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Development Of A High Pressure Optically Accessible Combustor And Shear Co Axial Injector

Christopher David Navarro
University of Texas at El Paso, cdnavarro@miners.utep.edu

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CHRISTOPHER DAVID NAVARRO
Department of Mechanical Engineering

APPROVED:

Ahsan Choudhuri Ph.D., Chair

Norman Love Ph.D.

Eric MacDonald Ph.D.

Benjamin C. Flores, Ph.D.
Interim Dean of the Graduate School

Dedication

I would like to dedicate this work to my parents, Samuel and Maria, for without their inspiration and support I would not be the man I am today.

DEVELOPMENT OF A HIGH PRESSURE OPTICALLY ACCESSIBLE COMBUSTOR AND SHEAR CO AXIAL INJECTOR

by

CHRISTOPHER DAVID NAVARRO, B.S.M.E.

THESIS

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Abstract

A trend in the last decade in the field of propulsion and rocketry is leaning toward the use of the combination of Liquid Methane and Liquid Oxygen as propellant fuels. This is in contrast with the earlier trend of using Hydrogen systems and toxic hypergolic systems. The Multi-Purpose Optically Accessible Combustor (MOAC) and Shear Coaxial injectors have been developed to investigate injector design and combustion research involving Oxygen and Methane propellants. The MOAC is intended for the experimentation and research of combustion of liquid and gaseous propellants. Development of the MOAC system and versatility to use a number of injector styles is discussed. Development of Shear Coaxial injectors common with Oxygen and Methane systems and geometric influences are discussed as well. Instrumentation critical to obtaining test data for analysis of the thermodynamic properties of both the propellants and the combustion chamber are detailed. Optical instrumentation associated with the MOAC system is thoroughly described to identify the characteristics of the spray and combustion dynamics. Finally, testing parameters will be explained as well as a summary of initial test results concluded from initial testing.

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Chapter 1: Introduction

In recent years, a push for hydrocarbon fueled engines for use in rocket propulsion systems has begun in aerospace research. Several reasons exist for this new push for hydrocarbons and of particular interest is the use of methane as a fuel. Hydrocarbons such as Methane and Kerosene are safer to handle as well as less corrosive than hypergolic fuels leading to longer engine life. Methane is the leading hydrocarbon for a fuel based on its high energy density, cryogenic storage capacity, and cooling properties. Methane is also considered a green propellant, which does not have the toxicity of hypergolic propellant such as Nitrogen Tetroxide and Unsymmetrical Dimethylhydrazine (UDMH).

In situ resource utilization has discovered Methane can be extracted from lunar regolith and thus can be used for fueling spacecraft from the moon. This is advantageous, as spacecraft departing Earth do not require extra mass for propellant required beyond launch necessities.

The majority of spacecraft propulsion research and development for bi-propellant engines to date has been on hydrogen fuels and hypergolic fuel combinations. Thus the majority of engine designs that use hydrocarbon fuels are based on hydrogen optimized conditions. This lack of development on methane is the driving factor for research into methane and oxygen propellant based engine design.

Figure 1: XCOR's 7,500 lbf XR-5M15 Engine (left), NASA Project Morpheus (Right); Both engines use oxygen/methane as a propellant combination.

1.1 Center for Space Exploration Technology And Research

The Center for Space Exploration Technology Research (cSETR), established under the direction of Dr. Ahsan Choudhuri, promotes the research and education in propulsion and energy engineering. The cSETR conducts a wide range of research topics such as green propulsion, in-situ resource utilizations, structures, clean power generation, carbon monoxide sequestration, etc. As a University Research Center (URC) for the National Aeronautics and Space Administration (NASA), the cSETR performs fundamental research on ignition, heat transfer characteristics and injector dynamics for LOX/Hydrocarbon engines; focusing on LOX/Methane propellants due to the potential application on the lunar ascent engine (NASA Exploration Systems Architecture Study, 2005) and Mars in-situ resource utilization.

1.2 Project Purpose and Objectives

The bi-propellant rocket engine is composed of different components that seem elegantly simple in operation but in fact have significant effort put into the design. Of particular interest is the design of the injector which injects the oxidizer and fuel chemical propellants to feed into the combustion chamber. The injector has a large influence into the performance of the engine and in fact, poorly designed injectors may cause combustion instabilities which may lead to degradation in performance or damage to the engine.

As stated above, research and development of methane as a fuel for rocket engines is lacking. The purpose of this project is to create a platform to investigate the dynamics of injector geometries on methane and oxygen combustion as related to the combustion process required for the compressible flow fluid mechanics that dictate rocket engine characteristics.

Injector performance has a strong effect on the combustion dynamics occurring within the combustion chamber of a bipropellant rocket engine. Improper design of the engine injector can lead to engines that are larger than required, leading to unnecessary system mass and are susceptible to combustion instabilities while operating. This project will describe the development of system hardware to investigate the effects that geometries of a shear co-axial injector will have on break up lengths of the liquid oxygen fluid steam as it is injected into the combustion chamber. Instrumentation and optical techniques are presented that will assist in this physics investigation.

Chapter 2: Combustor and Injector Hardware

Experimentation for evaluating the injector parameters uses hardware designed for optically accessing the fluid flow and flame characteristics. The several injectors will use the hardware established at cSETR for this project and additional investigations related to propulsion. The following sections describe the hardware to be used in the current investigation.

2.1 The Multi-Purpose Optically Accessible Combustor

2.1.1 MOAC Description

All combustion and injector analysis will be conducted using the MOAC system hardware. The MOAC system is designed from the ground up to be a windowed combustion chamber capable of withstanding the pressures and temperatures of a simulated rocket engine. The MOAC system is composed of a stainless steel 304 body and components and four fused quartz windows. The system is designed to be modular and contains removable components that allow for tailoring of the physical parameters required for reaching stagnation requirements in compressible fluids as well as various injector geometries. To accomplish this, the combustor has removable and replaceable sections for the rocket throat and for attaching the injector to the system. These modular sections provide quick test parameter turnaround time and allow for different tests limited only by allowing the combustor to cool down to handling temperatures. The modular sections also provide the added benefit of being installed on the inner walls of the combustor thus allowing for self-sealing capability provided by the internal pressure pressing against the components when the combustor is operating. The combustor has four quartz windows allowing for access for optical instrumentation. Two windows encompass the entire combustion area. The other two windows span the length of the combustion area but are 3 centimeters across to allow for a laser sheet to be inserted into the chamber from PIV systems. All windows are 3.5 cm in thickness due to pressure and temperature requirements. The combustor has an internal

combustion volume of 80x80x150mm and can withstand pressures up to 20 bar and temperatures of 3000 k abet for short time interval tests (20 to 30 seconds). Combustor wall thicknesses of 4.2 cm allow for these pressure and temperature conditions to be achieved for this time frame. Current throat section is a 6mm diameter circle. Analytical and finite element modeling are used to provide these dimensions for the combustor and its windows to maximize performance without over designing and encumbering the combustor. The chamber is designed to be able to be assembled and cleaned prior to each occurrence of a test session. Mounting brackets are installed on each window to ensure that the proper retention force is applied to the quartz windows. Side windows are torqued to 10 n-m for each of 20 m5 bolts that constrain the bracket while smaller window brackets are torqued to 2.15 n-m for each of its 10 m3 bolts. Bolts for all components of the system are SS 316 hex head bolts. Sealing the chamber is custom cutout gasket material composed of alumina silica placed between the components as well as high temperature RTV silicone. High pressure sensor ports are built in the MOAC allowing for both temperature and pressure measurements to be taken. Temperature measurement is achieved via a compression fitted thermocouple, 1/8th inch in diameter that is used to probe the chamber. Two of these temperature ports exist at different points along the chamber, 1.5 inches and 4.5 inches away from the injector face. The pressure transducer, rated for 0-500 psig, installed in the system is attached to a ¼ inch NPT port that is equipped with a pressure shock snubber to ensure that the ignition pressure does not damage the sensor. A similar NPT port is used for attachment of the pilot flame igniter in the system.

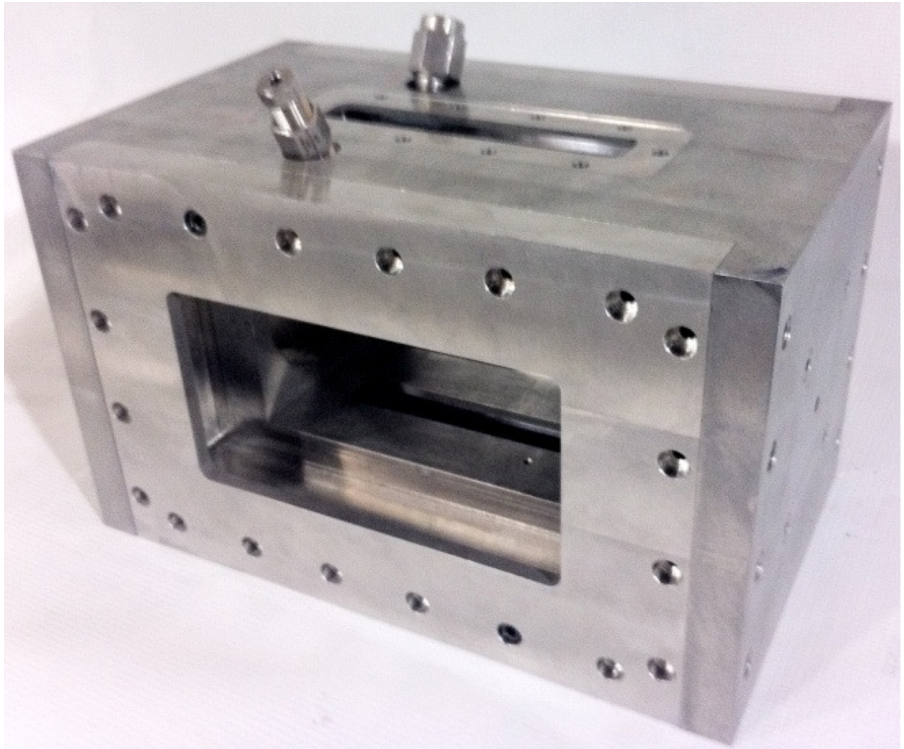

Figure 2: Fully Assembled MOAC system with attached instrumentation adaptors.

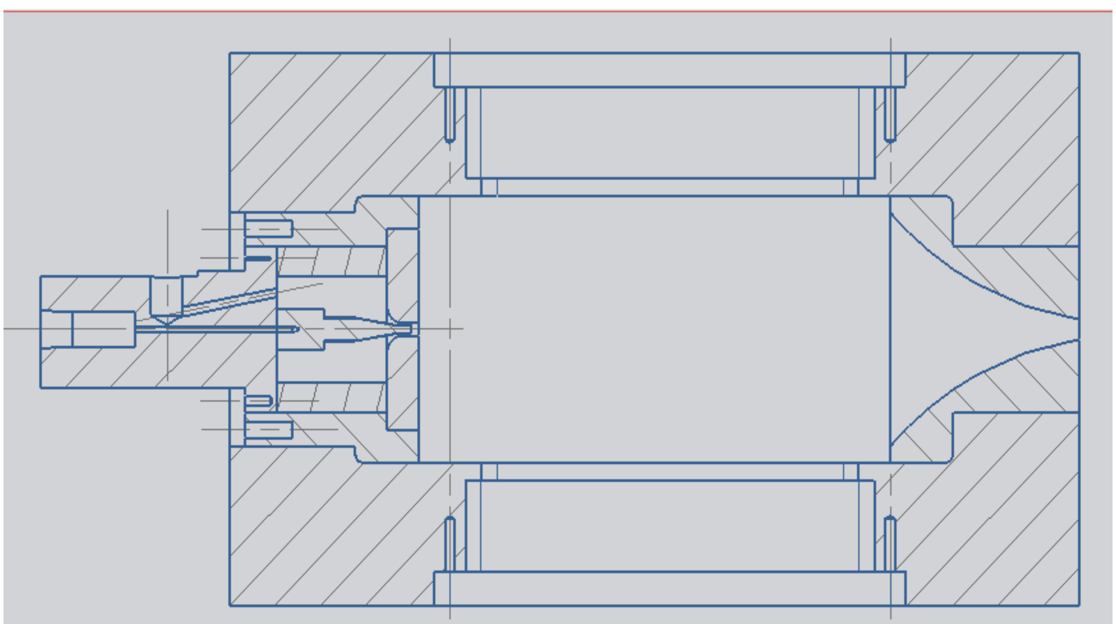

Figure 3: MOAC Chamber Cut away. Coaxial injector shown installed

2.1.2 MOAC Development

The MOAC was developed from the ground up to withstand the environment of a bi-propellant rocket engine. Analytical as well as Finite Element Analysis was used in the development of the chamber to handle the anticipated combustor conditions. FEA models gave supporting results in terms of anticipated stresses as well as thermal and stress displacements.

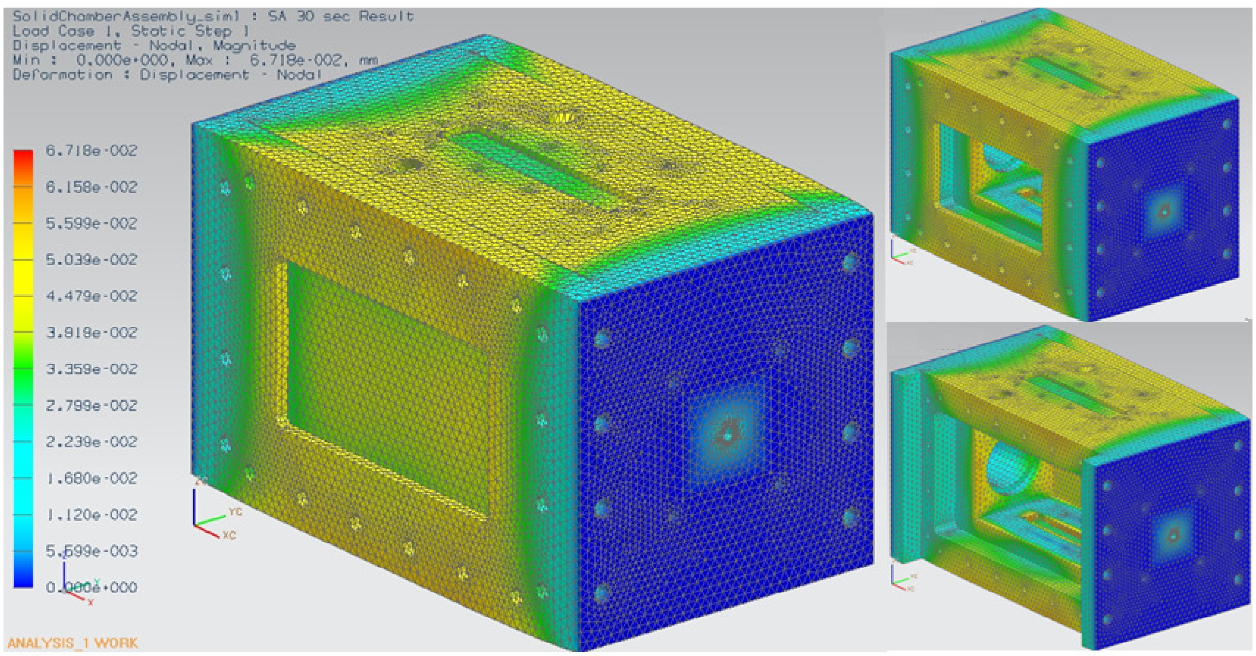

Figure 4: FEA Displacement simulation.

2.2 MOAC Modular Components

For the MOAC, integration of the various components required all together combines to produce a functional combustor. The MOAC is composed of the following components; the main combustor body, the igniter adapter, converging section, quartz windows, and window brackets. Each of these components required special attention to the design of the component to ensure functionality as well as full integration with the body and other components. The quartz windows serve as two complete walls

for the combustion chamber, while the converging section and injector/ injector mounting section will form the face and exit of the chamber. This design required special shapes for the components to allow for complete combustor assembly.

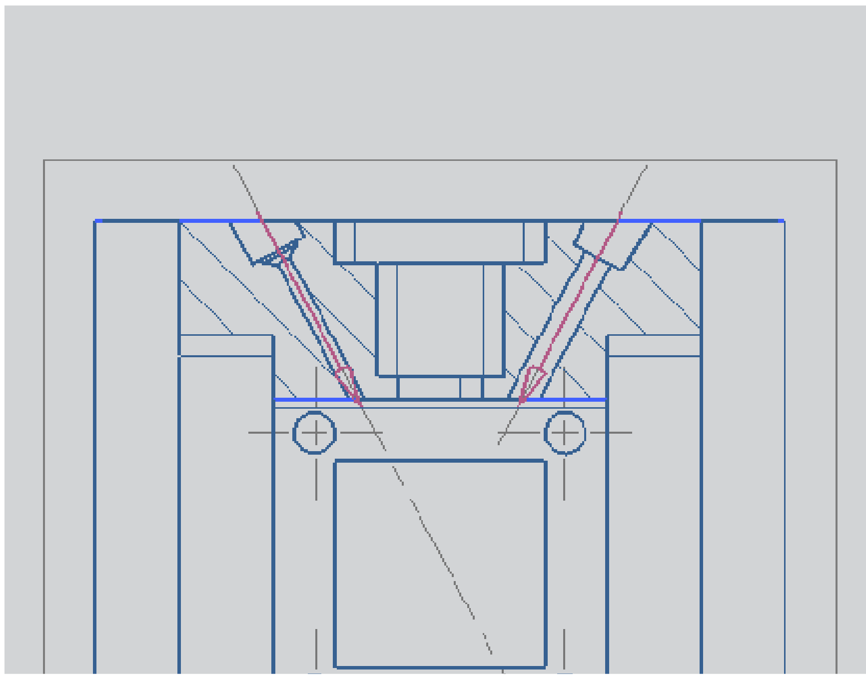

Figure 5: Cross sectional view of insturmentaional ports.

2.2.1 Windows

The driving factor of design for the chamber is the requirement for optical accessibility. The best design of a window in order to provide for optical access is a flat window. This allows for minimal change in the image from refraction of the windows. This window is also favorable because it is cheaper compared to quartz windows with curved surfaces. The window material chosen is fused quartz for it properties toward heat transfer and pressure. Sapphire windows may be substituted in place of

quartz due to its increased strength but currently is too expensive to integrate into the combustor and would require another bracket design compared to quartz. Because of the requirement of flat faced windows and their placement in the chamber, the chamber geometry must necessarily be square. Square geometry does in fact allow for a slightly easier design and manufacturing process.

2.2.2 Brackets

The square windows led to a square retainer bracket design as well. The brackets were installed around the window to help encompass the entire perimeter of the window. The brackets allow space for the gasket assembly to fit into the window and to the body itself. The tolerances on the bracket to the window and body can be a bit relaxed as the bracket has to fit both the window and the combustor body. The manufacturing of the windows is completed by use of a band saw and can have millimeter differences in length side to side. The brackets are a millimeter larger in both directions as to allow for this uncertainty in window size. The windows may be sanded down as well to allow for clearance to the body and bracket thus creating a more ideal fit if the window state from the original manufacturer is undesirable.

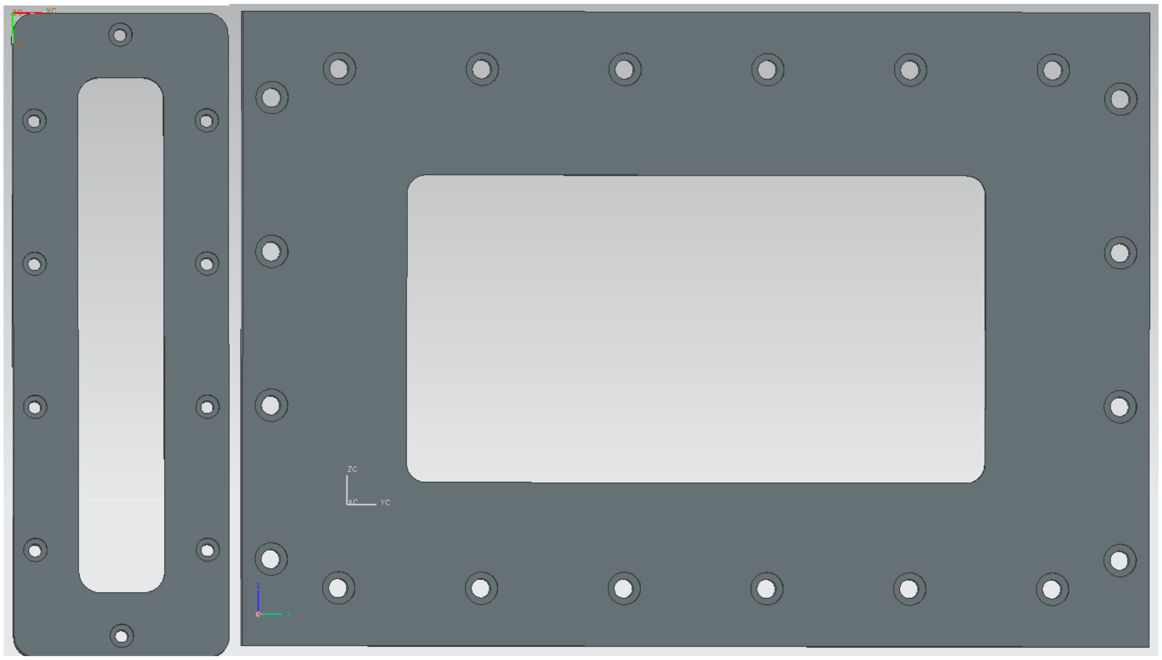

Figure 6: Window bracket designs for the upper windows (Left) and Main optical windows (Right).

2.2.3 Injector and Exit Modules

The combustor is designed to be scalable to different thrust and pressure values. To accomplish this, variable geometries that define the throat and injector need to be able to be included in the combustor. Modular sections for both the injector and converging sections are needed to swap out components for the required geometry to coincide with the preferred pressures. The necessity of modules requires that the geometries be manufactured in such a way that the module components can be easily installed and secured into the main chamber body. The modules are also mandated to be self-sealing from the inside of the chamber which helps mitigate leaks from the chamber but complicates the design of each module.

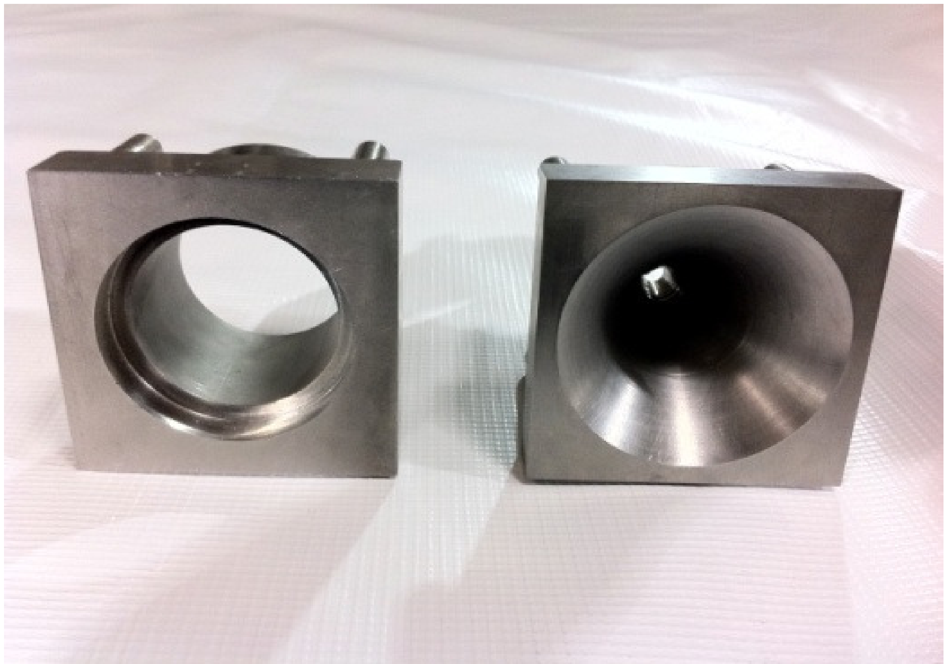

Figure 7: Completed MOAC Modules, Injector adaptor (left) and converging section (Right).

The injector adaptor module is built to house module injectors to the MOAC for various testing parameters. The Injector adaptor module allows for an injector to install flush to the face of the module which serves as the combustor wall. This is accomplished with a recessed fitting that allows the injector to seat tightly in the adaptor housing. The injector is designed from the beginning to be circular in geometry so the adaptor housing is circular and centered to the middle of the combustion chamber. The adaptor has screw wells installed with M5 threading to allow for retention of the injector once in the chamber. The retention is assisted with a retainer piece that serves as a constraining link for the combustor and the injector. The injector retainer is constrained by four cylindrical pillars that serve to be screw wells for M5 bolts as well. These pillars extend from the back side of the injector adaptor and through the back side of the combustor body. The bolts are then installed with washers to constrain the adaptor to the body. A similar geometry is used with the converging section to secure it to the body.

Figure 8: Injector and injector adaptor module mounting surface.

The modular converging section is built similarly to the injector adaptor to allow for common tooling for manufacturing, installation and retention purposes. The converging section houses no other additional components and is one complete part. The section used a parabolic geometry to curve into a predetermined throat area for achieving stagnation flow required in rocketry. The geometry itself is convex rather than concave only for the purpose of clearance to the body of the chamber. A concave geometry would require additional material mass to the section and would take longer to manufacture.

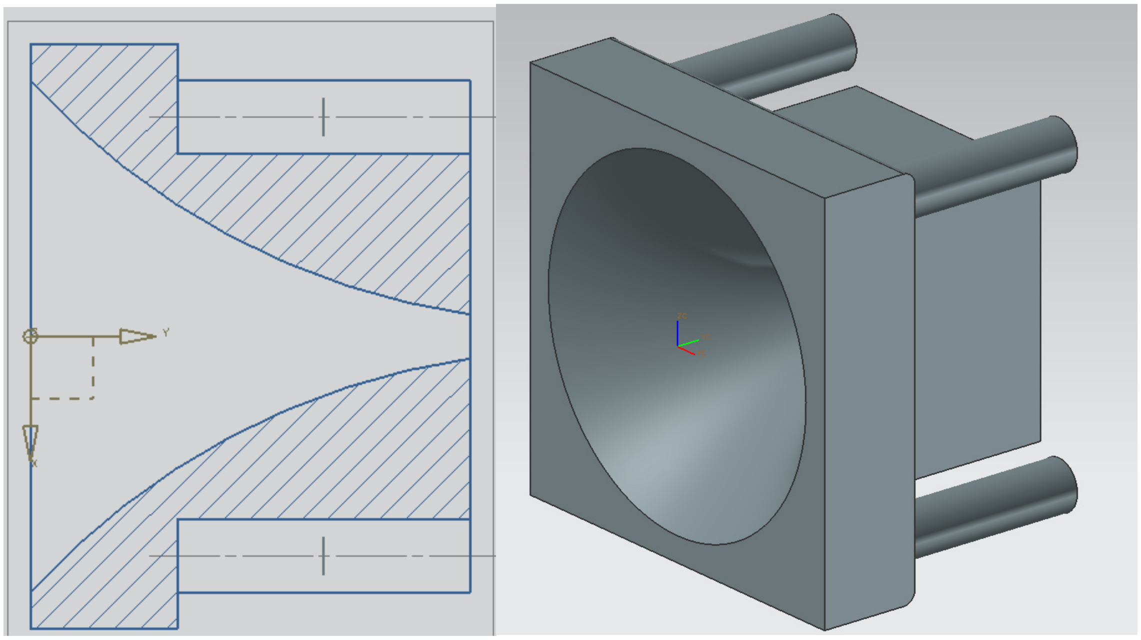

Figure 9: Converging section module and cut away.

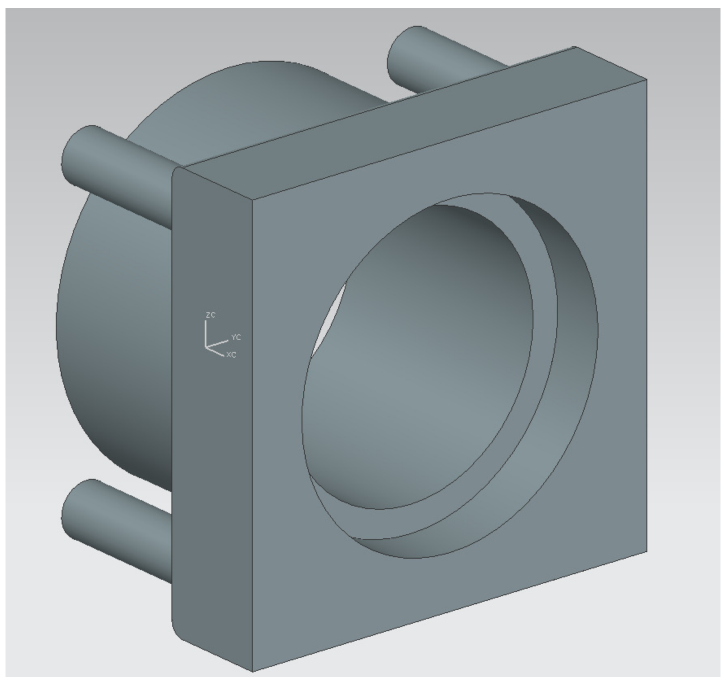

Figure 10: Injector adaptor module.

2.3 Cryogenic Feed System

2.3.1 Delivery System

The MOAC system is integrated with the cryogenic feed system developed at cSETR for providing liquid oxygen and liquid methane to various propulsion test articles. The cryogenic system is

a pressure fed system that can deliver various flow rates of cryogenics to the test article and contains flow metering, pressure, and temperature diagnostic capabilities. The system is controlled remotely from an adjacent control room and is monitored via closed circuit video feed as well as exterior windows to the test bunker from where all tests will take place in. The cryogenic delivery system is insulated via Cryogel™ insulating material and is composed of stainless steel materials or other materials compatible for liquid oxygen service. In addition, the cryogenic system is pre-chilled via liquid nitrogen and is purged using gaseous nitrogen immediately prior to testing.

The feed system is equipped with both cryogenic flow meters and gas flow meters to analyze flow data entering the MOAC chamber. The Cryogenic meter is a positive displacement type flow meter while the gas flow meter is a turbine style. The pressure sensors are cryogenic thin film transducers while temperature data is acquired by both a cryogenic diode and an E type thermocouple. The diode serves the purpose of verifying cooling line conditioning of the transfer system for cryogenic delivery and the E type thermocouple serves to allow for temperature measurement of the propellant fluid as it is delivered to the test article.

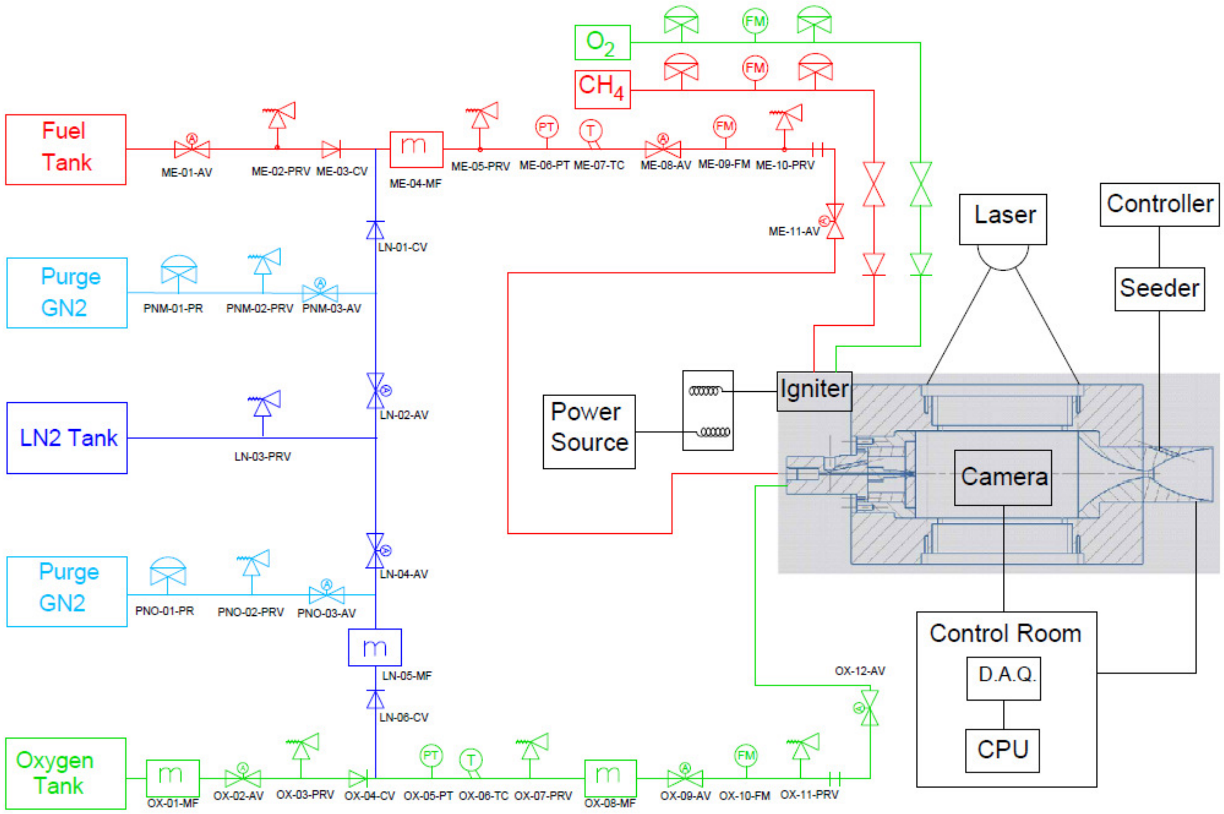

Figure 11: Layout schematic of MOAC System

Figure 12: Propellant Storage inside test bunker.

2.3.2 MOAC Ignition

The MOAC is designed to be ignited by several different methods. These methods include spark ignition from the injector, laser ignition, and pilot flame ignition. For this case, the ignition of liquid oxygen and methane fuel spray is ignited by the pilot flame igniter attached to the MOAC chamber body. A FNPT port on the body allows for a pressure transducer or pilot flame igniter to be installed. The igniter itself is developed from previous work conducted at cSETR to develop micro thrusters. The igniter design is a methane swirl injected design that is easily manufactured in house at the university. It is comprised of a methane fuel manifold and an oxygen manifold in line together that fires the flame into the chamber. The ignition process of the igniter is done via an internal spark ignition system featuring two electrodes inserted into the igniter combustion chamber. The igniter can be mounted at two different points along the MOAC combustion chamber allowing for further flexibility in the investigation of ignition of the main propellant sprays. The igniter currently operates at a mixture ratio of approximately 4 and is progressing towards a leaner mixture ratio to minimize soot build up in the chamber allowing for longer total firing sessions before flame dramatics can no longer be analyzed due to poor visibility.

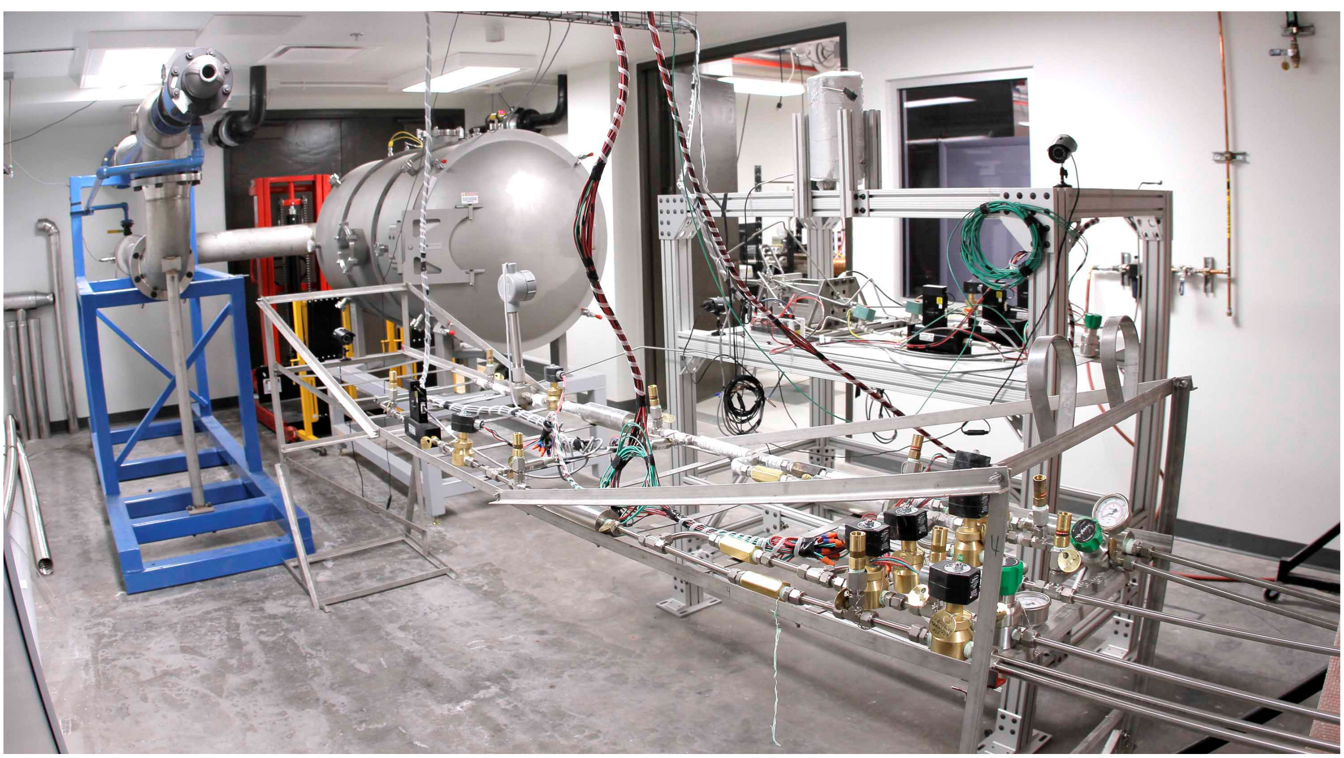

Figure 13: Cryogenic Delivery system installed in cSETR Bunker.

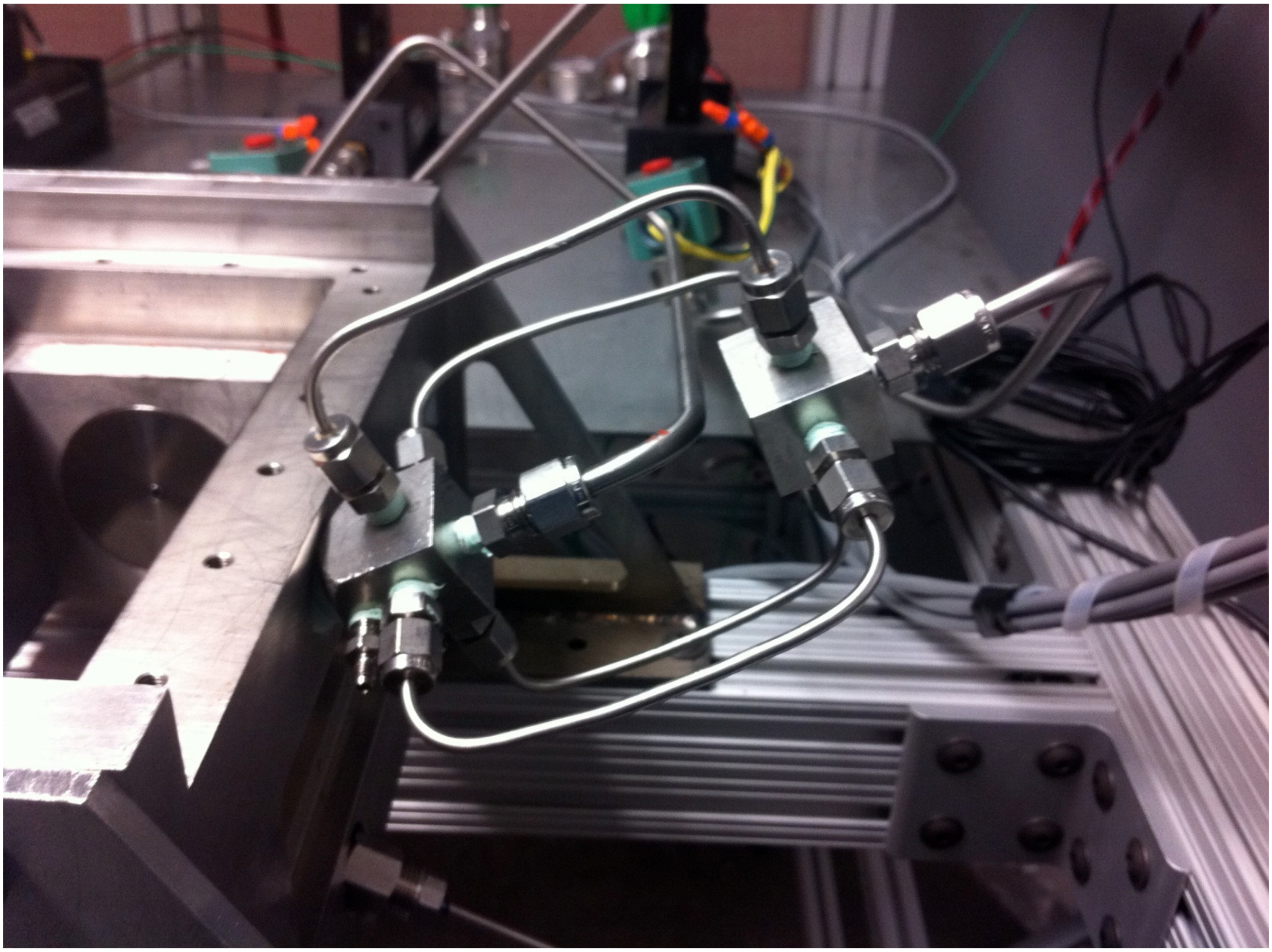

Figure 14: Pilot Flame swirl igniter shown installed on MOAC

2.4 Imbedded instrumentation

The MOAC is designed to be an optical accessible tool to investigate flame and combustion dynamics. In addition to the optical access, the MOAC has intrusive sensor ports built into the combustor body to acquire pressure and temperature data for thermodynamic analysis. These ports are angled in at 63 degrees from the vertical to allow for temperature measurements close to the center of the combustor volume. The 63 degree angle also allows for ignition from the pilot flame to intersect the centered propellant stream. Angling also allows for the smaller quartz window to be placed in the center of the combustor face. Dual thermocouple ports are built for 1/8 inch closed sheathed thermocouple styles.

The thermocouples are fitted to the system via Hi-Pressure thermocouple fittings using a compression sealing system to the thermocouple sheath. The section of the sheath that is exposed to the combustion chamber may be coated in silica for thermocouple variations that oxidize when exposed to oxygen. The silica coating may affect the response time for temperature measurement during very short duration tests. These types are needed as general K type thermocouples do not reach the temperature range that is expected for methane and oxygen flames. For testing purposes N type thermocouples are used for temporary measurements of the firing process. N type thermocouples are similar in range to K type thermocouples but are generally more stable at higher temperatures then their K type counterparts. The MOAC is also coupled with pressure transducer ports at two different lengths in the combustion chamber. The pressure transducers are fitted to the chamber body via NPT fittings and these fittings can be used for ignition ports as well. The pressure transducers are fitted into pressure snubbers which are then fitted onto the chamber body. These snubbers serve to protect the transducers in the event of a quick high pressure spike that could damage the sensor. Currently, general purpose pressure transducers are being used for pressure measurements but higher quality dynamic measurements are to be done with dynamic pressure transducers attached to the combustor. The dynamic pressure transducer will not require a pressure snubber to protect from a pressure spike.

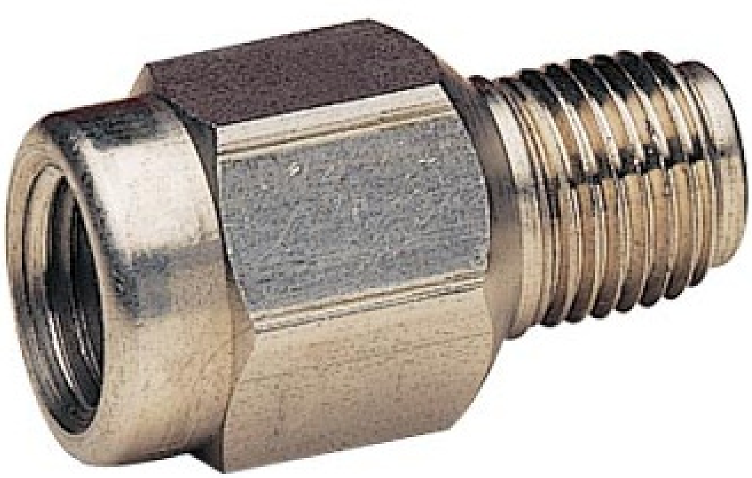

Figure 15: Pressure Snubber

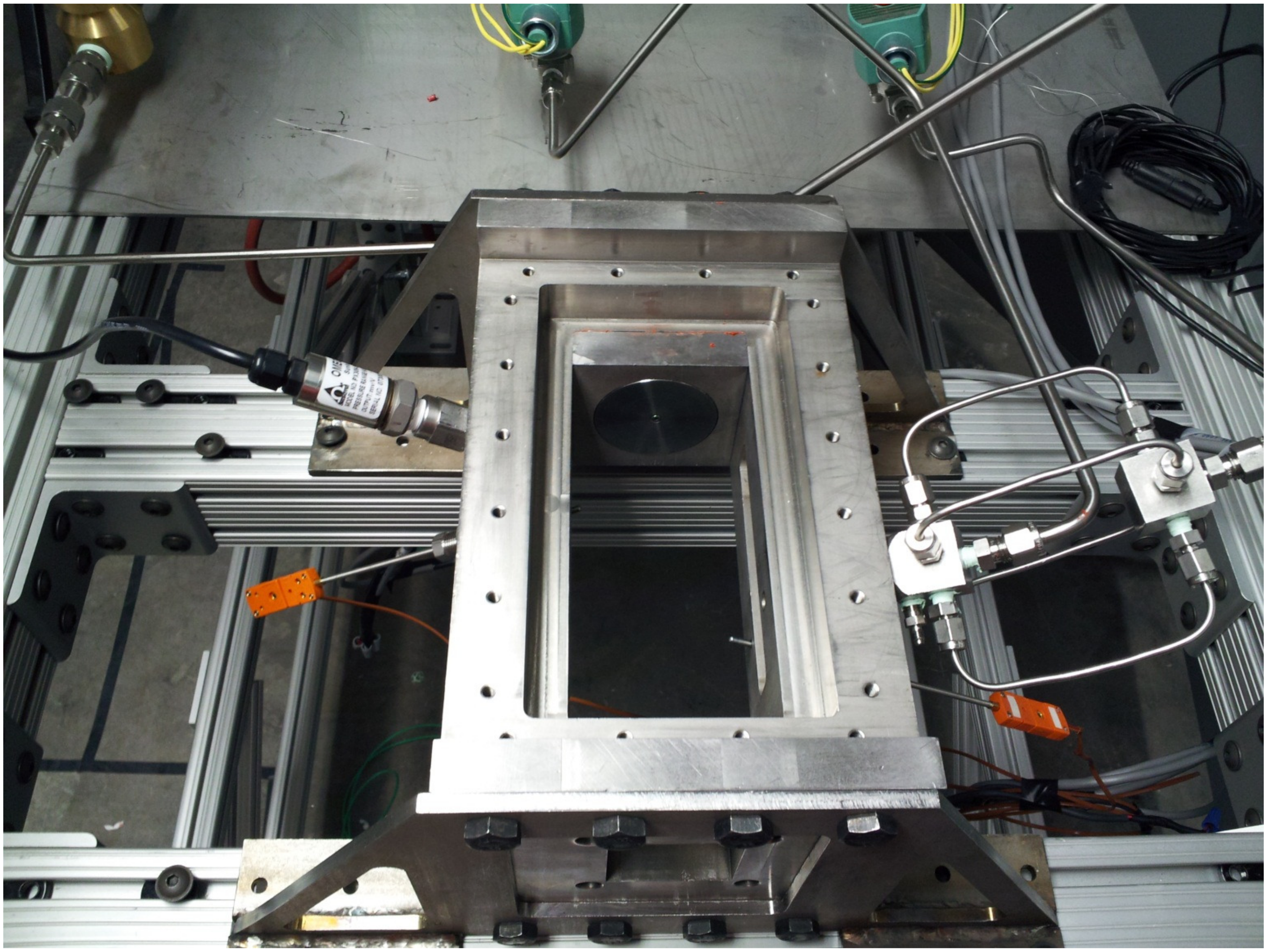

Figure 16: Instrumentation installed on the MOAC Chamber; Pressure Transducer and N Type thermocouples shown

2.5 Coaxial injector

2.5.1 Injector Development

For the investigation of shear co-axial sprays, a co-axial injector is designed to facilitate the experiment. There are a number of parameters that the injector has to be capable of meeting. The injector has to be compatible with liquid oxygen as well as both methane and hydrogen fuels. This compatibility requirement leads to the selection of stainless steel as the body material. Stainless steel benefits the injector as the expansion and contraction due to firing the engine or to pre-test chilling of

liquid nitrogen has the same coefficient of thermal expansion. Compatibility with the geometry of the MOAC led to the unique design of the injector. The MOAC requires modular components for the injector to be installed and inserted from inside the chamber itself. This constrains the actual size of the injector to be inserted into the combustor to the same maximum length and width as the combustor area. The decision was made to make the injector body itself one piece and free of additional bolts or constraining devices to keep the manifolds in place. This decision dictates a design that contains manifolds and feed ports for both the liquid oxygen oxidizer and the liquid/ gaseous methane fuel. The ports themselves are quarter inch FNPT threading that connect to the tubing of the feed system. Female treading is not ideal for this application but due to the geometry constraints, the threads were necessary for operation. However, with the proper use of Teflon sealing tape, this issue is mitigated.

The injector has the injection ports centered coaxially on the chamber face into the combustor. The injection ports consist of a liquid oxygen orifice which is surrounded by the methane injection port. The liquid oxygen is delivered to the injector face from its feed port in the rear of the port in a straight line direction. The liquid oxygen pathway is designed to ensure that there is no surface that any particle, which in the unlikely event makes its way in the liquid oxygen flow, does impact and cause an ignition point inside the injector. The methane fuel path differs from the oxygen path as the feed port is located on the side of the injector perpendicular to the lox path. The injector then routes the methane into the fuel manifold chamber which then acts like a plenum for the fluid flow. The manifold chamber allows the methane injection port to spray methane evenly around the liquid oxygen port and maintain the pressure and velocity across the axis. The methane fuel manifold is situated around the liquid oxygen delivery post which allows for both of the propellants to be injected into the chamber axially. The oxygen post, fuel manifold, and the injector body are designed to be manufactured individually. These

parts are then attached to the injector main body by welds or brazing techniques to complete one complete injector.

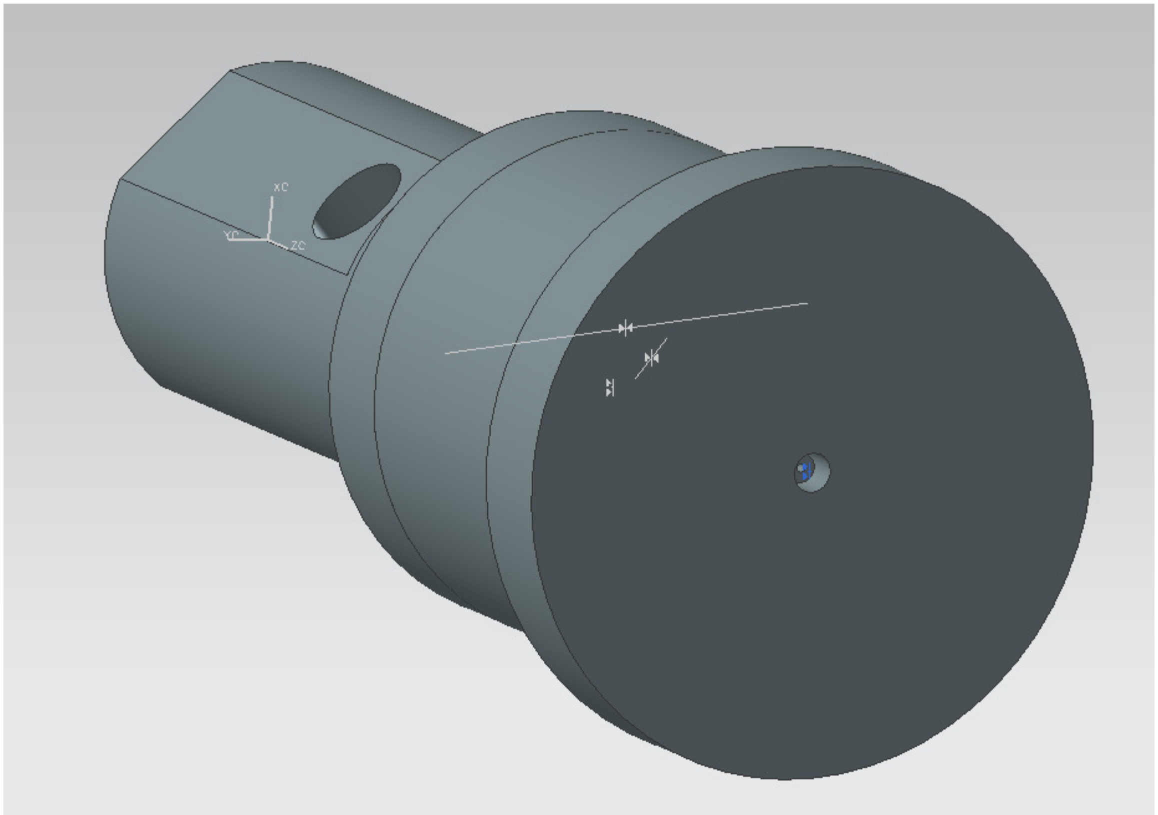

Figure 17: Coaxial Injector

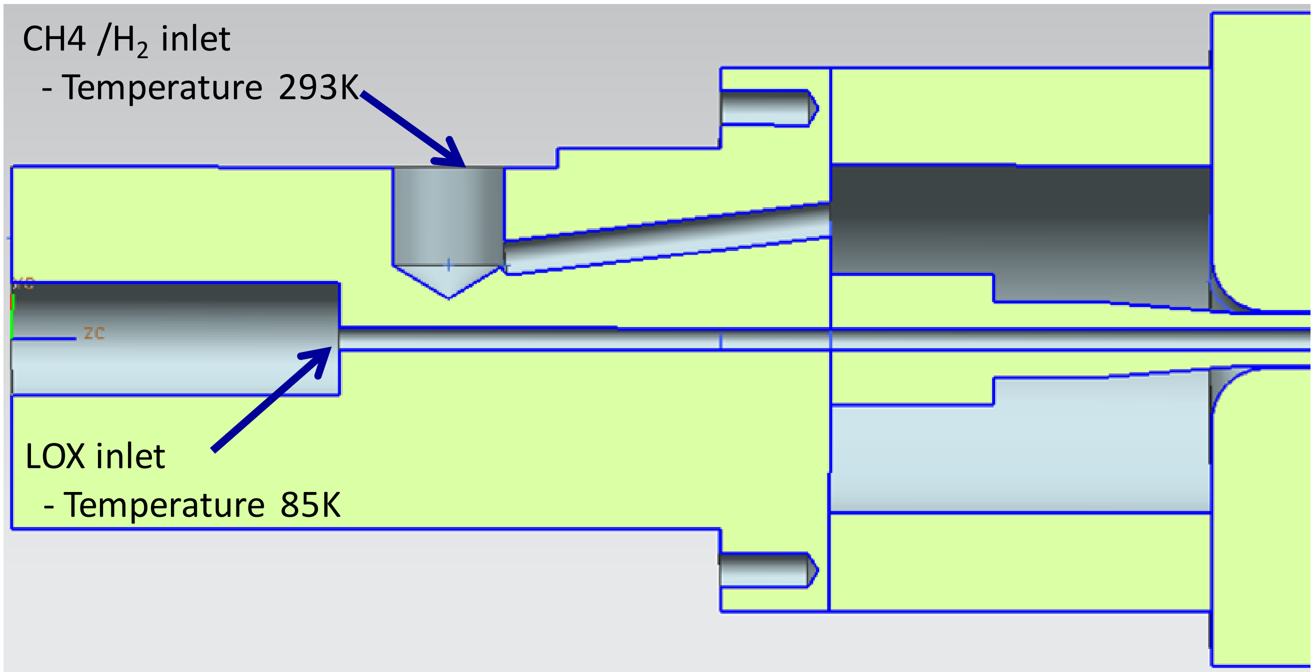

Figure 18: Coaxial injector cut way

2.5.2 Injector Element Scalability and Sizing

The injector is designed for scalability as well. A 50 mm diameter is allowed for any style or shape of injector that can be manufactured to be installed in the system. The liquid oxygen post and fuel manifolds can be designed in such a way that the injector shape and style is consistent for each injector but the area of the propellant paths can be larger or smaller depending on what flow rates are needed for each injector style. The rear of the injector houses the feed ports for the propellants. This design shape allows for additional flow capability if necessary by allowing a larger liquid oxygen fitting and / or an additional fuel inlet. The injection ports are developed from methods detailed by Huzel and Huang. They present equations to determine the area of injection and the diameter of ports if more than one port is deemed necessary. The equations are stated as

$$A_{Inj} = \dot{W}\sqrt{\frac{2.238K}{\rho \Delta P}} \tag{1}$$

$$d_{orifice} = \left(\frac{3.627K\dot{W}^2}{\rho\Delta PN^2}\right)^{0.25} \quad (2)$$

The equations offer a sizing direction onto the recommended flow velocities into the chamber These equations take into consideration a twenty percent pressure drop across the injector from the feed system. The term K refers to a fluid flow exit coefficient ranging from values of 1.2 for radiused orifices to 1.7 for sharp edged orifices. The Coaxial injector uses a K Value of 1.5 For the injectors tested and under the conditions desired, the flow velocities of gaseous methane are in order of magnitude of larger than liquid oxygen flow which is normal and expected for typical shear coaxial injectors.

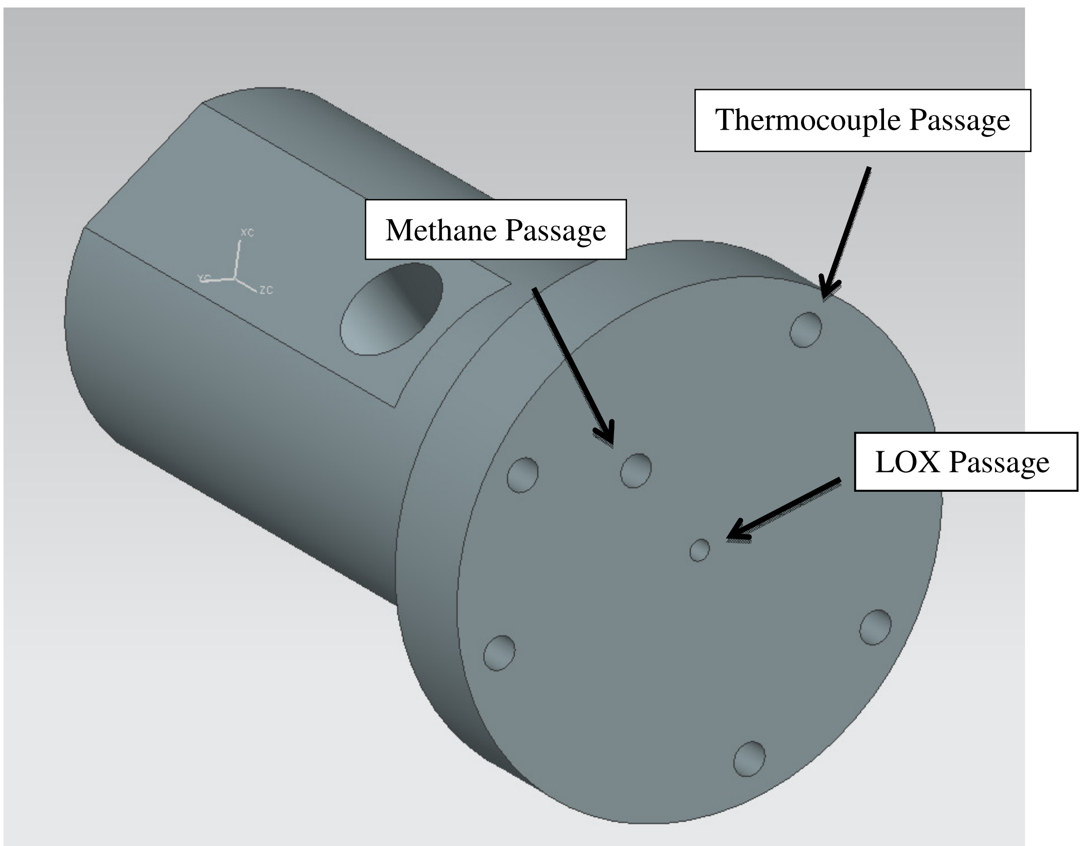

Figure 19: Injector base

2.5.3 Injector Advantages

The injector design presents different capabilities that are advantageous to future investigations and testing. The injector style can provide enough propellant flow required for the entire thrust and pressure range capable by the MOAC system. Adjustment of the injection orifice size can be tailored to each thrust range required for testing parameter. The design of the fuel manifold and liquid oxygen delivery post allows for manipulation of the post length and diameter to manipulate the atomization efficiency. The injector is also fitted with several access ports to determine the heat soak into the injector. The fuel manifold contains 5 separate ports for 1/8 inch thermocouples to acquire temperature data from different lengths down the injector. The temperature ports begin 5 mm away from the face of the injector to the combustor and the port depth continues for 5mm each port away from the previous temperature port. The thermocouple probes allow instantaneous feedback of injector thermal conditions and monitor temperature close to brazing areas to minimize any damage to the injector.

The design can be utilized to investigate other injector types. In this project's scope, only shear coaxial injectors are investigated. The integrated LOX post can be machined in different styles to allow for different injection techniques. The other injector types that can be fabricated are impinging doublets and a liquid oxygen swirl coaxial injector type. A shear coaxial injector consisting of multiple ports can also be constructed using the method of modifying the liquid oxygen delivery post. The drawback to these styles of injectors is that manufacturing is more involved and complicated than a simple shear coaxial injector element. In addition to the variability of injector styles, the MOAC injector form allows for larger propellant flow capabilities in the same design. The injector shape allows for an additional port for fuel delivery and for a larger port for oxidizer delivery. For additional fuel the inlet would be manifolded to the two ports from one original feed line. Because of the need for heat soak temperature

measurements and the range of flow rates for designed for this injector, only one port for fuel is used. A duel port fuel injector would block or inhibit the thermocouple to the temperature port.

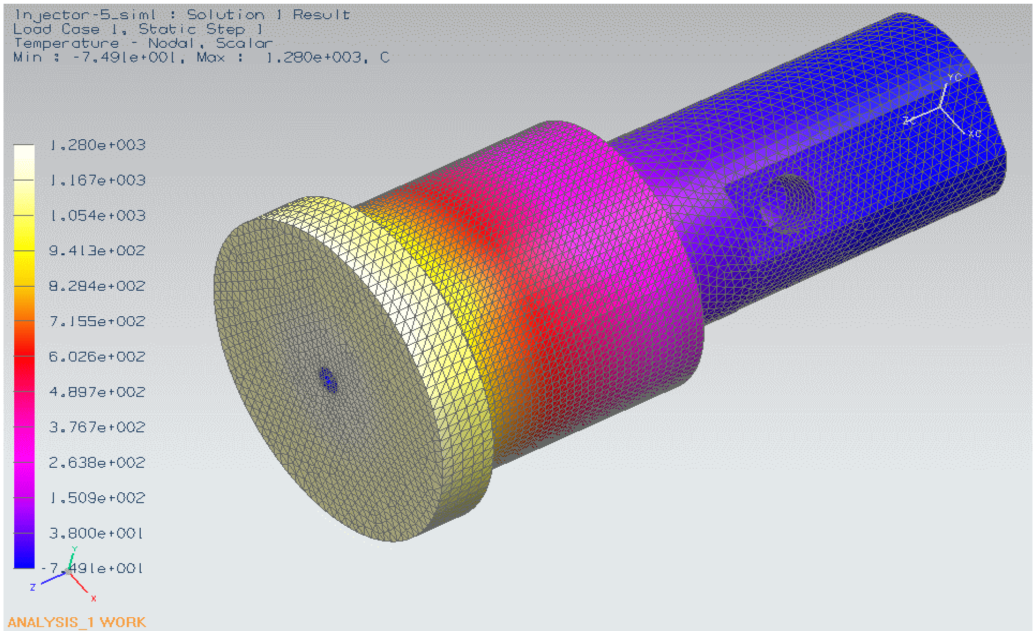

Figure 20: FEA Model to investigate combustion effects on injector and braze integrity.

2.5.4 Injector Manufacture and Assembly

The injector is manufactured in separate components to be brazed together as one piece. The injector base is the most complex geometry but is common in design across most injector styles. The LOX post and fuel manifold are smaller components with simpler geometries but they are used only with the specific intended injector style and performance necessary. The Lox post is brazed on to the injector base and followed by the fuel manifold to encompass the LOX post once its braze is cooled. The braze can be broken and both the LOX post and fuel manifold can be replaced leading to less required machining if different geometries are required for future investigation.

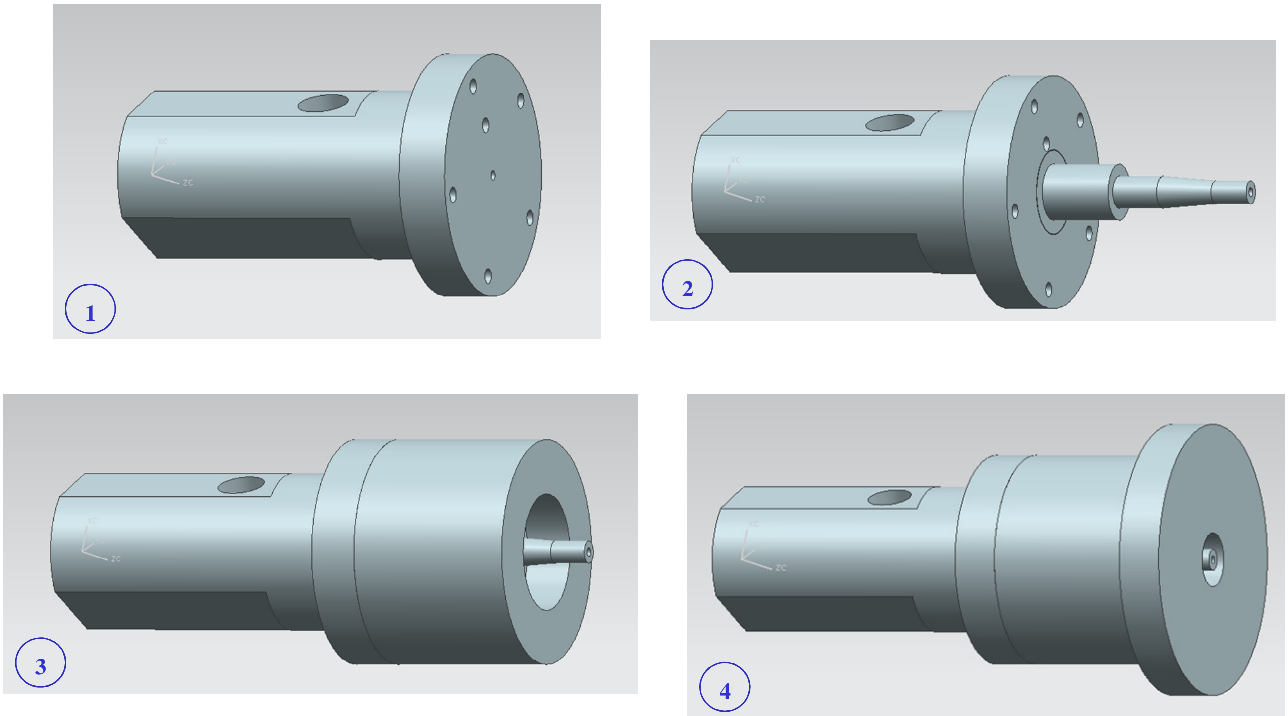

Figure 21: Assembly direction of Injector

2.5.5 Injector Geometry Variations

The injector style for this project accommodates three different injector styles. Each of these individual injectors is a shear coaxial style injector with one port but the difference in each of them is in the length parameters of the liquid oxygen delivery post. The liquid oxygen delivery port differs in three different injectors to study the effects the geometry has on the spray atomization of the propellant fluids. The first parameter of variability in the injectors is the post thickness between the liquid oxygen spray and methane spray. The second parameter for variability is the recessing of the liquid oxygen post in reference to the face of the methane injection orifice. These parameters are shown in Figure 22 below.

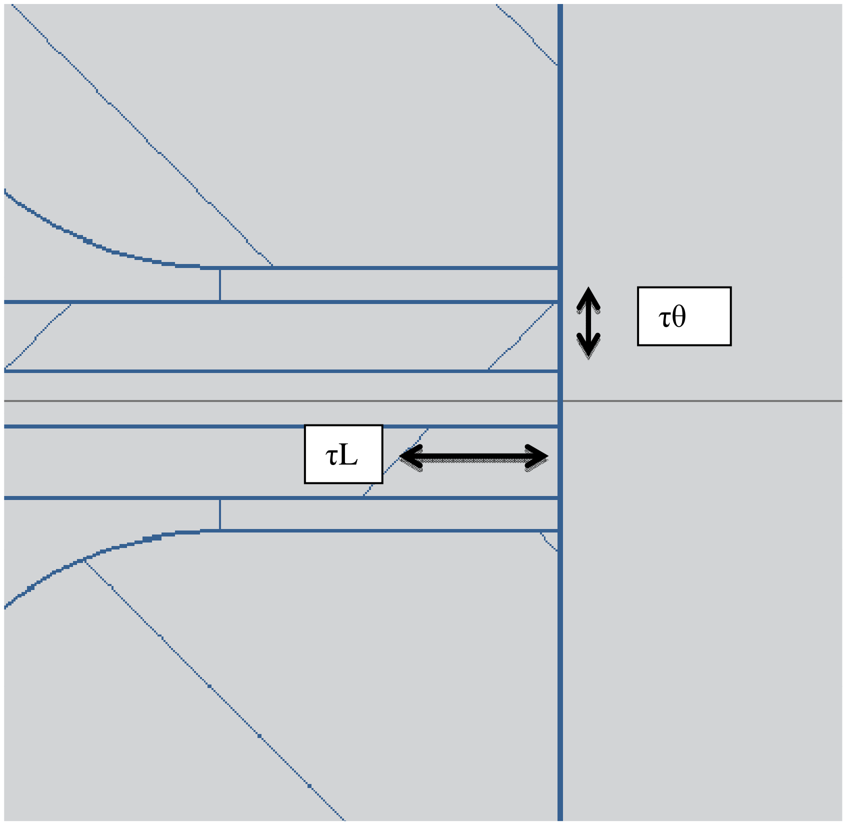

Figure 22: Description of Injector parameters

For this investigation the injectors have a parameter of τL and τθ that will change in length from the control injector A with a set value. Injector B has a recessed value of τL while injector C has a larger value of τθ. These three injectors will be validated using the same flow parameters to identify changes in Liquid oxygen atomization as well as flame anchoring.

2.6 Imagery Analysis

For this investigation a variety of optical instrumentation will be used for acquiring data for this project. These optical systems are widely used in combustion and aeronautical research and for this project it is no exception.

2.6.1 High Definition and High Speed Imagery

High definition and high speed imagery will be used for investigation of the performance of both the MOAC system and the associated injectors. High definition video and picture stills will be utilized to investigate the process of ignition and flame propagation. High speed imagery will allow for in depth analysis of the ignition sequence and can further help investigate the rapid combustion sequences that occur in the combustion process.

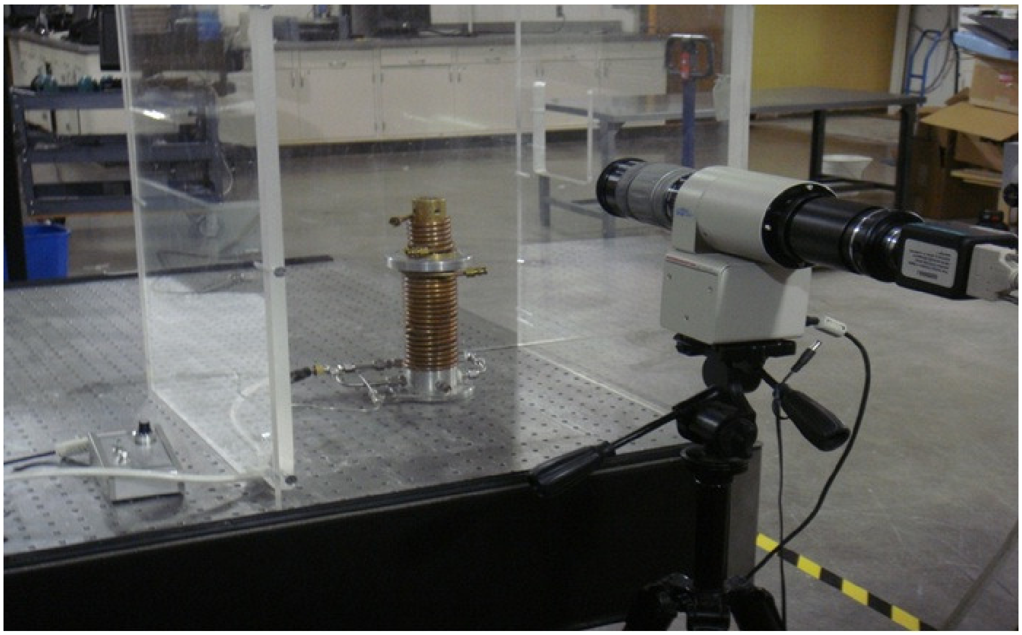

Figure 23: OH filter installed on camera.

2.6.2 OH Intensifier

OH intensifier imagery will be used for studying the structure of the resulting flame of ignition. The camera utilizes a filter than is sensitive to the wavelength generated by the OH radicals and highlights the particles' intensity in the image. This imagery allows for investigation of flame dynamics occurring inside the chamber without having the bright luminescence of the flame cause issue in the video data. This method of measurement allows for analysis of the flame structures and reaction characteristics of the combustion.

2.6.3 Schlieren Imaging

Schlieren imagery is also utilized for imagery analysis of the propellant spray and the flames' dynamics. The Schlieren system takes advantage of the refraction of light through different density mediums and thus can highlight fluid systems interacting. The system that will be employed in the cSETR is a Z-type Schlieren consisting of two mirrors set up in a z alignment. The camera for the Schlieren system is a monochrome CCD camera while the light source is a 1kW halogen light source specially made for optics and Schlieren systems. The CCD Camera has a variable frame rate of capture ideal for identifying major fluid interactions. If smaller time interval processes are required, then the High Speed Camera referenced above can be integrated into the system. The Schlieren system will use 6 inch diameter mirrors with a focus length of 24 inches. Each of the optical components in the system has an F number of 4 as well. Each of these lens materials close to the actual light source are required to be composed of ? quartz lens as the light source produces 1000W of energy and can reach 900°C at the light housing.

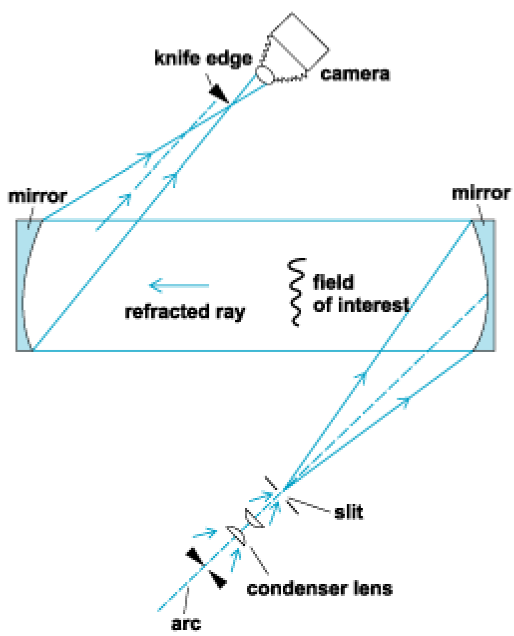

Figure 24: Schematic of typical Z-type Schlieren

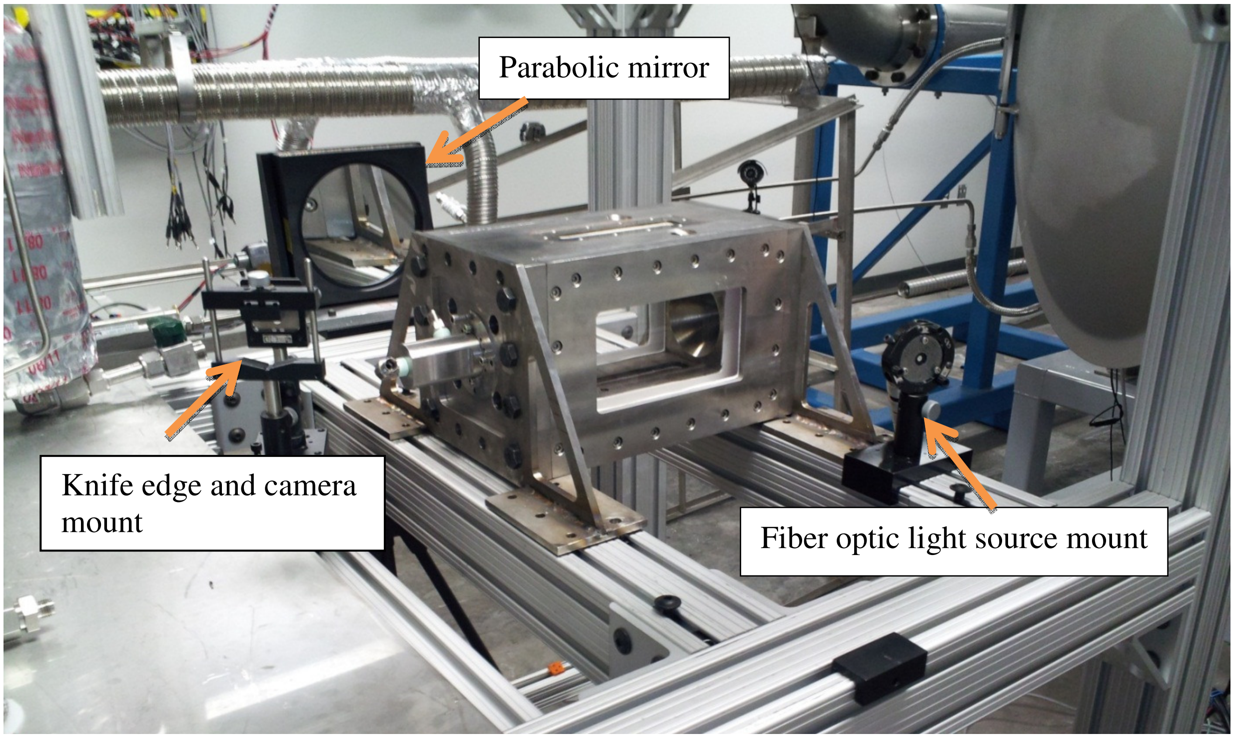

Figure 25: Schlieren system installed with MOAC. First condensing mirror is located outside of picture.

Currently the Schlieren system uses a condensing and focusing lens combination to generate a point light source at a pinhole. In the future, a fiber optic wire assembly to create a point source is to be used for the Schlieren system for ease of use and set up. The Schlieren system is designed to be used on combustor tests in ambient conditions as well as the Multipurpose Altitude Simulation System. Imagery from the Schlieren system will allow for investigation into the spray dynamics of the propellant fluids as they mix in the combustion chamber. In addition, care must be used with the Schlieren system as the light source emits ultra violet radiation and can cause UV burns to exposed skin if proper precautions are not taken.

Figure 26: Lot Oriel 1000W light source system.

2.6.4 Image Analysis

Imagery analysis with be done with ImageJ Software © post testing to determine the lengths of droplets and stream lengths. Stills for this software will be taken using the aforementioned imaging methods. The software takes a reference length of known value like the length of a port or window and can use this reference to identify break up lengths and other fluid parameters.

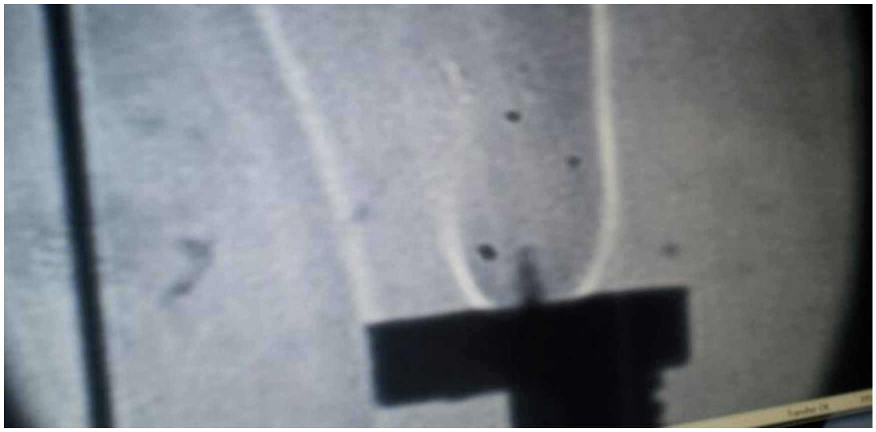

Figure 27: Schlieren Image of candle taken with Schlieren system.

2.6.5 CCTV Test Visualization

In addition to these imagery tools, a Closed Circuit Television camera system is in place inside the testing facilities. Four cameras in total allow test engineers to monitor the tests remotely and instantaneously. Each of these four cameras visualizes a custom angle of the MOAC or Test Article and each is seen on a screen inside the control room adjacent to the testing bunker. This video feed can be recorded as well for identifying events that may have occurred during the test process that may need to be reviewed at a later time.

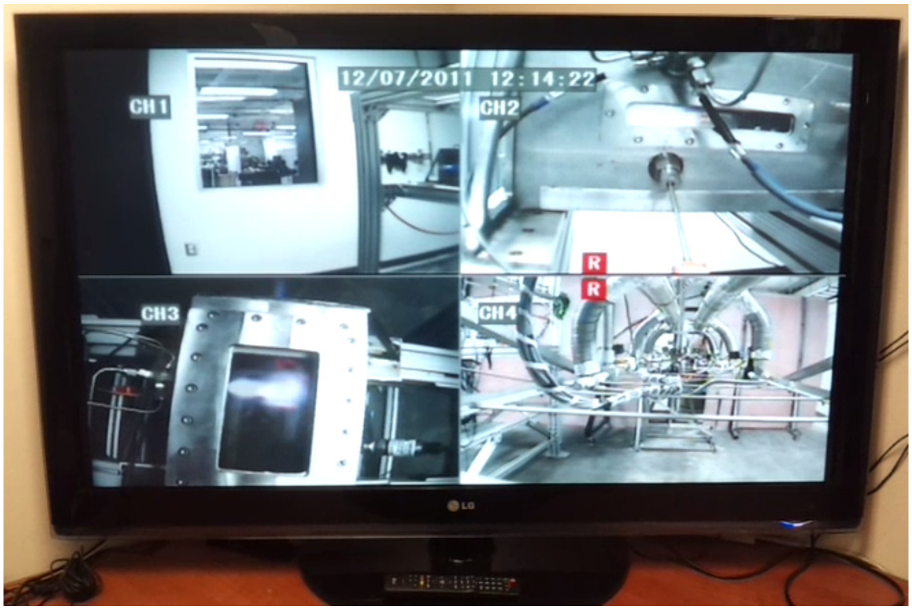

Figure 28: CCTV use of Testing from remote control room.

2.7 Cold Gas Methane

In realistic bi-propellant engines, typical propulsion systems employ regenerative cooling for the combustion chamber. To quickly summarize regenerative cooling, the propellant fuel is flowed through small cooling channels that are built into the exterior of the combustion chamber, throat, and nozzle. The channels help keep the combustion chamber from being damaged due to the high heat of the combustion process. Methane is preferred to be stored as a cryogenic liquid since as a cryogen it has a high energy density and takes up less space than as a gas. Upon cooling down of the chamber, methane would not remain in its liquid phase but change to gas. It is ideal for modeling the combustion conditions that typical engines currently use, thus a system for bringing methane gas down to cold but not cryogenic temperature is recommended. To accomplish this task, a cold gas methane condensing unit is being developed at the cSETR to provide an option that can deliver gaseous methane at various pressures and temperatures of approximately 130-200° K. These conditions are indicative of what state methane will arrive in when actually injected into the combustion chamber. In addition, cold gas combustion is usedin the ignition systems of current flight hardware. The sytems takes advantage of cryogenic tank boil of gasses to provide propellants for ignition or gas generation devices. Development of methane cryogenics has been done previously at the cSETR for cryogenic condensing systems.

Previous methane systems developed at the Center focused on production of cryogenic liquid methane via natural convection condensing systems using liquid nitrogen as a low temperature source. This is convenient as the methane will drip and collect in the production dewar container and can be used at a later time for testing. However, this process can only make a finite amount of methane at a given time for testing purposes and can complicate testing procedures due to the logistics of maintaining a constant methane state. A natural convection condensing system has been developed to mitigate this logistical problem since for most of the testing to occur, gaseous methane is suitable.

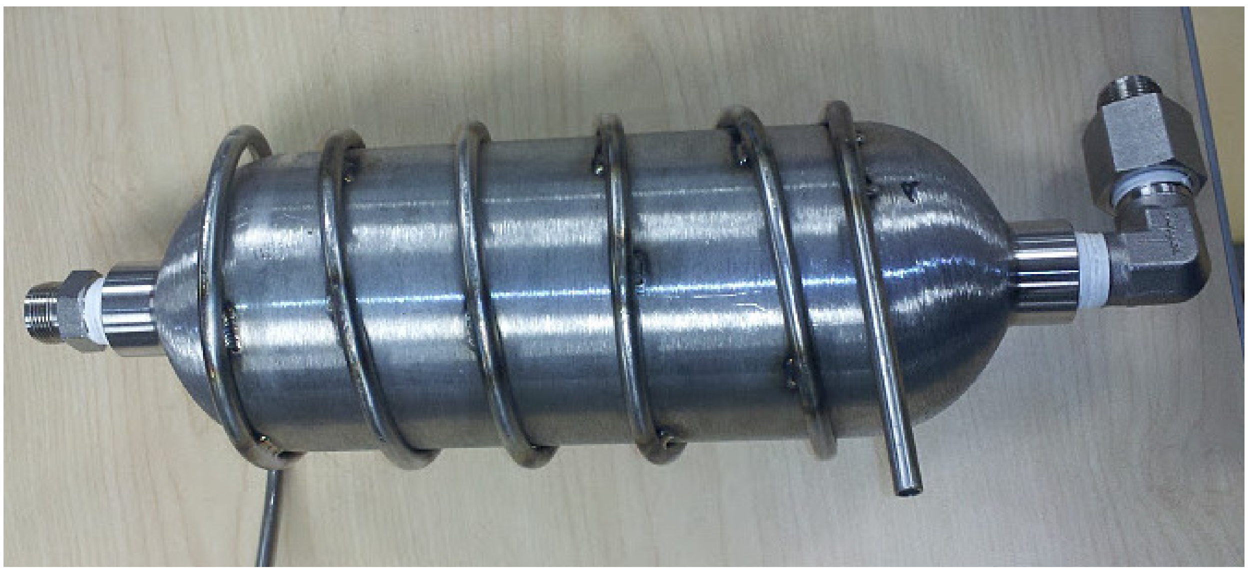

Figure 29: Chilled cylinder catch tank shown without insulation installed.

The system consists of two separate main components: the methane condenser coil bath and the chilled catch tank. The coil system is a stainless steel tubing coil that is placed in a bath of liquid nitrogen. The coil is set to be the appropriate length required to condense methane to the thermodynamic conditions desired. This length is computed using empirical heat transfer relations to determine the heat transfer out to the liquid nitrogen pool. The coil can be expanded for different diameter tubing to permit possible system expansion capability later. The second component of the methane condensing system is the chilled catch tank. The tank preserves the methane prior to entering the test article at chilled conditions and at the pressure required for testing. The tank as well as its chilling components are composed of stainless steel. The catch tank is chilled via stainless steel coil tubing that is welded to the

outer side of the tank. The tank itself contains a large amount of thermo mass that can place time constraints on chilling down methane as well as chilling the tank down to the temperatures needed. Tests conducted without a cooling coil determined that the thermal mass and heat transfer is too much to contain a properly chilled gas or cryogenic liquid. The coil will run liquid nitrogen around the test tank cylinder chilling the entire tank via conduction. This chilling process allows the testing process to be more efficient as the methane itself is not used to cool down its own handling materials such as the steel cylinder that serves as a holding tank. The coil takes five turns around the cylinder tank and exits to the liquid nitrogen pool that chills the methane coil in the system. Nitrogen jacketed coils have been used with success in condensing liquid methane for testing in regenerative heat transfer testing with 4-5 times more coils to ensure methane stays in liquid form. This set up may freeze portions of the methane but for gaseous systems only 5 coils turns are required to cool down the cylinder to proper temperatures. The cylinder tank is insulated with spray foam insulation that is readily available from hardware stores and forms a close seal of insulations that cannot be done with Cryogel™ insulation due to the geometry of the coil over the cylinder tank. Based upon the results of the performance of methane, a similar approach will be used to condense oxygen down to similar temperatures for ignition using cold temperature, higher density gas methane and oxygen.

Figure 30: Cold gas cylinder installed on ambient test stand.

Figure 31: Insulated Nitrogen chilling line to cold gas cylinder

Chapter 3: Experimental Procedure

The objective of the MOAC is to allow for the investigation of spray and flame dynamics of propellants used for combustion. A Summary of characteristics the MOAC can analyze is described below.

3.1 Spray Dynamics

The nature of a coaxial shear injector works on the basis of the interaction of two fluids to induce the atomization of the liquid oxygen. The shear forces induced by velocity of the gaseous methane induce surface instabilities in the centralized liquid oxygen fluid jet.   The differences in velocity, viscosity, and density of the two fluids form the basis of the investigation of atomization effectiveness. There are different methods that exist currently to begin investigation of the process of methane and oxygen atomization. These methods are primarily in this investigation, the Weber and Ohnesorge Numbers as well as the Momentum flux relation. These relations will be detailed in the discussion below.

The Weber number, a dimensionless relation used in fluid mechanics to describe the interaction between fluid flows of two different fluids. Its relationship to fluid parameters is to describe the measure of fluids inertia to its surface tension. The normal Weber number can be described as equation (3) for a single velocity fluid.

$$We = \frac{\rho (V)^2 d}{\sigma} \tag{3}$$

In the case for analysis of two fluid velocities, a modified Weber number shown in equation (4) will be used for the investigation of this project.

$$We = \frac{\rho_f \left(V_f - V_{Ox}\right)^2 d_{Ox}}{\sigma} \tag{4}$$

It is to be noted that the Weber number takes into consideration the ambient or surrounding gas density in the analysis. The domain of the Weber number also describes the jet breakup regimes for nozzle sprays.

The Momentum flux ratio relates the momentum flux of the fuel to the oxidizer as shown in equation (5).

$$J = \frac{(\rho V^2)_f}{(\rho V^2)_{Ox}} \tag{5}$$

The momentum flux itself describes the transfer of momentum across a unit area for a given fluid. Generally the greater the momentum flux ratio, the more effective the atomization process occurs in fluid jet sprays. The momentum flux is helpful in the scaling of injector performance across engine sizes.

The Ohnesorge Number is a fluid dynamics dimensionless number relating fluid viscous forces to internal and surface tension forces. The Ohnesorge number is given in equation (6) below.

$$Oh = \frac{\mu}{\sqrt{\rho \sigma d}} \tag{6}$$

It can be seen as well that the Ohnesorge number is a fuction of both the Weber number and the Reynolds Number.

$$Oh = \frac{\sqrt{We}}{Re} \tag{7}$$

The Ohnesorge number is typically used to classify atomization sprays in cold flow regimes, but trends have begun to use the relation to classify in hot fire testing as well in addition to relating the cold flow analysis to hot fire testing. In this project the Ohnesorge number will be used when analyzing hot fire sprays.

As described earlier, the injectors vary in parameters τ_L and τ_θ. These parameters will be the factors of variability in this investigation of spray atomization. The values of τ_L and τ_θ are manipulated in each

injector but only one variable for each injector. Injector A is deemed the control Injector with a given length of τ_L of 1.42 mm and a τ_θ value of 0 mm. Injector B is equipped with a recessed liquid oxygen post which gives it a value of τ_θ=5 mm along with a τ_L=1.42 mm. Injector C has a larger liquid oxygen post radius that characterizes the injector with values of τ_L=2.26 mm and a τ_θ=0 mm.

Table 1.1: Injector Geometry parameters

Injector	τ_θ (mm)	τ_L (mm)
A	0	1.42
B	5	1.42
C	0	2.26

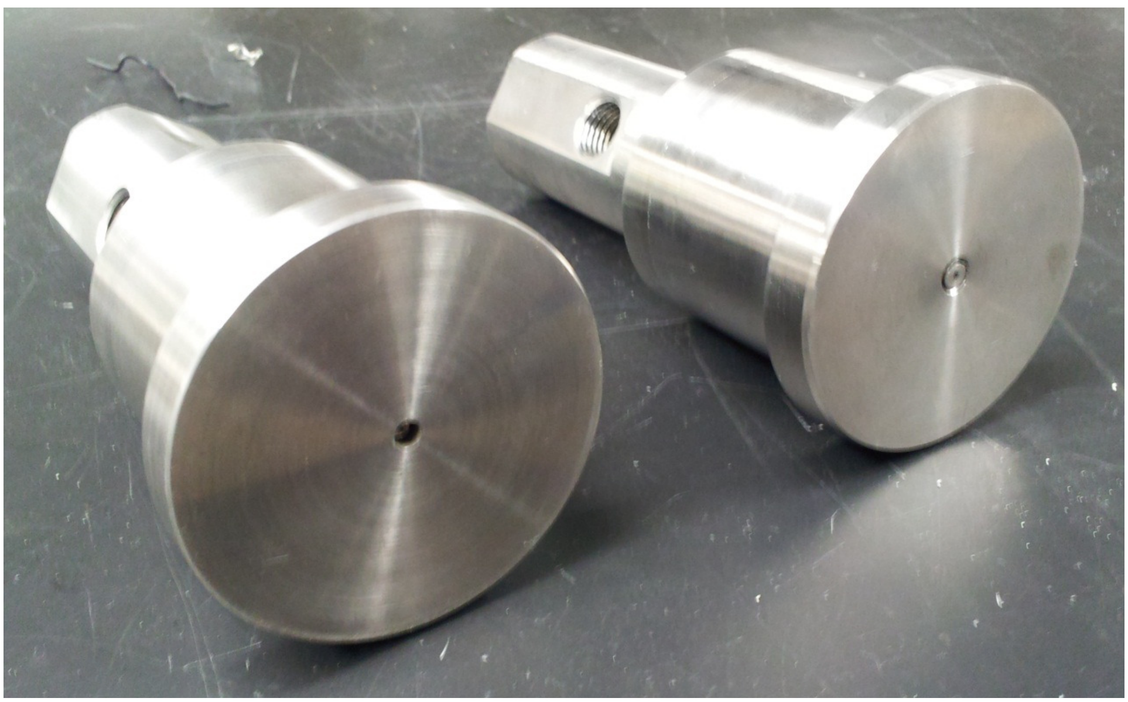

Figure 32: Recessed and Large injector post geometry injectors.

These injectors will be each tested with the same values of Weber Number, Momentum flux ratio, and Ohnesorge number to characterize the effects that each injectors' geometry has on the corresponding break up lengths. These injectors will attempt to characterize the break up lengths to include these geometry patterns. Upon final testing, the dimensionless characteristics will be plotted against the breakup lengths to determine any correlation among sizing.

The break up lengths of liquid oxygen will have two length parameters to identify in each test. There is an initial spray atomization point along the length of the liquid oxygen central core. This point is where the liquid oxygen surface instabilities begin to grow rapidly and lift droplets into the surrounding methane spray. This point is critical as the flame can stabilize anywhere past this point on the spray length, at this point the liquid oxygen core spray is still intact even though the outer layer of fluid is lifted away. The next critical point along the fluid spray line is the point where the liquid oxygen core is broken. This is evident by the discontinuity of one intact spray cone and the individual droplets that begin to disperse from the liquid oxygen.

The flame anchor position is also of note in this project investigation. The flame anchor is the point in which the flame anchors itself in the propellant spray line. As stated earlier, the flame can only anchor once the liquid oxygen core has begun to atomize. The flame may not actually anchor exactly at this position but may stabilize further down the spray core if mixing conditions do not favor combustion. The flame anchor position is critical as the limits of flammability are much more constrained than other hydrocarbons and oxygen in use such as hydrogen fuels. The combination of breakup length and flame anchor position is critical to the design of a combustion chamber. Too long of a breakup length for a given combustion chamber can lead to poor engine performance, combustion instabilities, and possible overpressure or underpressure ignition. This goes as well for flame anchor as a poor flame anchor position leads to combustion instabilities as well. Proper design of an injector and combustion chamber

combination allows for complete breakup, mixing, and reaction of the propellants with no need for additional chamber space that inhibits pressuring the chamber.

3.2 Test Preparation

The MOAC system must be properly prepared in advance of any significant testing. Improper preparation of the MOAC chamber and injector set-up can cause a failure of proper testing as well as physical and fire hazards. Test set up for the MOAC involves proper passivation for propellants use ensuring that no fire hazards exist as well as protection from secondary hazards.

Prior to the installation on the ambient test frame stand, the chamber must be built up to test ready condition. All components that are to test and have been tested must be cleaned from any soot that may have begun accumulating from prior tests. This is most important on window pieces as soot becomes readily visible forming on the surfaces after just a few seconds of testing. The soot inhibits any visual analysis of the combustion dynamics and observation required during testing. Prior to installation the MOAC is completely disassembled and each and every component is cleaned. This is done by using a commercial off the shelf cleaner and paper towels. Any residual RTV silicone from previous tests is removed by hand or by razor blade scraping. Once all visible traces of soot and silicone are removed, then the windows and components are wiped with isopropyl alcohol and left do dry. Windows are wiped with "Windex ©" to ensure they are as transparent as possible. If testing is not to occur for some time, then components are stored in clear plastic bags until assembly.

While the parts are drying or in storage, Alumina Silica gaskets are cut to specific shapes to fit between the proper mating components. The Alumina Silica is rated for temperatures of 1300°C and is fire retardant. Each gasket is cut from a precut master for each window. For each window section there are three gasket sections. One gasket is placed between the window and the main chamber body. This gasket is the main flame protection and can last anywhere from 5-10 minutes of hot fire conditions. Another gasket is placed around the window and seals between the body and the window retainer

bracket. This gasket is cut out with holes for the retention bolts for the retainer brackets to properly fit without any excess material from the gaskets causing a fitting issue with the bolts. Finally, a third gasket is placed in between the window retainer bracket and the window itself to protect the window against any contact stresses from the bracket. An application of high temperature RTV Silicone is applied to the outer perimeter of the windows where the main chamber body meets the side of the window. This ensures the chamber is sealed tight to the windows. It is important that the RTV cure after the window brackets are installed so the RTV can form and seal to the body, bracket, and window.

Prior to installing windows the injector adaptor, injector, and converging sections must be installed into the chamber body. Both the injector adaptor and the converging section have RTV installed on the extending retention pillars to seal the body to the modules. The injector is installed in the correct position relative to the chamber for the required plumbing of the propellants. The injector has RTV installed behind the injector face to allow for a proper seal similarly to the modules. The injector retainer is installed immediately to allow the RTV to cure in the correct position and not risk any movement of the injector.

Windows then have the brackets installed onto them to secure them in place and contain the pressure. Large window brackets use 20 M5 bolts to fasten securely to the combustor body. Small windows require 10 M3 bolts for retention. Each of the brackets is installed using a modified star pattern for torqueing the bolts to the body. The bolt pattern focuses on tightening the outer bolts close to the front and rear of the combustor and working toward the center of the bracket alternating up and down the combustor to get each bolt. Both brackets require this process for torqueing. Care must be taken to not over tighten the bolts while monitoring windows as to not incur a crack or chip in the windows which can prorogate under pressured use. Once these bolts are installed the side window, bolts are tightened to 10.33 Nm while the smaller window bracket bolts are tightened to 2.2 Nm. Over torqueing the bolts can lead to damage to the windows.

The MOAC is bolted to a stainless steel testing frame that allows installation onto the ambient test stand or for future tests inside the Multi Altitude Simulation System (MASS) Chamber. The test frame allows for mounting the MOAC in various positions for optical or testing preference. The test

frame rests on ceramic insulation plates 1/8 of an inch thick to prevent any major heat transfer to the ambient test stand which is composed of Aluminum. The MOAC is secured to the frame by the 80/20 bolt system that is compatible with the railing. From this point instrumentation, injector and igniter fittings are installed to the MOAC and the chamber is now ready for testing.

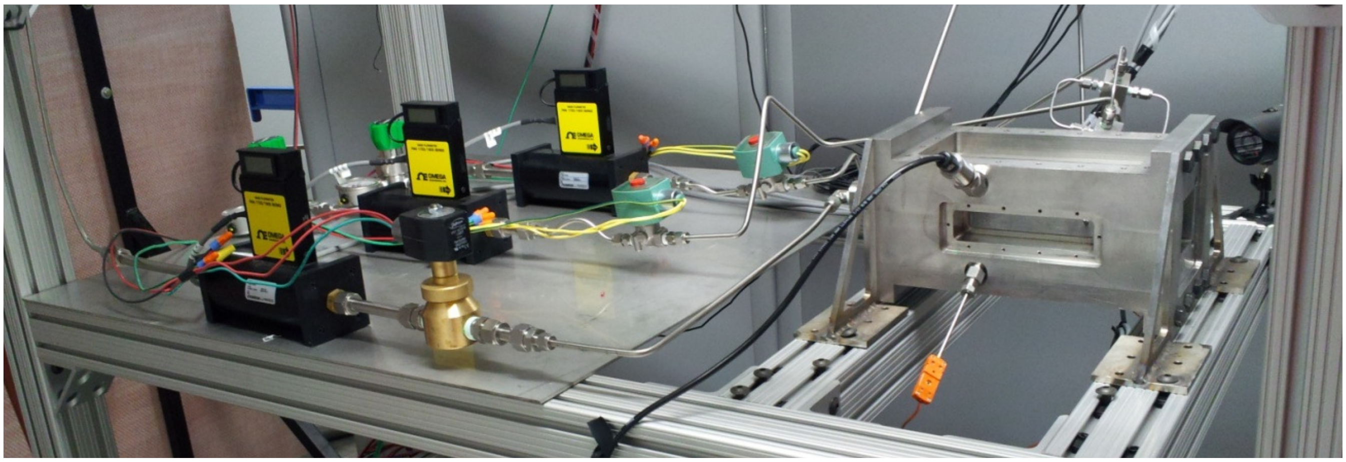

Figure 33: MOAC system installed for on ambient test stand.

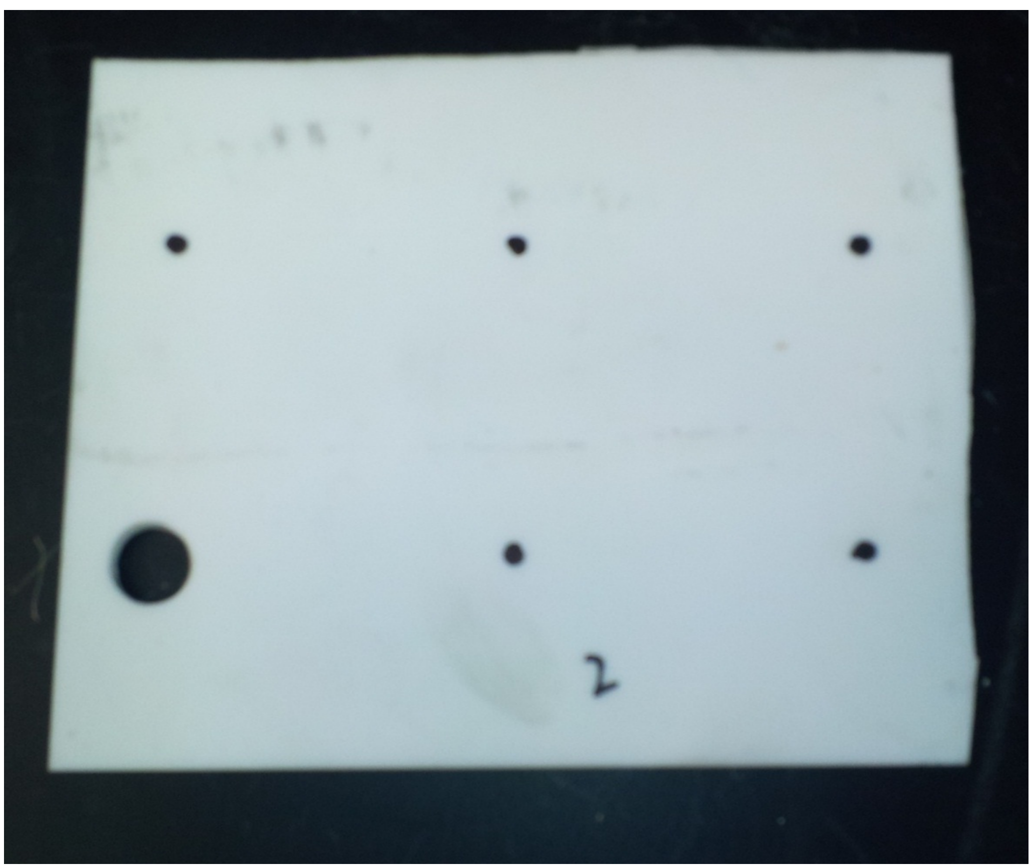

Figure 34: Ceramic Insulator for the ambient test stand.

Chapter 4: Results and Discussion

The chamber has undergone testing with combinations of methane and air and methane and oxygen. Each of these tests has been ignited with the swirl gaseous igniter using methane and oxygen fuels and oxidizer combination. In addition, the cold gas methane system and Schlieren imaging system has been tested and implemented into the ambient test stand.

4.1 Combustor Testing

The combustor has undergone air and methane testing as well as oxygen and methane testing to characterize the performance of the delivery and the MOAC system concurrently. Methane and Air testing was done with an Air/Fuel ratio of 17.3. The chamber performed well to seal the flame inside the combustor and allow complete visual investigation of flame characteristics. Complete ignition of the methane and air combination did occur in this series of testing. Injection velocities of both the methane and air proved to be too high for proper mixing to occur with the injector. The injector is a shear coaxial injector designed and optimized to be used with liquid oxygen and gaseous methane fuels. Because the fluids were both gaseous, the shear mixing effects were minimized and the fuel and oxidizer cannot mix correctly. Reducing flow velocities to levels that support air and methane flames proved difficult as the facility's installed compressed air system would inhibit dropping air pressure to appropriate levels.

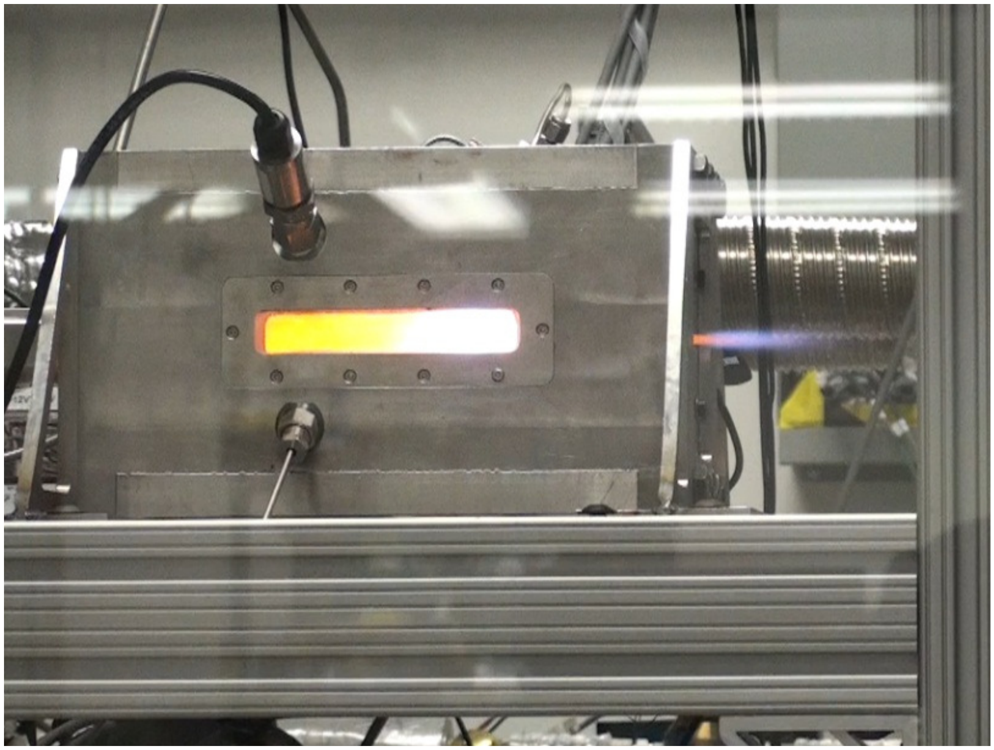

Figure 35: Combustor undergoing firing

Oxygen and Methane tests conducted went well. The MOAC was fired for up to 25 seconds at a time in this series of testing. A Mixture Ratio of 3.5 was used for this testing but raised to a value of 4 as tests progressed. This Mixture Ratio yielded flow rates of 42 LPM and 56 LPM for methane and oxygen, respectively. Once again the MOAC did not display any issue with this testing combination. No shaking of the chamber or stand occurred throughout testing nor did the quartz windows receive any damage or crack propagation. Several hard ignitions of this propellant combination occurred by injecting methane into the chamber prior to ignition. This is done to allow the combustion process to occur without having the introduction of oxygen blow out the flame from the igniter. Pressures and flow rates were adjusted to allow simultaneous injection of methane and oxygen. Ignition could only occur with the igniter turned on. Due to the gas-gas nature of this test the mixing could not occur in proper order to allow standalone ignition. Predicted pressures from this testing was expected to be 35 psi but due to a transducer hardware failure pressure, data was not confirmed. Injection pressure for these tests were in the order of 40 -50 psi.

Igniter performance while installed on the MOAC showed no issue in performance compared to stand alone tests. Ignition was not hampered by the 40 mm travel length nor the 7mm diameter entrance into the chamber allowed by the MOAC for the flame to travel.

Alumina Silica gaskets need to be replaced after each testing session as they degrade and can cause a leak or fire issue if neglected. Ceramic insulators contain the heat energy to the MOAC system itself and no heat transfer to the aluminum ambient test stand occurred. Slight issues with the expansion of the MOAC and subsequent cool down caused some difficulty with the large window assembly from the combustor body. With proper sizing and sanding of the window, this issue can be mitigated.

4.2 Cold Gas Testing

The Cold Gas Condensing System has been tested with mixed results. The condensing coil and the Chilled Cylinder have undergone individual tests to determine their effectiveness of creating cold gas methane for experimentation. The Condensing coil was used independently to verify cooling effect and the coil does work well in submerged liquid nitrogen to chill and even condense methane gas to a liquid phase. Liquid nitrogen at ambient pressure exists at approximately 77K while Methane is a liquid between 95K through 120K depending on its pressure. Thus, if gas flow in the coil containing methane is interrupted, the line is quick to freeze with solid methane blocking the passage.

The chilled cylinder underwent testing to investigate how its chilling capacity is compared to the coil. The Cylinder is chilled with Liquid nitrogen running along its cooling channels and exits into a catch Dewar. The cylinder is chilled to the point the nitrogen fluid exiting the cooling channels is liquid in phase. While this chilling process is occurring, the methane is present in the cylinder and cooling from the effects of the nitrogen. Results of this method proved fruitful for condensing methane between tests. Flow rate considerations limit the feasibility of using the cylinder by itself as a condensing source as the internal volume of the cylinder is 1 liter and will not allow enough methane to be condensed. The cold gas was used in conjunction with testing of an Oxygen/Methane pencil thruster with flow rates of 40 liters per min. This equates to approximately 1.5 to 2 seconds of cold gas methane in use before the chilled gas is exhausted and warmer gas takes its place. The cylinder cannot continue chilling methane

gas down to temperature levels required for cold gas testing for continued use. The combination coil and chiller would still be the best option but submersion of the coil will result in freezing of the line. Gaseous nitrogen and helium can be used to mitigate this issue after flow of methane.

4.3 Schlieren Testing

The Schlieren optical assembly is the only optical component of the testing tools that need to be developed and installed specifically for the MOAC assembly. Schlieren imaging was tested on an optical table for component evaluation and then the system was transferred and configured for use on the ambient test stand. The imaging system is capable of producing a Schlieren image while light is being transmitted through two of the combustor windows.

Chapter 5: Conclusions and Future work

5.1 Conclusions

The Multi-Purpose Optically Accessible Combustor proves to be a viable piece of hardware capable of proper investigation of combustion ignition physics. The adaptability for different test requirements allows the MOAC to be a test bed for various injectors and propulsion conditions. The injector design allows for a variety of injector styles and sizes to be implemented with the MOAC. This design allows for simple implementation of such injector styles with small lead time to build any custom hardware components. Supplementary systems such as the optical systems and cold gas implementation allow for a well-rounded propulsion research capability.

5.2 Future Work

Future work would entail complete testing using liquid oxygen propellant across all three injector styles. Characterization of the break up lengths compared to the Momentum Flux Ratio, Weber Number, and Ohnesorge Number as the first combustion investigation with the MOAC system. Cold Gas Characterization will be conducted to determine the complete process of maintaining cold gas ignition as well as cold gas fed propulsion. The system will also be fitted toward oxygen for duel chilled gas ignition. Multiple post injector dynamics and Liquid oxygen swirl injectors may be developed to further investigate injector dynamics. Additional optical investigation involving Particle Image Velocimetry within the chamber will be conducted as well.

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Vita

Mr. Christopher Navarro is a researcher at the Center for Space Exploration Technology and Research located at the University of Texas at El Paso. He received his Bachelors of Science in Mechanical Engineering from the University of Texas at El Paso in 2008 and has experience in the automotive field with General Motors and astronautics with NASA.

Permanent address: 1991 Gus Moran

El Paso, TX 79936

This thesis/dissertation was typed by Christopher Navarro