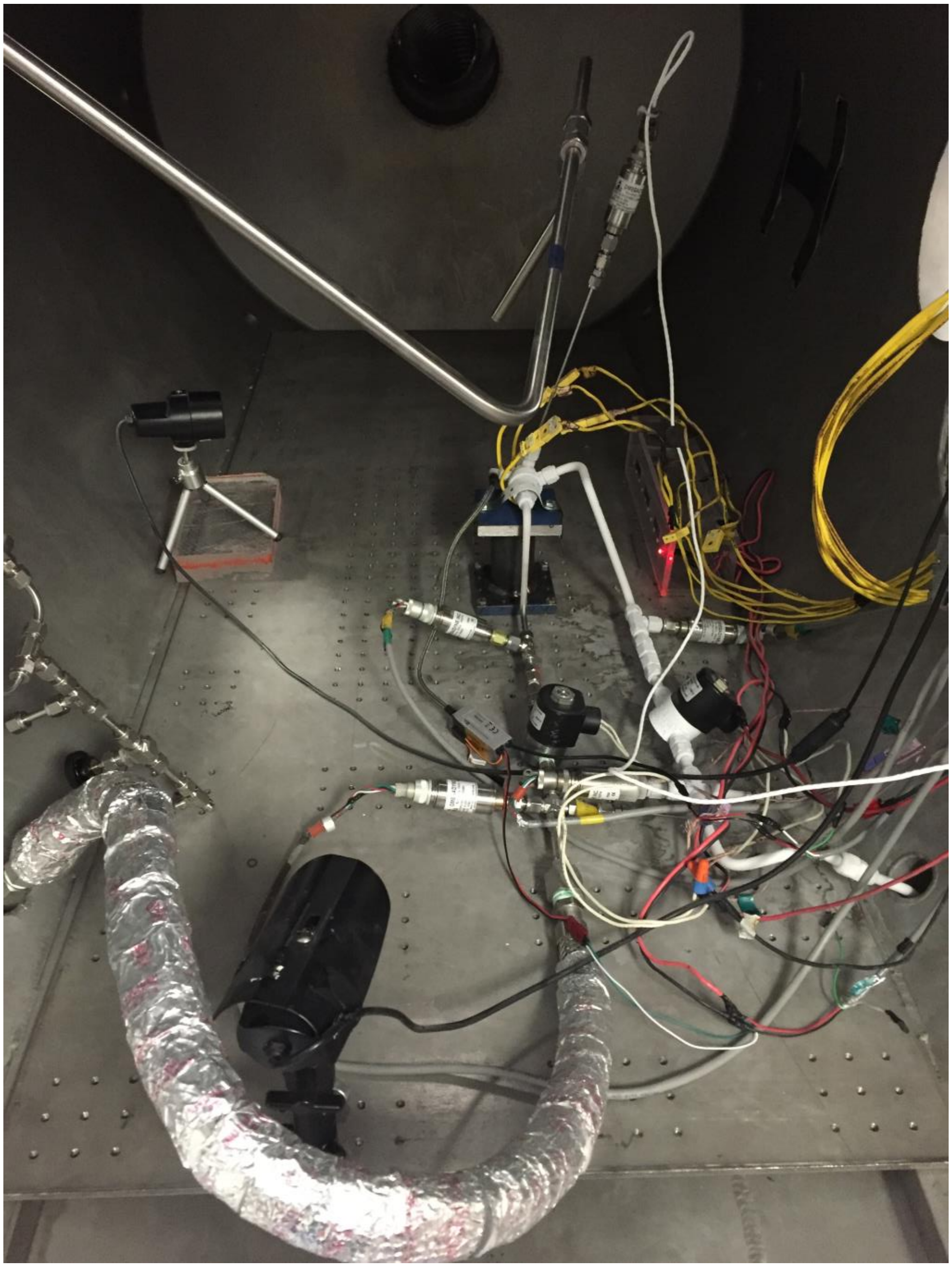

Figure 2.15 Test article and instrumentation installed in the MASS

Figure 2.16 bunker exhaust duct

2.4.4 Mobile Methane-Condensing Unit (MMCU)

The Mobile Methane-Condensing Unit was designed by previous students from the cSETR in order to accommodate testing that required liquid methane. The reason behind the development of a mobile methane condensing unit was mainly due to the quantities in which liquid methane can be bought are too large for the laboratory storage capabilities.

The unit can produce about 15 liters of liquid methane. The unit contains two copper coils, one inside the run tank and another one around the run tank. The condensing unit is as well wrapped with a cryogenic insulating material to help maintain the low temperature. The advantage of this unit is that it serves as a condensing unit and as a run tank, thus eliminating the need of a secondary run tank unit for testing of the torch igniter. The method in which the unit condenses methane is that the gaseous methane is introduced at a desired pressure into the tank, and liquid nitrogen is flown through the coil at a higher pressure than the methane. The liquid

nitrogen lowers the temperature of the gaseous methane until it begins to condensate inside the tank. E type thermocouples are located throughout the vertical length of the condensing unit to measure the amount of liquid methane inside the unit. The pressure inside the tank and the temperature are constantly monitored from console for a safe operation. The liquid methane is then pressurized to a desired value with helium gas. Figure 2.17 shows a picture of the mobile methane-condensing unit.

Figure 2.17 Mobile Methane Condensing Unit

2.4.5 List of test components

The instrumentation and main components in the test article of the troch igniter are listed below. A component identifier number was assigned to each instrumentation and component in the test article for ease of recognition. This list was developed to keep track of the instrumentation used during testing as well as to know the location within the data acquisition system at the control room. Solenoid valves used in the delivery system of the propellants are of either 120 V AC or 12 V DC.

Table 2.2 Instrumentation and component list

Component Identifier	**Description**	**Data Acquisition Device Number**	**Physical Channel Port Number**	**Patch Panel Port Number**	**Signal Conditioner**	**Required Voltage**
SV-OP	120V ac Valve	DEV 4	Port 1/ Line 4	Row 1/Port 5	N/A	120V ac
SV-OS	120V ac Valve	DEV 4	Port 1/ Line 0	Row 1/Port 1	N/A	120V ac
SV-CD1	120V ac Valve	DEV 4	Port 1/ Line 3	Row 0/Port 2	N/A	120V ac
SV-CD 2	120V ac Valve	DEV 4	Port 1/ Line 3	Row 0/Port 2	N/A	120V ac
SV-OD	120V ac Valve	DEV 4	Port 1/ Line 2	Row 1/Port 3	N/A	120V ac
SV-OB	12V dc Solenoid Valve	DEV 6	Port 1/ Line 2	Row 3/Port 6	N/A	12V dc
SV-OT	12V dc Solenoid Valve	DEV 3	Port 1/ Line 4	Row 1/Port 6	N/A	12V dc
SV-MS	12V dc Solenoid Valve	DEV 6	Port 1/ Line 7	Row 1/Port 15	N/A	12V dc
SV-MP	12V dc Solenoid Valve	DEV 6	Port 1/ Line 6	Row 3/Port 8	N/A	12V dc
SV-MT	12V dc Solenoid Valve	DEV 3	Port 1/ Line 5	Row 1/Port 14	N/A	12V dc
TC-O1	Thermocoupl	DEV 7	AI 9	N/A	N/A	Provided by

	e					Thermocouple Hub (DEV7)
TC-O2	Thermocouple	DEV 7	AI 0	N/A	N/A	Provided by Thermocouple Hub (DEV7)
TC-M1	Thermocouple	DEV 7	AI 1	N/A	N/A	Provided by Thermocouple Hub (DEV7)
PT-O1	Pressure Transducer	DEV 5	AI 0	Row 2/Port 1	SG1	Provided by Signal Conditioner
PT-O2	Pressure Transducer	DEV 5	AI 4	Row 2/Port 10	SG 2	Provided by Signal Conditioner
PT-M1	Pressure Transducer	DEV 5	AI 1	Row 2/Port 12	SG 3	Provided by Signal Conditioner
PT-CP	Pressure Transducer	DEV 5	AI 7	N/A	N/A	14-32 V dc
ING-01	Spark Ignition Source	DEV 6	Port 1/ Line 4	N/A	Square Wave 5V/2.4 A/ 150Hz	8.5 V dc
RV-02	Pressure Relief valve	N/A	N/A	N/A	N/A	N/A
RV-04	Pressure Relief Valve	N/A	N/A	N/A	N/A	N/A

2.4.6 Propellant flow measurement

In line orifices as previously mentioned, will restrict the flow of the oxidizer and fuel at a specific upstream pressure. Instrumentation in the test set up will record the upstream/downstream pressures and temperatures of the orifices to determine the delta pressure across the orifice and the flow rate through the orifice. The propellant flow through the orifices was verified with Omega mass flow meters. The flow meters measured the volumetric flow rate in the line. The manufacturer calibrated the flow meters with nitrogen gas and provided the

conversion factors to covert the given reference flow rate to the actual flow rate. In this case, the actual flow of the oxygen the displayed volume flow rate has to be multiplied by a factor of 0.9926, and the methane by a factor of 0.75.

The in-line orifices are commercially available 1/8" Male-Male NPT Threaded Type 303 Stainless Steel in-line orifices purchased from McMaster-Carr. The orifice diameters for the fuel and oxidizer are 0.089" and 0.078", respectively. These orifices provide a flow restriction, introduce a ΔP between the upstream pressure and the injection pressure of the swirl torch igniter, as well as to accurately measure the oxidizer and fuel mass flow rates during hot fire testing.

These orifices were sized using the following conditions:

a. The oxidizer and fuel are in the gaseous state at ambient temperatures
b. System upstream pressures (tank pressures) for the oxidizer and fuel are 195 psia
c. Chamber pressure is 153 psia
d. Desired mass flow rate for oxidizer and fuel are 0.012 +/-0.002 lb/s and 0.008 +/-0.002 lb/s, respectively.

2.4.7 Data Acquisition

A control room is located adjacent to the test bunker. In this room the console is located and it is used to remotely run all tests. Power supplies are located in this room and it powers all instrumentation and test components inside the test bunker. Testing and data collection is conducted using NI LabVIEW. A labview program was written which allows the Test Conductor to switch between manual and automatic valve control mode. Manual mode is used to adjust the pressure and flow rates in the delivery lines and more importantly conduct component

checkouts prior to a hot fire test. The program will record the data from the thermocouples and pressure transducers after a test sequence is completed. This data is written into lvm files. In figure 2.18, the GUI of the program utilized for testing is presented.

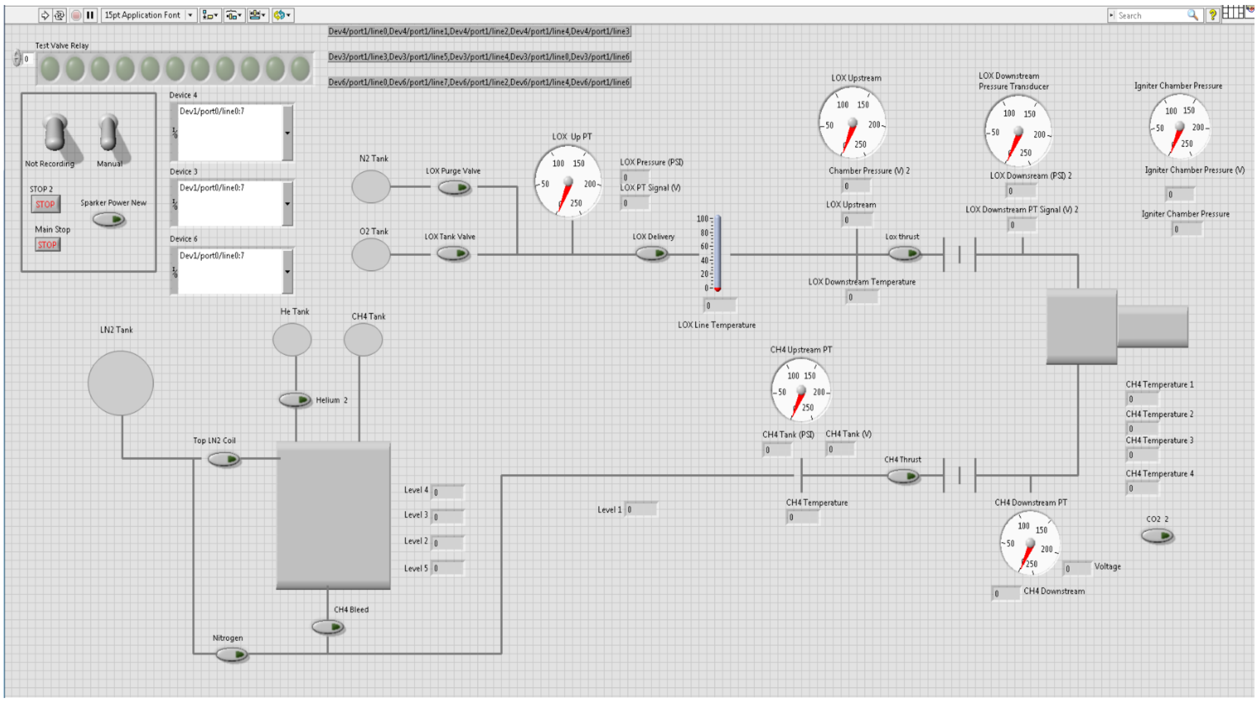

Figure 2.18 Guide User Interface for the torch igniter test campaign

2.4.8 Data Reduction

Matlab paired with REFPROP was used to analyze the data obtained from the tests. A spreadsheet was created which in instead read the temperature and pressure data points obtained and calculated the density at those specific data points. A data reduction code was used to perform calculation such as to obtain the mass flow rate through the orifices corresponding to the upstream and downstream pressures recorded and ultimately compared to the measured values from the mass flow meter.

Chapter 3

In this chapter, the test approach for the test campaign of the fourth iteration design of the torch igniter is detailed. A set of test requirements was established for the development of this torch igniter. The test requirements will be compared with the results to determine if they were met once the testing of the torch igniter is completed. The test plan for the torch igniter was set to test the igniter at wide range of inlet conditions, inlet pressure and temperature of the propellants was varied. The test campaign was separated in two phases, one focused on gaseous propellants with varying inlet pressure and the second phase focused on testing propellants at liquid and two phase conditions at the inlet of the torch igniter. The parameters tested on both phases of the test campaign are detailed in the section of test program for the torch igniter.

3.1 Test Requirements

The torch igniter will be fed from the main tanks in order to minimize weight and space associated with the inclusion of a secondary or independent tank system. In doing so the igniter will need to operate at wide range of inlet pressures and flow rates managed by the implementation of inline orifices that allow for a set range of torch igniter chamber pressure. Table 3.1 shows the set operational requirements for the torch igniter.

Table 3.1 Torch Igniter Operational Requirements

Inlet Valve Pressure	120 - 200 psia
Chamber Pressure	80 - 150 psia
Total Mass Flow	0.01 - 0.02 lbs/s
Mixture Ratio	1-3
Maximum burn time	3 seconds
Igniter Temperature	-185 F - 200 F

The main requirement for the torch ignition system is it must ignite the propellants at all inlet conditions; at any combination of the propellants of being in a gaseous, cold gas or in a liquid state. This allows the torch igniter to be feed from the main engine propulsion manifold system, which would be in a liquid state. Feeding the torch igniter from the main engine feed system reduces the complexity of a potential vehicle by avoiding separate propellant storage and handling systems for the igniter.

In order to create a more versatile igniter, so that it could be operated over a wide range of main engine tank pressures, in-line orifices need to be added in order to reduce the main tank pressure to the desired operating inlet pressures. These in-line orifices could then be easily sized according to the desired main tank pressure and replaced without significant system modifications. In-line orifices upstream of the swirl torch igniter will meter the flow rate of the propellants and reduce the inlet pressure to the swirl igniter. The in-line orifices are commercially available 1/8" Male-Male NPT threaded type 303 Stainless Steel in-line orifices. The orifice diameters for the fuel and oxidizer are 0.089" and 0.078", respectively. The igniter system may be operated at a significantly lower pressure than that of the main engine. The replaceable inline-orifices enables use a wide range of main tank operation pressures for the igniter operation.

In addition, during testing of previous design iteration, it was observed that the chamber pressure port and chamber pressure extension tube were operating at elevated temperatures, which could damage the pressure sensing equipment in use [4]. The solution was the inclusion of a chamber pressure port orifice measuring 0.030 inch. This orifice diameter was demonstrated to

be small enough to prevent combustion within the pressure port tube, while exhibiting minimal impact on instrumentation response time.

The test requirement for the propellant mixture ratio was set to be between one and three. Figure 3.1 present a plot of temperature with respect to mixture ratio in oxygen/methane combustion. The stoichiometric mixture ratio of oxygen/methane combustion is of four. The combustion temperature is at its highest at stoichiometric ratio. A combustion temperature of almost 5500 °F is expected if the torch igniter runs at a mixture ratio of four. The requirement of testing at a low mixture ration was with the intent of keeping combustion temperature to a low margin but yet achieve sufficient temperature to igniter a propulsion system. A combustion temperature range of 1500-5000 °F is expected in this test campaign at the troch igniter combustion chamber. The torch igniter will be monitored closely to prevent hardware damage from the hot fire tests and avoid overheating of the torch igniter body.

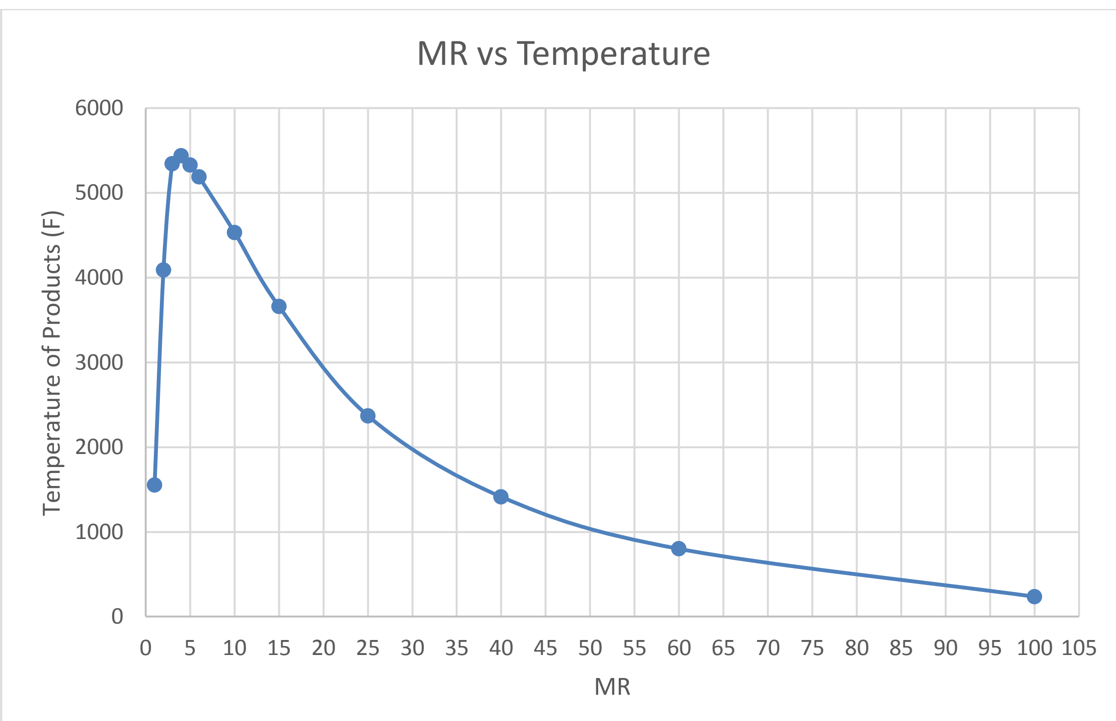

Figure 3.1 Relationship of oxygen/methane combustion temperature and mixture ratio

3.2 Test Program

Each configuration of tank pressures was run for a total of five trials as shown in Table 2. A sequence created on LabView controlled the operation of the sparker and valves as well as recorded various pressures and temperatures throughout the runlines in order to monitor the system operations. For each trial, the sparker ran at 400 Hz for a total of three seconds; one second before the flow of propellant and for three seconds during the propellant flow.

3.2.1. Gas/gas

The gaseous oxygen and gaseous methane test matrix is shown in Table 3.2. Five trials were completed for each configuration. Due to testing at ambient temperatures with no preconditioning or film cooling, heat soak at the pressure chamber was observed. Each trial will be limited to being run at a maximum of 1000 °F. If the chamber temperature surpasses 1000 °F in any one trial, it was allowed to cool down to the maximum chamber temperature before the next trial was completed in order to prevent any instrumentation damage. Propellant inlet pressures of 120-200 psia were tested.

Table 3.2 General Test Matrix

Oxygen Tank Pressure, psia	Methane Tank Pressure, psia	Trials
120	120	5
	140	5
	160	5
	180	5
	200	5
130	120	5
	…	5

	200	5
…	…	5
200	120	5
	…	5

3.2.2. Two Phase and Liquid/Liquid

The same test matrix shown in table 3.2 was used on both the two phase and liquid/liquid test configurations. For two phase flow, liquid nitrogen was used to precondition the lines before firing. The lines were preconditioned to or below boiling point temperatures associated boiling points of both oxygen and methane at the tank pressures defined by the test matrix. All lines were insulated using cryogel so minimal piping was exposed to ambient temperatures. Unlike the gas/gas test runs, the preconditioning act as a cooling mechanism so heat soak was not observed at the chamber and trials could be completed consecutively with little time between tests.

3.2.3. Propellant Inlet Conditions

As per the operational requirements, gaseous oxygen and methane propellant states are one of the testing conditions for the torch igniter. This requirement will be met by feeding gaseous oxygen and methane from K-bottles at pressures described in the operational requirements. These tanks directly feed to the igniter through a series of pipes and valves and will be a simulation of what would be seen in the completed vehicle. The valves are programmed using LabView software in order to control the sequence and burn time. An inline orifices, thermocouples, and pressure transducers are implemented in order to measure m and mixture ratio. Tests were performed with

Two-phase and liquid-liquid propellant states will also be tested on the torch igniter to demonstrate operability under cryogenic conditions. Liquid methane is condensed using an in-house condensing unit, as it is not easily obtained through commercial vendors. The condensing unit operates similar to a heat exchanger, two sets of winding coils flow liquid nitrogen around methane filled chamber. The condensing process takes place at low pressures due to the manufacturing process. For cryogenic states the same test configuration as the gas/gas tests is used with an addition of insulated lines using cryogel and an implementation of line preconditioning using liquid nitrogen, liquid methane, and liquid oxygen. These tests were run with little time between fires as the issue of heat soak was not be a problem with cryogenic fuel.

Chapter 4

4.1 Results and Discussion

The developmental testing for this igniter iteration was conducted in two testing phases. The first phase was focused on expanding the previously conducted gas/gas propellant combination testing through the increase of the igniter's operating chamber pressure and varying of the propellant mixture ratio. Previous iterations of this design were tested with propellant mixture ratios between 2-4 and chamber pressures between 80-100 psia[4]. The second phase of testing was concentrated on demonstrating the igniter's performance when operated with two-phase or liquid propellant combinations.

4.1.1. Gaseous CH_4/ gaseous O_2

The main objective of this phase of testing was to demonstrate reliability of the hardware during steady-state operation with a propellant mixture ratio between 1-3 and chamber pressures between 100-150 psia. These parameters were selected with the overall goal of reducing operating temperature, while increasing the chamber pressure to be more compatible with larger main engines.

A total of 210 successful test runs were conducted for first testing phase. The test sequence conducted in this testing phase limited the torch igniter hot fire to three seconds. The hot fire time limit was set to prevent any hardware damage to the igniter or the spark plug. The hot fire test sequence was set with a one second spark plug lead to igniter the propellants in the combustion chamber as soon as possible and avoid a hard start in the igniter combustion chamber. The oxygen and methane inlet valves where energized at the same time at +1 in the sequence and de-energized at +4. A typical test sequence is depicted in figure 4.1, where the green blocks indicate energized. The valves are normally closed and will open when energized

by the sequence. Carbon dioxide was fed to the test article upon completion of the planned hot fire duration as a precaution in case an unwanted fire occurred.

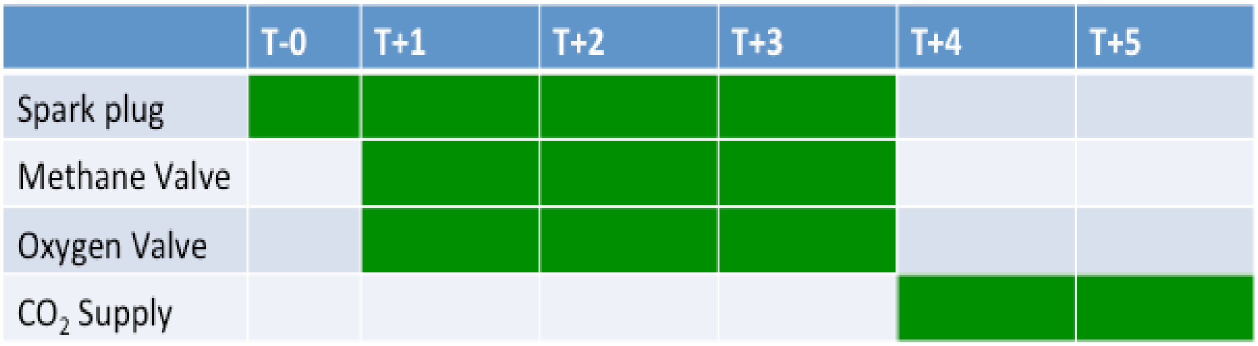

Figure 4.1 Test sequence timeline for the torch igniter

The torch igniter had 4 k-type thermocouples spot welded in the different sections of the igniter body to monitor igniter body temperature and one combustion chamber static pressure sensor. There were no redlines set during igniter hot fire test, the igniter instrumentation was monitored in console during a test sequence. The torch igniter body temperature was recorded pre and posttest since it did not had active cooling it was essential to monitor the igniter body temperature rise between hot fire tests. It was observed that the torch igniter body had an average temperature difference of approximately 410 °F after a single hot fire test.

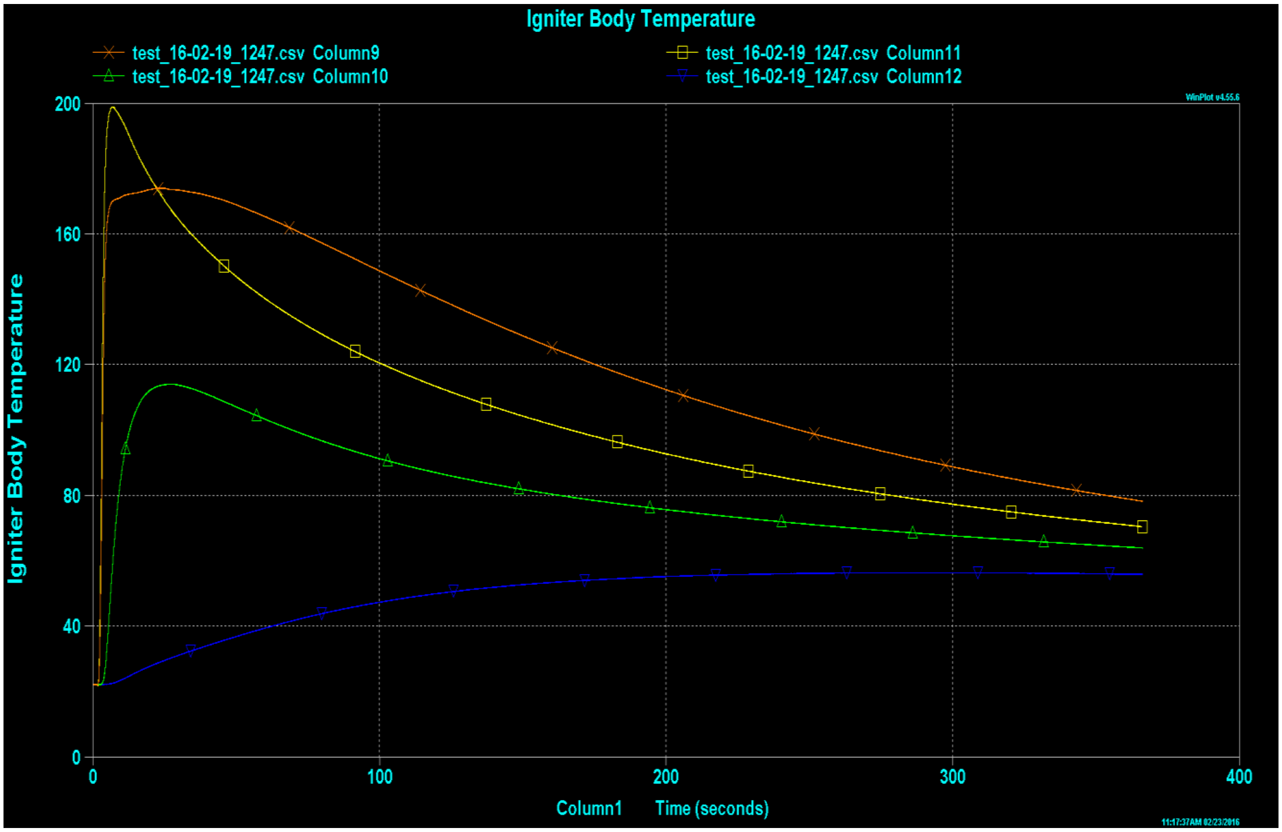

Figure 4.2 Torch igniter body temperature after a hot fire test

Figure 4.2, presents the torch igniter temperature profile after a hot fire test in degrees Celsius. The torch igniter k-type thermocouples were spot welded at the throat, combustion chamber, fuel manifold and at the oxidizer inlet. The highest temperature recorded was in the thermocouple welded by the throat of the torch igniter and the lowest by the oxidizer inlet. This igniter body delta temperature was repeatedly seen throughout the first phase of testing. A blueline for testing was set for the igniter body temperature to not exceed 1000 °F. This blueline did not affect the time in between test as the igniter body temperature remained within an acceptable temperature range of 400-750 °F. Although a high temperature limit was set, the torch igniter was also tested at igniter body temperatures above 1000 °F to determine if there was an impact in the torch igniter reliability. There were no significant differences observed in testing

the torch igniter at higher temperature than the blueline set and no hardware was compromised. Once determining the temperature profile after a single torch igniter hot fire test, it was important to obtain the torch igniter temperature duty cycle. Torch igniter hot fires were stacked up to obtain a temperature profile after a specific number of tests. In figure 4.3, the igniter body temperature profiles of five consecutive hot fire tests are depicted. Five hot fire tests were conducted with a two-minute separation between tests. All tests had the same temperature profile with a delta temperature of approximately 200 °F. The maximum temperature reached after the final hot fire test was of 650 °F which was well below the maximum allowable temperature set for the torch igniter.

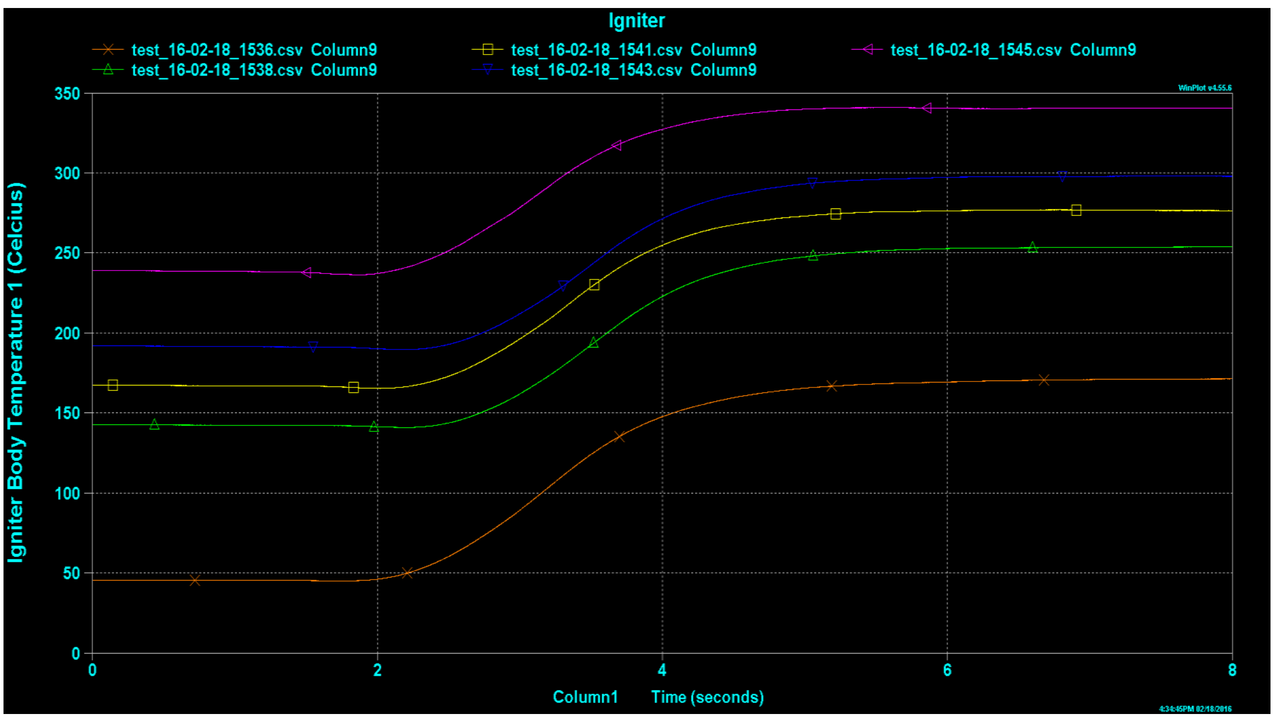

Figure 4.3 Igniter body temperature profile after five consecutive hot fire tests

The spark torch igniter was tested at different propellant inlet pressures ranging between 120 to 200 psia with an igniter total mass flow rate of 0.01 +/- 0.01 lbm/s. The gas/gas testing phase

had 100% (210/210) ignition success rate with no damage observed to the igniter or the spark plug. The data obtained from this test was analyzed to confirm that the igniter requirements for mixture ratio and chamber pressure were met. Figure 2 presents the igniter chamber pressure to corresponding mixture ratio. The chamber pressure in the torch igniter ranged from 60 to 150 psia as it was set in the requirements. The igniter chamber pressure oscillated in both test phases and this can be attributed to two factors. The igniter chamber pressure port is an orifice and could have restricted the combustion gases flowing to the pressure sensor differently throughout the first phase of the test campaign. Lastly, the torch igniter was tested at different propellant inlet pressures resulting in lower inlet pressures producing lower igniter chamber pressures.

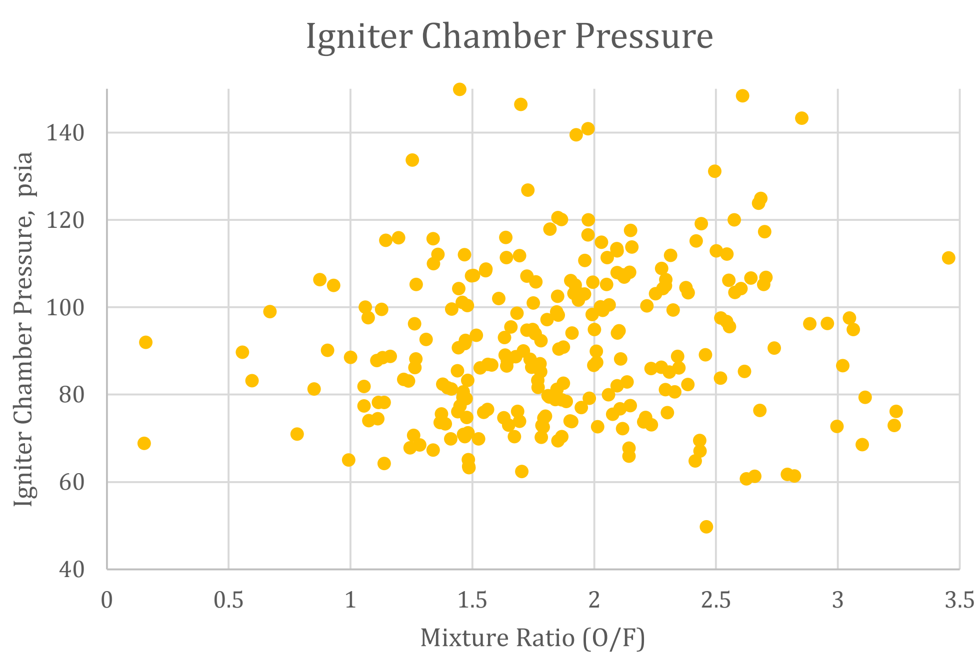

Figure 4.4 Igniter chamber pressure versus mixture ratio for all torch igniter test campaign.

Propellant condition is of upmost importance as one of the main requirements of the torch igniter is to be able to operate at different propellant inlet conditions. The torch igniter has a

pressure sensor and an E-type thermocouple at the igniter inlet valves to continuously monitor the propellant conditions as it is being injected into the torch igniter combustion chamber.

The velocity ratios with respect to mixture ratio are depicted in figure 4.5. The velocity ratio is the velocity of a single tangential methane port over the velocity of the oxygen. A noticeable trend can be observed from the data collected for the first phase of the test campaign. A lower mixture ratio corresponded to a higher velocity ratio. A low mixture ratio has more methane and thus resulting in higher velocity of the methane. As the mixture ratio increases the velocity ratio will decrease as expected. The velocity of methane ranged approximately between 60-150 ft/s and the velocity of the oxygen ranged 54-70 ft/s.

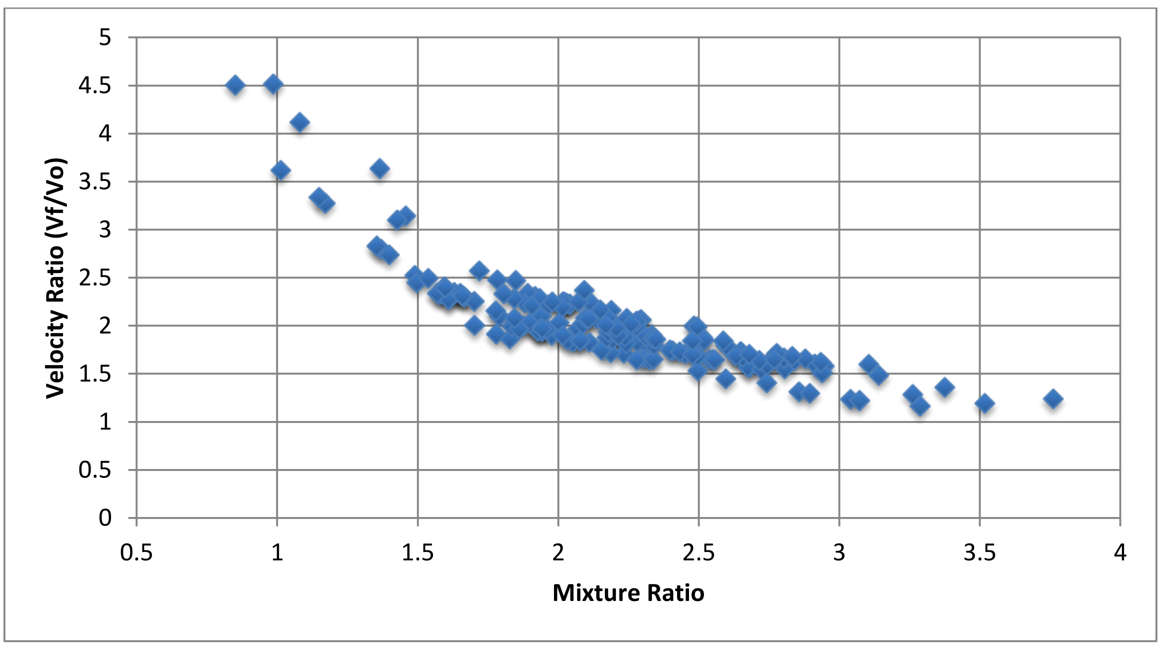

Figure 4.5 Velocity ratios with respect to mixture ratio for gas/gas test phase

4.1.2. Liquid CH_4/Liquid O_2

Although, gas/gas propellant combinations are the most expected operating conditions for this igniter during main engine starts; rapid restarts or pulsing operation can be conducive to liquid or two phase propellant conditions at the torch igniter inlets. Therefore, it was important to

demonstrate reliable operation of the igniter over a wide range of propellant quality. Like phase one, the propellant mixture ratio was maintained between 1-3, with operating chamber pressures ranging between 100-150 psia.

A total of 100 tests were conducted in the second test phase for the torch igniter. The second test phase fed the torch igniter with cryogenic propellants. For this test phase, some test runs had no precondition of the test article and runlines to simulate initial engine fed scenarios as well as test with precondition of the test article and the runlines for engine restart scenarios. The test sequence remained the same as in the first test phase to maintain a constant torch igniter test program. The test sequence was set to three seconds of hot fire. In figure 4.3 presents a still image of a torch igniter hot fire test with cryogenic propellants. The LED lights shown in Figure 4.3 served as a visual verification in console for spark plug and main valves being energized by the test script.

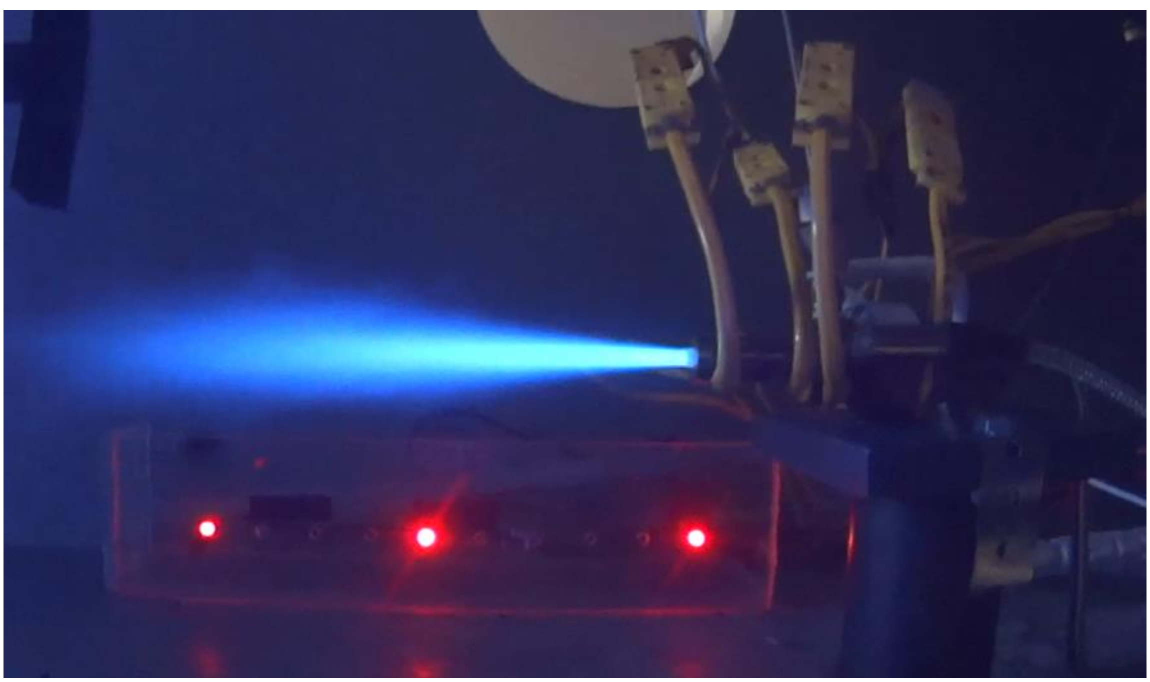

Figure 4.6 Liquid oxygen/liquid methane hot fire test

Torch igniter body temperatures after each hot fire test was recorded and compared to the previous temperature profiles collected. With cryogenic propellants, the igniter body temperature had a lower range as it was observed in the gas/gas test phase. The igniter body had a temperature delta of approximately 300 °F. This can be attributed to the preconditioning of the torch igniter prior to each hot fire test conducted. An addition test parameter that was of studied during the cryogenic test phase was the impact of low torch igniter body temperature. The igniter body temperature was dropped to -250 °F and visible frosting was observed in the igniter body in figure 4.7. No significant impact was observed due to the low igniter body temperatures. The torch igniter body temperature ranged was of -250 to 100 °F throughout the second phase of testing.

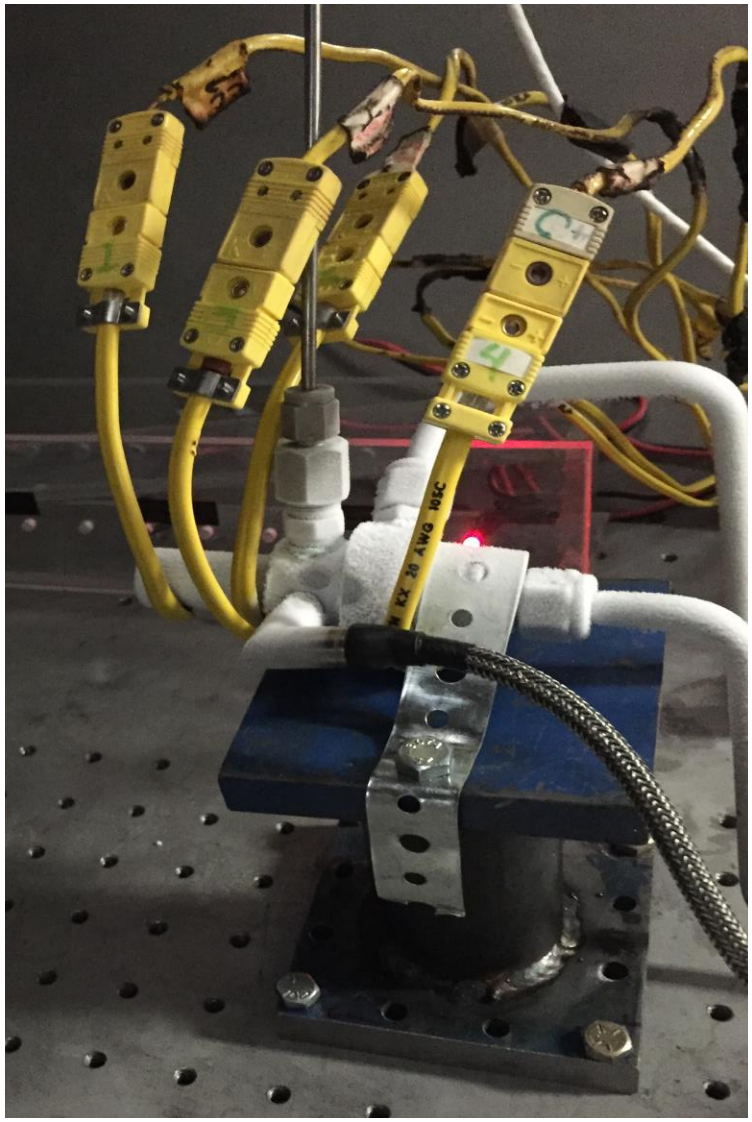

Figure 4.7 Torch igniter hot fire test at chamber pressure of 150 psia and MR of 2

The second phase for the torch igniter had a different success rate as compare to gas/gas testing. Out of the 100 tests conducted 66 successfully lit. This gave had a 66% (66/100) ignition success rate and other than heat stains no damage to the torch igniter or the spark plug was observed. The torch igniter test requirements were met in the 66 test runs that successfully ignited.

Similar to the gas/gas test phase, the torch igniter was tested at different propellant inlet pressures ranging between 120 to 200 psia with an igniter total mass flow rate of 0.01 +/- 0.01 lbm/s. The chamber pressure in the torch igniter ranged from 90- 140 psia. The data obtained for propellant condition in the first phase of testing was collected and plotted against the saturation curves for both oxygen and methane.

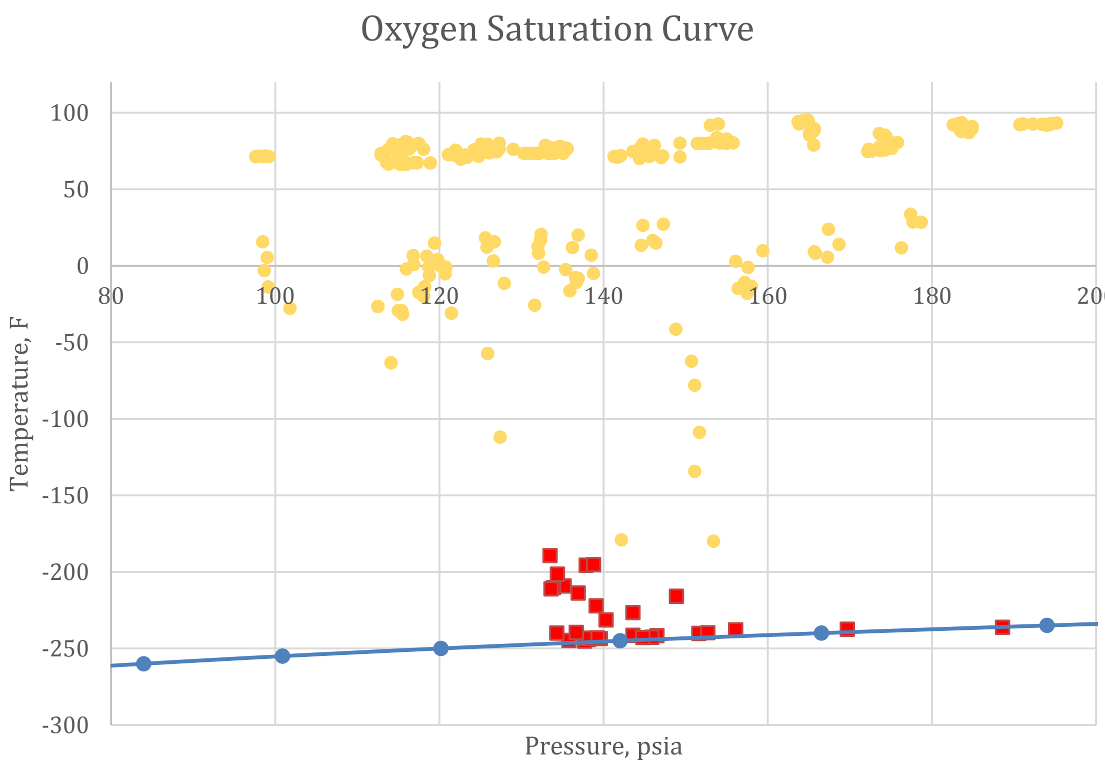

Figure 4.8 Propellant condition at the inlet of the torch igniter

The propellant condition fed to the torch igniter for the entirety of the test campaign can be observed in Figures 4.8 and 4.9. The saturation curves for oxygen and methane aid to understand what was the quality of the propellants for each successful and unsuccessful test. In both saturation plots, the orange data points represent the successful three-second hot fire test of the torch igniter and the red data points represent the unsuccessful test runs. The torch igniter

successfully ignited at a wide range of propellant inlet conditions, especially with methane, as set in the operational requirements.

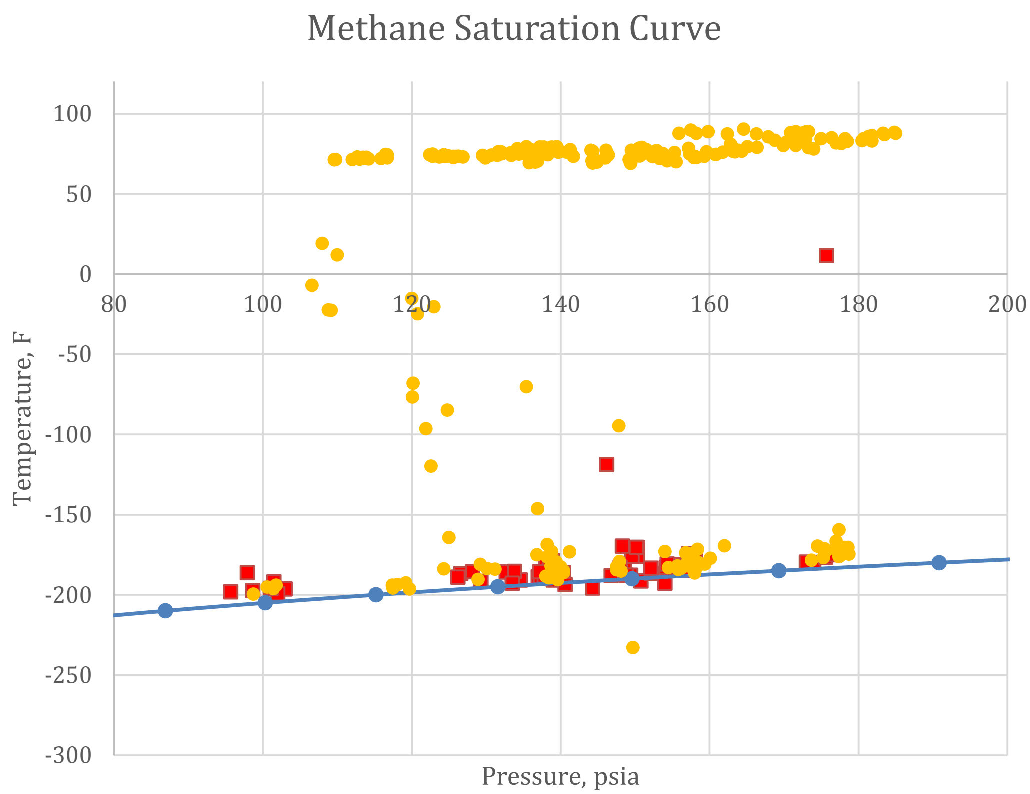

Figure 4.9 Propellant conditions at the inlet of the torch igniter

Even though issues were observed, the success rate of ignition with cryogenic propellants was higher than previous torch igniter iterations. In all of the unsuccessful tests saturated oxygen was injected to the torch igniter however it is important to point out that the oxygen continuously flashed at the main valve and igniter throughout the second phase of testing. Preconditioning the oxidizer runline and test article was a challenge throughout the test campaign. The reason behind this cloud be that the liquid oxygen sources was a 120 L dewar that needed to be self-pressurized to achieved a set inlet pressure in the test matrix set for the second phase of testing. The oxygen propellant condition was mostly constant when the dewar was almost full but as the level decrease so did the propellant quality. Insulation in the runlines aids this issue but did not solve it

completely. Liquid methane presented no issue during testing, the methane was condensed prior testing and the liquid condition was maintained during the test program. The liquid methane was vented prior to each test run to sub cool it and was pressurized with helium to the required set pressure in the test sequence. Improvements in the oxidizer feed system can be implemented to improve the ignition success rate of the torch igniter.

4.2 Outcome Observed

The test requirements form the testing of the fourth iteration torch igniter were mostly met. The torch igniter was tested at different propellant inlet conditions. Chamber pressure, mixture ratio and maximum burn time were successfully met in both testing phases of the torch igniter test campaign. The torch igniter met the range of chamber pressure of 80-150 psia established in the test requirement and within the mixture ratio range of 1-3.

The objectives of this dissertation were set to analyze the performance of the torch igniter under different inlet condition and to test the robustness of the torch igniter. The torch igniter performed accordingly under gas/gas conditions but partially met the liquid/liquid conditions due to complications with the liquid oxygen source. The oxygen system used throughout testing was more fitted to be a transfer system more than a run system. The liquid oxygen was an autogenous system in which the fluid was maintained at saturated conditions but not at the sub cooled condition that it was required for testing. The oxygen system was the source for the unsuccessful liquid oxygen and liquid methane test runs. The secondary objective of the torch igniter test campaign was to determine the duty cycle and robustness of the system. Since re ignition and reliability are of upmost importance, the igniter was tested over 310 times. Each hot fire test was set to three seconds of steady state combustion resulting in close to 1000 seconds of sustained combustion time. The torch igniter was tested at different time intervals and igniter body temperatures. The igniter was tested at hot, warm and cold temperatures in which no damage to the hardware was observed. This dissertation objective was successfully met as the igniter was

proven to resist and operate reliably in a rigorous duty cycle test. The igniter demonstrated the capability of recycling within seconds if the occasion required it.

If additional torch igniter testing is required, implementing a liquid oxygen run tank system as the one utilized in the methane system will improve the ignition success rate of the torch igniter as it will provide consistent propellant condition and pressure. As previously mentioned, the liquid oxygen system limitation experienced in testing affected the capability of testing both liquid propellants at sub-cooled conditions.

Chapter 5

5.1 Conclusion

Developmental testing of a swirl injected torch igniter was conducted with wide variations in propellant quality. The performance testing was conducted using gas/gas and liquid propellant combinations. These tests served as a method of characterizing igniter performance via igniter chamber pressure and propellant flow rates while demonstrating the system's survivability with repeated ignitions. Torch igniter requirements were met in this test campaign however issues with oxidizer condition were observed in the second phase of the torch igniter test campaign. The torch igniter design modification mitigated the issues encountered in the previous design iterations of the torch igniter. A total of 310 test runs were conducted in the torch igniter developmental test campaign. Steady state ignition was achieved in 210 out of 210 tests with an ignition success rate of 100% for gaseous propellants in the first phase of the test campaign. For liquid conditions in the second test phase of the torch igniter, ignition was achieved in 66 out of 100 test with an ignition success rate of 66%. The propellant quality was plotted with the saturation curve to quantify the condition of the propellant that was fed to both successful and unsuccessful test runs.

The literature review compiled in this dissertation presents a direct comparison of the test effort and relevance of the study. The literature review detailed the current igniter technologies using oxygen/methane as propellants. The igniter technology developed and tested in this dissertation showed promising results as it was tested at a wide range of operability conditions and most importantly contributing to exiting efforts in development of oxygen/methane propulsion systems.

This testing campaign demonstrated that this ignition system operates over a wide range of inlet pressures and flow rates and a significant improvement to previous torch igniter iterations, thus serving as the main ignition source for a 500 and 2000lb rocket engines that are being developed at University of Texas at El Paso. The next step for this torch ignition system will be to replicate this test campaign under vacuum conditions. It is critical to understand the performance of the torch igniter under these conditions. The performance and ignitability limits of the torch igniter may vary at vacuum conditions. Testing the torch igniter at these conditions will deliver a final product that will be capable of igniting oxygen and methane at any propellant and operating condition.

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Appendix

PROVISIONAL APPLICATION

FOR

UNITED STATES LETTERS PATENT

TITLE: SWIRL TORCH IGNITER

INVENTORS: Norman D. LOVE Jr., Luis Eduardo SANCHEZ, Ahsan Reza CHOUDHURI, and Charles Scott HILL

SWIRL TORCH IGNITER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Not applicable.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0002] This invention was made with government support by the National Aeronautics and Space Administration (Grant No. NNX09AV09A). The government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] This disclosure relates generally to ignition systems. More specifically, this disclosure relates to techniques utilizing spark igniters or torch igniters for ignition applications.

DESCRIPTION OF THE RELATED ART

[0004] Igniters have been used in many applications to initiate or ignite a combustive reaction. For example, conventional gas ovens are equipped with electrical igniters to ignite the gas flowing through a burner in the heating compartment. Other examples include igniters used to ignite or ‘light up' gas turbine engines. Yet other examples include igniters used to ignite combustion in rocket engines.

[0005] Interest in commercial space exploration is driving a push for developments that reduce costs and provide improved technology for space commercialization. Various types of fuels have been used for rocket propulsion in the aerospace industry. Previous research and development efforts have been directed towards traditional fuels such as hydrogen and kerosene. Recently, the use of methane as a rocket propellant has reemerged in the aerospace industry.

[0006] The lack of focused research in the use of methane and other fuels for rocket engine propellant has left a void in the development of improved ignition sources for propulsion systems. Thus, a need remains for improved techniques to ignite propellant mixtures comprising fuels such as methane.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The following figures form part of the present specification and are included to further demonstrate certain aspects of the present claimed subject matter, and should not be used to limit or define the present claimed subject matter. The present claimed subject matter may be better understood by reference to one or more of these drawings in combination with the description of embodiments presented herein. Consequently, a more complete understanding of the present embodiments and further features and advantages thereof may be acquired by referring to the following description taken in conjunction with the accompanying drawings, in which like reference numerals may identify like elements, wherein:

[0008] Figure 1A is a schematic drawing illustrating a longitudinal cross-sectional of an igniter body according to some embodiments;

[0009] Figure 1B is a circumferential cross-sectional view of the igniter body of Figure 1A;

[0010] Figure 2 is a modeled velocity vector diagram of an oxidizer-fuel intersection in an igniter according to some embodiments;

[0011] Figure 3A is a schematic drawing illustrating a three-dimensional perspective view of an igniter according to some embodiments;

[0012] Figure 3B illustrates a top view of the igniter of Figure 3A;

[0013] Figure 3C is a longitudinal cross-sectional view of the igniter of Figure 3A, taken along section H-H of Figure 3B;

[0014] Figure 3D is a circumferential cross-sectional view of the igniter of Figure 3A taken along section I-I shown in Figure 3C;

[0015] Figure 4 is a photo image of an igniter according to some embodiments;

[0016] Figure 5 is a photo image of a sparking element used in some embodiments;

[0017] Figure 6 is a schematic drawing of a conventional rocket engine;

[0018] Figure 7 is a schematic drawing of the rocket engine of Figure 6 implemented with an igniter according to some embodiments;

[0019] Figure 8 is another schematic drawing of the rocket engine of Figure 6 implemented with an igniter according to some embodiments; and

[0020] Figure 9 is a flow chart illustrating, at a top level, a method for igniting a torch flame according to some embodiments.

DETAILED DESCRIPTION

[0021] The foregoing description of the figures is provided for the convenience of the reader. It should be understood, however, that the embodiments are not limited to the precise arrangements and configurations shown in the figures. Also, the figures are not necessarily drawn to scale, and certain features may be shown exaggerated in scale or in generalized or schematic form, in the interest of clarity and conciseness. Relatedly, certain features may be omitted in certain figures, and this may not be explicitly noted in all cases.

[0022] While various embodiments are described herein, it should be appreciated that the present invention encompasses many inventive concepts that may be embodied in a wide variety of contexts. Thus, the following detailed description of exemplary embodiments, read in conjunction with the accompanying drawings, is merely illustrative and is not to be taken as limiting the scope of the invention. Rather, the scope of the invention is defined by the appended claims and equivalents thereof.

[0023] Illustrative embodiments of the invention are described below. In the interest of clarity, not all features of an actual implementation are necessarily described for each embodiment disclosed in this specification. In the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the design-specific goals, which will vary from one implementation to another. It will be appreciated that such a development effort, while possibly complex and time-consuming, would nevertheless be a routine undertaking for persons of ordinary skill in the art having the benefit of this disclosure.

[0024] Liquid methane (LCH4) is a good propellant for rocket engine propulsion. Methane has a relatively high specific impulse, a competitive energy density, and is safer to handle and store compared to some other propellants. Other advantages include the ability to store both methane and oxidizer at similar temperatures. It is also non-toxic and less expensive, compared to liquid hydrogen and hypergolic propellants. It has also been suggested that methane could be

synthesized from carbon rich atmospheres or other sources in outer space, expanding *in situ* resource utilization. The National Aeronautics and Space Administration (NASA) has identified the propellant combination of liquid oxygen (LOX) and liquid methane as a propellant combination for next generation propulsion systems.

[0025] In order to design a reliable ignition source for implementation in rocket engine propulsion, it is important to understand how the ignition system operates under different test environments. To fulfill this objective, the inventors of this disclosure devoted a significant amount of time, expense, and effort to construct and implement a testing facility to evaluate and analyze igniter embodiments of the invention. This research included development of a cryogenic delivery system, development of an optically accessible combustion chamber to view igniter testing, and implementation of a data acquisition and remote control system. This extensive effort led to the design and production of reliable igniters, particularly for use with, but not limited to, oxygen-methane mixtures.

[0027] Analysis and characterization of igniter embodiments of the invention involved the determination of ignitability limits at different propellant inlet conditions. Propellant temperature and mixture ratio were among the variable factors associated with ignition that were incorporated in test matrices. In this regard, in some embodiments described herein, the temperature and pressure of fuel and oxidizer may be monitored and regulated in order to control the temperature, pressure and flow rates of the fuel and oxidizer. Testing included consideration of different oxidizer-fuel phase interactions (i.e., gas-gas, liquid-gas, liquid-liquid). Igniter analysis included: liquid oxygen in combination with cold gaseous methane and liquid methane; ambient temperature gaseous oxygen in combination with gaseous methane at ambient and lower temperatures; liquid oxygen interacting with ambient temperature gaseous methane; and ambient temperature gaseous oxygen with liquid methane. Other considerations made during design of the igniter embodiments included geometry aspects such as tangential and oxidizer post length, diameter, and location of the ignition source; this is further described with respect to the disclosed embodiments, wherein tangential post is referred to as “tangential fuel passage” (e.g., 16) and oxidizer post is referred to as “oxidizer inlet channel” (e.g., 15). For some igniter applications, it is convenient to use the main fuel source as the fuel source for the igniter (e.g., in a space context), e.g., to use the boil-off, that is, the gas formed in fuel (e.g., LCH4) and oxidizer (e.g., LOX) storage tanks above the liquid by evaporation. Such implementations were

factored into the igniter analysis. Figure 1A shows a longitudinal cross-section of an igniter 10, or of a portion thereof, according to some embodiments. This view shows in phantom (dotted lines) the internal ports or passages formed in the igniter body 12. The upstream end of igniter 10/body 12 includes an oxidizer inlet port 14. Oxidizer inlet port 14 leads (downstream) into an oxidizer inlet channel 15, which extends (in the direction from left to right in the figure) along a portion of the longitudinal axis of the igniter body 12. Four tangential fuel passages 16 are formed to intersect with the oxidizer inlet channel 15 (two fuel passages 16 are shown in Figure 1A; all four are shown in Figure 1B, discussed below). Other embodiments may be formed with two, three, or more than four fuel passages 16. However, at least two fuel passages are preferred in order to generate a swirling mixture, as further described below. The oxidizer inlet channel 15 leads to a central mixer section 18, just past the intersection with the fuel passages 16. The mixer section 18 leads to a combustion chamber 19, which is located at the end of igniter 10/body 12 that is longitudinally opposite to inlet port 14. A sparking element (not shown in Figure 1A) is used to ignite the swirling mixture in the combustion chamber 19 (described below with reference to Figure 4).

[0028] Figure 1B shows a circumferential cross-sectional view of the igniter 10 of Figure 1A, with the fuel passages 16 shown in phantom (dotted lines). As seen in Figure 1B, the fuel passages 16 are formed radially through the body 12 to tangentially intersect with the oxidizer inlet channel 15. Each fuel passage 16 is formed such that the intersection with the oxidizer inlet channel 15 is slightly offset from the central longitudinal axis of the inlet channel 15, as depicted in Figure 1B. This configuration produces an internal mixture swirl powered by the momentum of the colliding injections of fuel (from fuel passages 16) and oxidizer (from oxidizer inlet channel 15). In operation, the oxidizer flows through the inlet channel 15 (from left to right in Figure 1A) and meets the four tangential fuel passages 16 in order to form a swirl that causes the mixing of the propellants (i.e., fuel and oxidizer) prior to ignition.

[0029] In Figure 1B, the fuel passages 16 are formed/disposed in igniter body 12 so as to be circumferentially spaced apart along the outer circumference of igniter body 12, at intervals that are evenly spaced apart in the circumferential direction (specifically, at 0 degrees, 90 degrees, 180 degrees and 270 degrees), thus dividing the outer circumference into four circumferentially extending quadrants. In other embodiments, the circumferential locations of the fuel passages 16, and/or the spacing between those circumferential locations, may be different from that shown

in Figure 1B. The spacing may but need not be equal between every two adjacent fuel passages 16. As previously mentioned, the sparking element used to ignite the fuel-oxidizer mixture is not shown in Figure 1A or Figure 1B for clarity of illustration of the internal passages configured to produce the swirling mixture; the sparking element is described below with respect to Figure 4.

[0030] Figure 2 shows modeled velocity vectors of the fuel-oxidizer mixture at the location along the longitudinal extent of body 12 at which methane, for example, is injected through the fuel passages 16 to mix with the oxidizer flowing through the oxidizer inlet channel 15. This is at the intersection where fuel enters from the passages 16 to mix with oxidizer in the inlet channel 15, which occurs longitudinally as the mixture enters the central mixer section 18. The modeled velocity vectors illustrate the swirling of the fuel-oxidizer mixture.

[0031] The igniter 10 body may be formed of any suitable material (e.g., metal) as known in the art, taking into consideration that input oxidizer and/or fuel temperatures and phases may vary. Although the igniter 10 embodiment depicted in Figure 1A and Figure 1B is formed with a cylindrical body 12 having a longitudinal axis, other embodiments of the invention may be formed with different body geometries (e.g., square or other polyhedron configuration). The oxidizer and fuel passage configuration and dimensions in such embodiments can also be varied, provided the disclosed tangential intersection configuration to produce mixture swirl is maintained.

[0032] Figures 3A-D illustrate another igniter 20, according to some embodiments. Figure 3A shows a three-dimensional perspective view of the igniter 20; Figure 3B shows a top view of the igniter 20; Figure 3C is a longitudinal cross-sectional view of the igniter of Figure 3A, taken along section H-H of Figure 3B; Figure 3D is a circumferential cross-sectional view of the igniter of Figure 3A taken along section I-I shown in Figure 3C. As seen in Figures 3A-3D, the igniter 20 includes an elongated body 22 with (in order from upstream to downstream (left to right in Figures 3A, 3B and 3C)) an oxidizer inlet port 24 at the upstream end, a longitudinal oxidizer inlet channel 25 extending longitudinally through body 22, a sparking element port 26, a mixing chamber 35, and an extended combustion chamber 27 leading to a torch flame outlet 28 at the downstream end of body 22. Figure 3C shows a contoured nozzle exit at the torch flame outlet 28. Further, an annular groove or channel 30 is formed around the entire circumference of the body 22 in between the oxidizer inlet port 24 and the sparking element port 26. The annular

channel 30 is formed to extend radially inward, to a uniform depth all around the circumference of body 22. Channel 30 may be understood as defined by an annular base or bottom 32 and two annular sidewalls 33. At the base 32 of channel 30, fuel passages 34 are formed extending radially through the body 22 and intersecting into oxidizer inlet channel 25, as shown, e.g., in Figure 3D.

[0033] As in the manner described for igniter 10, here too in igniter 20 the fuel passages 34 intersect with the oxidizer inlet channel 25 tangentially, as seen in Figure 3D, in such a fashion as to produce a swirling mixture of the propellants (e.g., methane and oxidizer). Sparking element port 26 may include a spark plug for igniting the swirling fuel-oxidizer mixture, as described below with reference to Figure 4. As seen in Figure 3C, mixing section 35 extends longitudinally between the fuel passages 34 and the sparking element port 26. Figures 3A, 3C and 4 show a circular opening longitudinally aligned with sparking element port 26 but circumferentially removed from sparking element port 26 (labeled as "¼ - 32 THRU" in Figure 3C). This opening may be used, e.g., for conducting pressure measurements. This opening is not necessary for igniter 20 (or 10) and may be omitted from embodiments described herein.

[0034] Although, as seen in Figure 3D, igniter 20 is also configured with four fuel passages 34, other embodiments may be formed with two, three, or more than four fuel passages 34. The igniter 20 dimensions depicted in Figures 3B-3D are exemplary of one embodiment. The dimensions shown in Figures 3B-3D are in inches. Other embodiments may be implemented with varying dimensions and tolerances.

[0035] Turning to Figure 4, the igniter 20 of Figures 3A-3D is shown ready for connection to oxidizer and fuel feed lines. An annular yoke or ring 36 is disposed on the igniter body 22 over annular channel 30 so as to encircle the channel 30 and to seal the channel 30 from the ambient environment, to create a sealed or enclosed channel. The ring 36 is fitted with a primary fuel inlet 38. In this embodiment, the ring 36 has been welded onto the body 22 to fully seal the ring over the channel 30. Those skilled in the art will appreciate that other embodiments may be implemented with the ring 36 formed on the body 22 such that the igniter 20 is a single unit (e.g., using modern machining, casting techniques, 3D printing, etc.). The porting on the igniters 20, 10 may be formed via conventional drilling or other known means (e.g., water-jet cutting techniques).

[0036] The primary fuel inlet 38 is configured with a conventional connector to receive a fuel feed line. With this configuration, fuel can be injected into the igniter 20 via a feed line connected to the primary inlet 38. The fuel flow then proceeds circumferentially around/through the annular channel 30 within/under ring 36, enters the fuel passages 34, and flows through the fuel passages 34 to collide with the oxidizer flow in the oxidizer inlet channel 25. Upon production of the swirling oxidizer-fuel mixture in the mixing section 35 (shown in Figure 3), a sparking element 40 is used to ignite (initiate combustion) of the mixture.

[0037] In some embodiments, the sparking element 40 is a spark plug mounted in the sparking element port 26. One embodiment may comprise an NGK® spark plug (¼ - 32 fitting, 5V ignition signal voltage, 8V ignition power voltage, 16kV ignition energy voltage, 300 Hz), as shown in Figure 5. The sparking element 40 provides an electrical discharge to ionize a fraction of the propellant (e.g., methane-oxidizer) stream, causing it to combust the fuel-oxidizer mixture and propagate a flame in the downstream direction from the sparking element 40 (i.e., rightward in Figures 3A-3C; leftward in Figure 4) through the igniter 20 body to emit an anchored torch flame at the downstream end, namely, torch flame outlet 28. It will be appreciated that the sparking element 40 may be coupled to a suitable electrical source for activation as needed according to the particular igniter 20 application.

[0038] Igniters according to disclosed embodiments may be used for various applications utilizing different propellant mixtures. As previously mentioned, the inventors carried out extensive testing of igniters for use in rocket propulsion systems utilizing oxygen for the oxidizer and methane for fuel. Turning to Figure 6, a conventional rocket engine 50 is shown. The engine 50 comprises a fuel inlet housing 52 at the upper end. Figure 7 shows a cut-away view of the fuel inlet housing 52 configured with an igniter 20. The igniter 20 is mounted on the housing 52 such that, when the igniter 20 is activated, the torch flame emitted from the downstream end ignites the propellant (e.g., methane and oxygen) in the engine 50 to light up the engine 50. Figure 8 shows another cut-away view of the fuel inlet housing 52 with the igniter 20 mounted thereto. For clarity of illustration, in Figures 7-8 the igniter 20 is shown without the oxidizer and fuel feed lines and without the sparking element 40 connected to the igniter body. It will be appreciated by those skilled in the art that these lines and connections can be implemented in various suitable ways tailored for the desired application.

[0039] Figure 9 is a flow chart illustrating a method 100 of the invention, i.e., a method for igniting a torch flame. At a first step, an oxidizer is inputted into a first (e.g., upstream) end of an igniter to create an oxidizer flow through the igniter. At a second step, fuel is input into a plurality of fuel inlet passages on the igniter configured to distribute the fuel in a direction tangential to the oxidizer flow to create a swirling fuel-oxidizer mixture. At a third step, the swirling fuel-oxidizer mixture is ignited with a sparking element mounted on the igniter to produce a torch flame emission from a second (e.g., downstream) end of the igniter.

[0040] In light of the principles and example embodiments described and illustrated herein, it will be recognized that the example embodiments can be modified in arrangement and detail without departing from such principles. Also, the foregoing discussion has focused on particular embodiments, but other configurations are also contemplated. In particular, even though expressions such as "in one embodiment," "in another embodiment," or the like are used herein, these phrases are meant to generally reference embodiment possibilities, and are not intended to limit the invention to particular embodiment configurations. As used herein, these terms may reference the same or different embodiments that are combinable into other embodiments. As a rule, any embodiment referenced herein is freely combinable with any one or more of the other embodiments referenced herein, and any number of features of different embodiments are combinable with one another, unless indicated otherwise or so dictated by the description herein.

[0041] Similarly, although example methods or processes have been described with regard to particular steps or operations performed in a particular sequence, numerous modifications could be applied to those methods or processes to derive numerous alternative embodiments of the present invention. For example, alternative embodiments may include methods or processes that use fewer than all of the disclosed steps or operations, methods or processes that use additional steps or operations, and methods or processes in which the individual steps or operations disclosed herein are combined, subdivided, rearranged, or otherwise altered. Similarly, this disclosure describes one or more embodiments wherein various operations are performed by certain systems, applications, module, components, etc. In alternative embodiments, however, those operations could be performed by different components. It will also be appreciated by those skilled in the art that embodiments of the invention may be configured for automated or computer controlled igniter activation. Conventional computers and applications configured with appropriate software may be used to implement such embodiments.

What is claimed is:

1. A torch igniter, comprising:

a body including an oxidizer inlet configured to facilitate oxidizer flow through the body toward an output end of the body;

the body including a plurality of fuel inlet passages configured to distribute fuel in a direction tangential to the oxidizer flow through the body to create a swirling fuel-oxidizer mixture;

a sparking element mounted on the body to produce a spark in the path of the swirling fuel-oxidizer mixture to ignite the mixture; and

wherein the output end of the body is configured to emit a torch flame when the fuel-oxidizer mixture is ignited.

2. A torch igniter according to claim 1, wherein the body includes a primary fuel inlet configured to distribute fuel to each of the plurality of fuel inlet passages.

3. A torch igniter according to claim 2, wherein the oxidizer inlet is configured to receive oxidizer comprising oxygen.

4. A torch igniter according to claim 3, wherein the primary fuel inlet is configured to receive fuel comprising methane.

5. A torch igniter according to claim 2, wherein the oxidizer inlet is configured to receive oxidizer in a liquid or gas phase.

6. A torch igniter according to claim 2, wherein the primary fuel inlet is configured to receive fuel in a liquid or gas phase.

7. A torch igniter, comprising:

a body including a first end and a second end;

the body including an oxidizer inlet disposed at the first end thereof;

the oxidizer inlet configured to facilitate oxidizer flow through the body;

the body including a primary fuel inlet configured to distribute fuel to a plurality of fuel inlet passages configured to distribute fuel in a direction tangential to the oxidizer flow through the body to create a swirling fuel-oxidizer mixture;

a sparking element mounted on the body to produce a spark in the path of the swirling fuel-oxidizer mixture to ignite the mixture; and

wherein the body is configured to emit a torch flame from the second end thereof when the fuel-oxidizer mixture is ignited.

8. A torch igniter according to claim 7, wherein the oxidizer inlet is configured to receive oxidizer comprising oxygen.

9. A torch igniter according to claim 8, wherein the primary fuel inlet is configured to receive fuel comprising methane.

10. A torch igniter according to claim 7, wherein the oxidizer inlet is configured to receive oxidizer in a liquid or gas phase.

11. A torch igniter according to claim 7, wherein the primary fuel inlet is configured to receive fuel in a liquid or gas phase.

12. A method for igniting a torch flame, comprising:

inputting an oxidizer into a first end of an igniter to create an oxidizer flow through the igniter;

inputting fuel into a plurality of fuel inlet passages on the igniter configured to distribute the fuel in a tangential direction to the oxidizer flow to create a swirling fuel-oxidizer mixture; and

igniting the swirling fuel-oxidizer mixture with a sparking element mounted on the igniter to produce a torch flame emission from a second end of the igniter.

SWIRL TORCH IGNITER

ABSTRACT OF THE DISCLOSURE

Swirl torch igniters configured for oxidizer and fuel flow through the igniter body to create an internal swirling fuel-oxidizer mixture to be ignited by a sparking element. Methods for igniting a torch flame.

Vita

Luis Sanchez earned his Bachelor of Engineering degree in Mechanical Engineering from The University of Texas at El Paso in 2009. In 2012 he received his Master of Science in Mechanical Engineering from The University of Texas at El Paso. In 2012 he joined the doctoral program in Energy Science and Engineering to later transfer in 2016 to the doctoral program in Mechanical Engineering at The University of Texas at El Paso.

Dr. Sanchez was the recipient of the Graduate Assistance in Areas of National Need (GAANN) fellowship. As a GAANN recipient, Luis Sanchez was an undergraduate lab instructor in the Department of Mechanical Engineering. While pursuing his doctoral degree, Luis Sanchez worked as a research assistant at the NASA Center for Space Exploration and Technology Research at the Department of Mechanical Engineering. He interned at NASA White Sands Test Facility in 2010 and at NASA Johnson Space Center in 2012.

Dr. Sanchez's dissertation entitled. "Development and Testing of Oxygen/Methane Torch Igniter Technologies for Propulsion Systems", was supervised by Dr. Ahsan Choudhuri. Dr. Sanchez has accepted a position as a Propulsion Test Engineer with the private space company Blue Origin.

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