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# Development Of The Control And Ignition Systems On A High Pressure Gas Turbine Combustor

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# DEVELOPMENT OF THE CONTROL AND IGNITION SYSTEMS ON A HIGH PRESSURE GAS TURBINE COMBUSTOR

by

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THESIS

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## Abstract

The ignition and control systems of a laboratory scale high pressure gas turbine combustor were developed in the present work. This work provides a detailed description of the design, development and testing of the remote control system developed for a High Pressure Gas Turbine Combustor (HPTC).

The combustor has the capability to operate at pressures up to 1.5 MPa and temperatures up to 2400 K. It is also designed for a maximum air and fuel flow rates of 81.93 g/s and 35.77 g/s respectively. The fuel used will be $CH_4$ for the early experiments but it is designed to operate using a mixture of $H_2$-CO with a hydrogen fuel composition variation of up to 30 percent. The HPTC also has optical accessibility capabilities in its combustion chamber with a converging nozzle that restricts the exhaust flow. It also has three circular ports which can be used as instrumentation ports to obtain real time data from the combustion chamber.

LabVIEW was used as the controlling interface for the user. A detailed outline of the LabVIEW programming is also described. LabVIEW controlled the proportional valves (ball valves), and solenoid valves; it also provided the user with data from mass flow meters as well as pressure transducers. Both proportional and solenoid valves are 1.91 cm and can withstand pressures of up to 1551 kPa. Thermal mass flow meters were used to obtain the flow in the lines with a range from 200-1000 L/min with an accuracy of 1.5 percent. Pressure transducers with a range from 0 to 2068 kPa were also positioned on the lines in order to know the line pressures.

The ignition system design, development and testing is also described with its integration to the High Pressure Gas Turbine Combustor. A modified spark plug was used to provide the igniter with an ignition source. A diffusion flame was used to ignite the main

line using methane as the fuel that utilizes the air in the combustion chamber as the oxidizer. Testing included a functional test of the equipment, and pressure testing prior to performing the ignition test. The system has the capability to withstand the maximum pressure allowed by the air compressor which is 758 kPa. Ignition testing was performed at lean conditions using equivalence ratios from 0.53-0.79. Both systems demonstrated to be reliable and stable. Future work on this combustor includes flashback and flame stability of hydrocarbons at high pressures.

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# Chapter 1: Introduction

Gas turbines are internal combustion engines that operate with a rotary motion. They are composed of three major parts: compressor, combustor, and turbine. Air is compressed to increase the pressure and then it is directed to the combustor where fuel is mixed with the incoming air, ignited and burned. The hot exhaust gases expand in the turbine and energy is recovered in the form of shaft power. The heat content can be discarded using a simple cycle, regenerative cycle, cogeneration, or the combined cycle. The discharge gases may contain pollutants such as oxides of sulfur (SOx), and nitrogen (NOx). NOx formation is typically dependent on the high temperatures of the combustor, formation and emission of CO is the result of incomplete combustion, while SOx appears if heavy oils are fired in the turbine. Integrated gasification combined cycle (IGCC) is the process to turn carbon based fuels into syngas and redirects any leftover heat to power a second turbine. Fossil fuels are still the main source of energy for gas turbines. However, fossil fuel fired power plants are responsible for over 40 percent of man-made carbon dioxide emissions which contributes to greenhouse gas production [1-4].

Restricting regulations concerning emissions is the driving force behind the development of combustors. New generation gas turbines need the capability to operate with alternative fuel types with high hydrogen content such as syngas and natural gas. The increased interest in the integration of gasification into power generation has led to the utilization of syngas. Coal is passed through the process of gasification to produce synthesis gas (syngas), a mixture of $H_2$, $CO$ and $CO_2$, which allocates for several different applications downstream. Syngas produces fewer pollutants when compared to traditional coal derived power generating technologies. Combustion of syngas is generally characterized by high laminar flame speeds and low ignition delay times which increases the propensity for a flame to flashback. In combustion, flashback is defined as the condition where the flame propagates upstream against the gas stream into the line.

Flashback is a critical design parameter due to the potential hazards presented both to hardware as well as an increment in pollutant emissions. Therefore, it is fundamental for the next generation gas turbine combustor to have a clear understanding of combustion using alternative fuel types such as syngas and natural gas [5-7].

The United States reserve of coal is estimated to be one of the largest in the world. In 2011 more than 90 percent of the coal produced was used to generate electricity. It also accounts for nearly 25 percent of the total primary energy production as well as producing approximately half of our nation’s electric power. Continuous advances in technology have reduced the environmental impacts associated with coal. Nonetheless, the need to achieve better pollutant emission control is still a challenge for gas turbine designers [8-9].

## 1.1 GAS TURBINES

Gas turbines have been an essential part of our society in power generation. Typical operation conditions set by the International Standards Organization (ISO) for the gas turbine industry are 15°C, 1 MPa and 60% relative humidity. Gas flowing through a turbine can be as hot as 1260°C compromising the integrity of some components in the turbine. Significant advances have been made over the last 50 years with improvements on efficiency, reliability, and horsepower among others. Superalloy materials, thermal barrier coatings, and ceramics have all been implemented in the design in order to reduce weight and operate at higher temperatures. Next generation gas turbine combustors need the capability to operate at higher temperatures using alternative fuels such as syngas [10-12].

Gas turbines consist of three major components: compressor, combustor and turbine. The compressor pressurizes ambient air and directs it towards the combustor section where fuel is added, ignited, and burned. There are two types of deflagration flames: diffusion and premixed. Fuel and air mix and combust simultaneously in a

diffusion flame, while in a premixed flame, fuel and air are thoroughly mixed prior to combustion. It is common for gas turbines to operate using a premixed flame due to the lean and uniform mixture which is delivered to the combustion area. Exhaust gases are then redirected to the turbine where their energy is recovered as shaft horsepower. The exiting gases can be discarded using a simple cycle, regenerative cycle, or as a combined cycle [1].

The simple cycle is the simplest gas turbine cycle without recovery of exhaust heat. Simple cycle turbine generators typically convert between 25 and 30 percent of the heating value to usable electricity [13]. These types of turbines are usually seen in smaller power plants that install a recuperator to capture waste heat to preheat combustion air and increase efficiencies and are used during emergencies or peak hours. Figure 1.1 demonstrates the simple cycle in its simplest form.

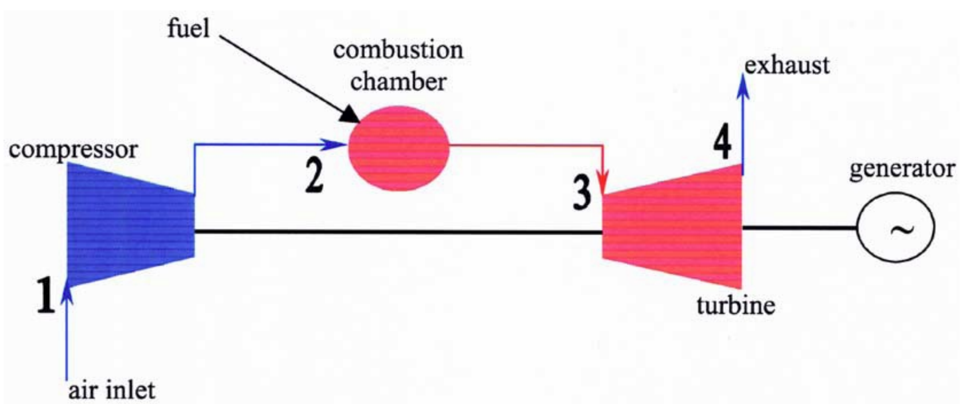


**Figure 1.1. The Simple Cycle [14]**

A regenerative cycle is similar to a simple cycle with the exception of an added heat exchanger. In this cycle, the combustion air is heated using exhaust gases from the turbine which reduces the fuel that is needed to reach the combustor temperatures. A drawback of this cycle is that recuperation is limited by the high temperatures of the compressor; therefore, cooling has to be implemented. Figure 1.2 demonstrates the regenerative cycle in its simplest form [1, 14].

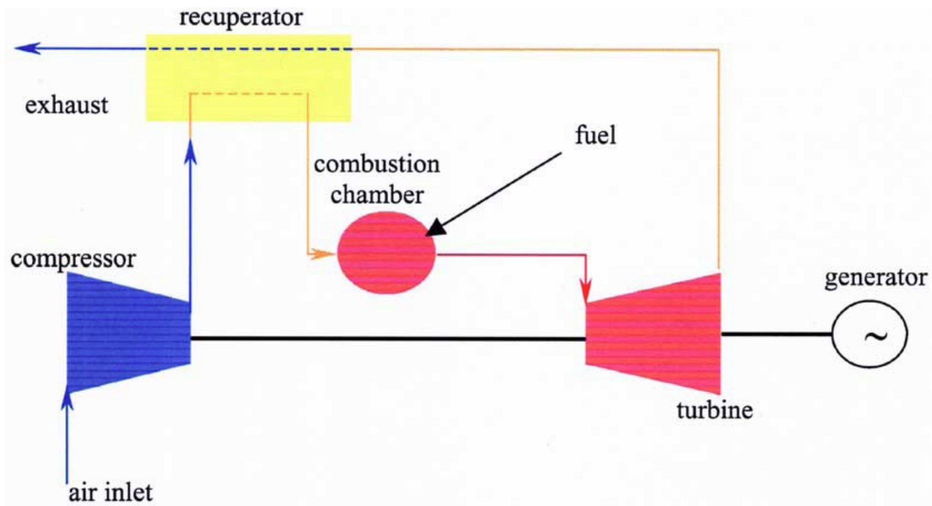


**Figure 1.2. The Regenerative Cycle [14]**

The combined cycle in gas turbine allows for the use of exhaust heat to be converted into steam for steam turbine generators by means of heat recovery steam generators for increased generation efficiency [15]. Figure 1.3 demonstrates the combined cycle in its simplest form which has a thermal efficiency of 50-58 percent in electrical power production [1]. These high efficiency values are achieved using large units above 300 MW.

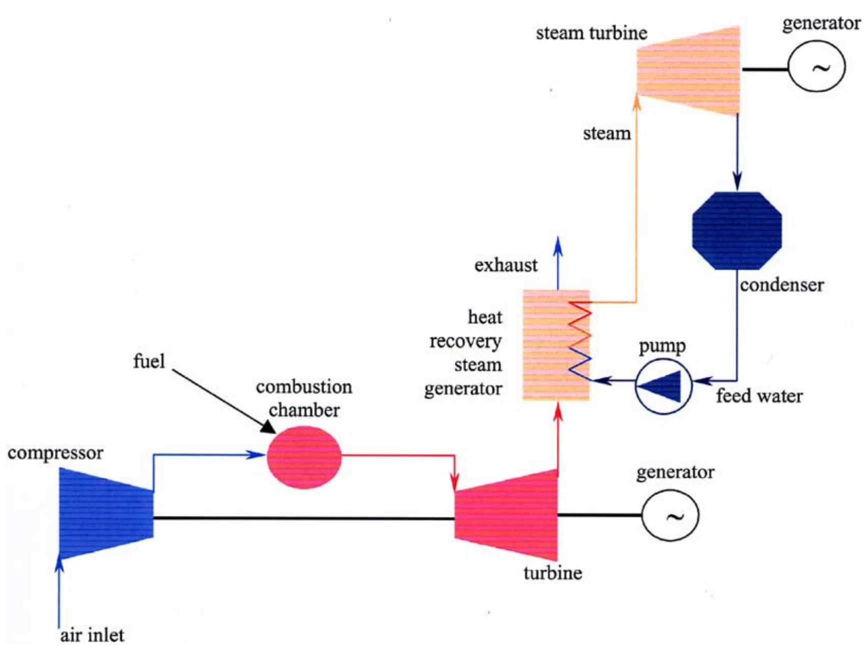


**Figure 1.3. The Combined Cycle [14]**

GE Power Systems developed a gas turbine combined cycle product capable of reaching 60 percent thermal efficiency [16]. This turbine uses a closed-loop steam cooling of the turbine which allows it to fire at a higher temperature for increased performance without increasing combustion temperatures or emissions [17]. Nevertheless, it is fundamental to have a clear understanding on combustion of alternative fuels for the advancement of gas turbines.

## 1.2 DESCRIPTION OF ATMOSPHERIC FLASHBACK

One of the major tasks to be considered for a gas turbine is the design of a stable mean flame position in order to avoid flashback. Serious hardware damage and an increment of pollutant emissions are associated with it. Flashback can be initiated due to the following: turbulent flame propagation in the core flow, flame propagation in the boundary layer, combustion instabilities, or combustion induced vortex breakdown (CIVB) [18, 19]. The first two mechanisms have been studied extensively for pure fuels. However, flashback propensity in syngas is largely unknown. Hydrogen has a high burning velocity and low lean flammability which tends to increase the potential for flashback. Syngas from coal gasification may contain as much as 30 percent of hydrogen by volume [20-21].

Combustion at atmospheric pressures has been studied extensively in the past. Examinations, both experimentally and computationally, of flame propagation, burning velocities of fuel mixtures, and flashback propensity have provided a clear understanding of combustion at atmospheric pressures.

Ilbas et al. [22] studied laminar burning velocities of hydrogen-air and hydrogen-methane-air mixtures at variable equivalence ratios. This study was carried for improvement in design of combustion systems where hydrogen is used as a fuel. Flame speeds were measured using a high-speed Schlieren photographic technique. Flame propagation was also studied with the optical access for filming. In their study, they

demonstrated that as hydrogen percentage is increased, the resultant burning velocity increased and in turn this widened the flammability limits.

Dong et al. [23] analyzed laminar flame speed of hydrogen/carbon monoxide fuel mixtures over a large range of fuel compositions. Carbon monoxide and hydrogen are two components that can be found in syngas. They analyzed various equivalence ratios, from lean to rich conditions. They derived empirical equations based on their experimental results that can be employed to calculate laminar flame speeds of hydrogen, carbon monoxide, and hydrogen/carbon monoxide mixtures.

Tang et al. [24] measured the propagation speeds of n-butane-air mixtures with hydrogen addition. They determine a linear increment of the laminar flame speed based on a hydrogen addition parameter and an effective fuel equivalence ratio. Furthermore, kinetic effects followed by thermal effects have the most influence on the increase in flame speeds associated with the variation of hydrogen.

Flashback has also been analyzed extensively for atmospheric pressures. Davu [21] developed a fundamental understanding on the flashback propensity of syngas at different compositions. He quantified the influence of mixture composition and combustion oscillation on flashback propensity. It was determined that the flashback propensity of hydrocarbon fuel blends is susceptible to the presence of external excitation and generally it correlates with the flame velocity and stoichiometry of the fuel mixtures.

Dam et al. [20] investigated the effects of hydrogen concentration, external excitation, critical velocity gradient, and flashback behavior of hydrogen-carbon monoxide and hydrogen-methane mixtures. It was determined that the critical velocity gradient changed nonlinearly with the increase of hydrogen in the mixture. The velocity gradient in hydrogen-carbon monoxide flames increased abruptly as hydrogen increased as well as for hydrogen-methane concentrations [20].

Dam et al. [25] also investigated flashback due to combustion induced vortex breakdown (CIVB) on hydrogen-carbon monoxide and syngas mixtures. Focusing mainly

on the effect of concentration of different constituents in fuel mixtures on flashback, it was determined that the percentage of hydrogen present in the mixture has a dominant effect on CIVB flashback. Flashback maps for syngas presented distinct behavior when various concentrations of diluents were present in the mixture, in this case carbon dioxide and nitrogen dioxide, carbon dioxide being more dominant.

Blesinger et al. [26] investigated turbulent burning along the vortex axis as well as combustion induced vortex breakdown. Focusing mainly on the effect of geometrical scaling of flashback on a cylindrical premixing zone, they compared two geometrically scaled burners and compared them at equal Reynolds number. It was demonstrated that geometrical scaling of the burner shifts the equivalence ratio which is different for both types of flashback.

And although there is a clear understanding of combustion at atmospheric pressures, behavior at high pressures is still largely unknown.

### 1.3 Description of High Pressure Flashback

High-pressure combustors are designed to simulate temperatures and pressures observed in operating conditions of gas turbines. Currently, there are a number of different combustors experimenting on similar operating conditions as gas turbines.

The department of engineering at Cambridge University [27-28] has developed a high pressure combustion facility able to operate with pressures up to 1 MPa, and temperatures up to 873 K. Research projects such as high pressure and temperature combustion laser diagnostic studies, turbulent flame structure in stratified combustion, and investigation of relight at low temperature conditions are being experimented using the high pressure combustion facility.

The University of California Irvine Combustion Laboratory [29-30] has explored component and system performance at elevated temperatures and pressures. Their facilities include two types of vessels; one with optical access and another for long

duration experiments. The vessels are subjected to pressures of 1520kPa and temperatures up to 649 °C. Several research projects carry on at the laboratory including: Fuel injection and mixing, diagnostics and modeling, alternative fuels, emissions, sensors and control, and materials.

The Department of Energy's National Energy Technology Laboratory [31] has a high-pressure combustion facility with two operational combustors: A dynamic gas turbine that simulates gas turbine conditions with acoustic feedback and an optically accessible SimVal combustor and test section. The dynamic gas turbine combustion test rig is used to model and study fluid flow and the SimVal is used to better understand combustion and emissions.

Physical Sciences Inc.[32] has developed an optically accessible combustor for planar laser induced fluorescence (PLIF) measurements that uses commercial style gas turbine fuel injectors. This combustor can operate at pressures up to 5 MPa, yet it has only been operated at 2 MPa and temperatures up to 550 K. PLIF can provide instantaneous two-dimensional measurements in flames.

A high pressure combustor was also designed in Italy that uses natural gas and hydrogen as fuel. It is a typical reverse-flow multi-can combustor similar to a gas turbine and can operate at pressures of 1 MPa with a dual fuel operation (liquid or gas). It is also a diffusion flame combustion process based on chemical reactions. The focus of this combustor was to evaluate the performance on a gas turbine combustor using hydrogen rich mixtures employing numerical and experimental methods [33].

All of these combustors are being used to have a fundamental understanding of combustion behavior at elevated temperatures and pressures. It is of great importance to understand this behavior in order to design the next generation gas turbines.

## 1.4 Description of Flashback at High Pressures in Gas Turbines

Gas turbines produce various pollutants in combustion to produce electricity such as: smoke, unburnt hydrocarbons, carbon dioxide, and other oxides. Fuel rich regions usually produce smoke. Incomplete combustion forms the unburnt hydrocarbons and carbon monoxide typically while idling. Carbon dioxide comes directly from the methane burnt. Regulations have been getting stricter reducing the pollutant levels emitted by gas turbines from approximately 200 ppm to 8 ppm over the past 30 years [34].

There are two types of combustors: diffusion and dry low NOx or dry low emission combustors. The original, diffusion combustors, were changed to wet by adding water or steam in the combustion zone. If the combustor does not feature variable geometry it is necessary to ignite the fuel in stages as power increases. Some of the common problems in gas turbines include auto-ignition, flashback, as well as combustion instability. This can generate a sudden loss of power or an engine shutdown.

Auto-ignition is the spontaneous ignition of a combustible mixture. Spark ignition engines must avoid it due to the hazards that are associated to the parts of the engine. Reasons for auto-ignition can be as follows: long fuel auto-ignition delay time assumed, variations in fuel composition, fuel residence time incorrectly calculated, or an early trigger caused by ingestion of combustible particles. Flashback, as previously discussed, occurs when the local flame speed is faster than the velocity of the fuel/air mixture leaving the duct. There are two main types of flashback that occur in a gas turbine: occurring in the free stream and occurring through the low-velocity flow in the boundary layer. Free stream mechanism usually occurs due to the flow reversal of the bulk flow. The other mechanism, boundary layer, deals with a delay in the flow in a boundary layer. In gas turbines, flashback usually occurs during unexpected engine transients. Pre-mixing is used in high pressure burners to enable combustion of lean mixtures. Combustion instability was associated with fuel-lean zones [35-36].

Several factors may affect a gas turbine, and as previously discussed, flashback is one that can cause severe damage to the components in them.

## 1.5 Objective of Thesis

The main objective of this work is to design and implement an ignition and control system for a high-pressure gas turbine combustor. Multiple experiments with methane air will be performed in order to have a fundamental understanding of the combustion behavior at elevated temperatures and pressures. In order to meet the project's objectives, the following tasks will be carried out:

1. Develop a delivery system that can successfully maintain pressures up to 207 kPa in the combustor.
2. Develop an ignition system that can successfully maintain a flame at pressures up to 207 kPa in the combustor.
3. Develop a delivery system that can successfully stabilize a flame at pressures of 207 kPa in the combustor after ignition.

## 1.6 Practical Relevance

The development of this control and ignition systems will aid to a better understanding of combustion at elevated temperatures and pressures. Experimentation will generate data that is needed to increase the knowledge of combustion at gas turbine operating conditions. Flame characteristics such as flame velocity, flame propagation, as well as flashback and blowout propensity can be examined using these systems. This understanding is fundamental for the advancement of gas turbines and the development of the next generation combustors.

# Chapter 2: Literature Review

A detailed background survey of the past research as well as the ongoing developments was performed. It was necessary to investigate past work, operating under similar conditions, in order to provide a better design. This chapter will review the descriptions of past experiments analyzing flashback at atmospheric pressures, flashback at high pressures, as well as flashback in gas turbines.

## 2.1 ATMOSPHERIC FLASHBACK MEASUREMENTS

Several projects at the University of Texas at El Paso (UTEP) have studied flashback at atmospheric pressures. Focusing mainly in using syngas and natural gas as a fuel, the projects include investigations of flashback propensity, critical velocity gradient, combustion oscillation, impact of composition, flame stability, as well as combustion induced vortex breakdown (CIVB).

Franco [37] studied flashback propensity for different compositions of syngas. Flashback propensity was quantified by generating critical boundary velocity gradient maps to analyze the influence of mixture composition and combustion oscillation (external excitation). The experiment consisted of a burner with glass tube adapters housed on a safety enclosure. The burner system included a mixing manifold, flow excitation hub, and flow conditioners. Manual valves were used to control fuel and air flowing in the lines and measured by digital mass flow meters. Flame arrestors were implemented for safety in order to prevent the flame to propagate into the fuel line. Flashback was monitored using a high-speed camera system. It was concluded that in most cases flashback presents at an earlier stage due to external excitation.

Another study in 2010 conducted by Dam et al. [20] investigated the critical velocity gradient and flashback behavior of hydrogen/carbon monoxide and hydrogen/methane mixtures. The experiment used a similar burner system as previously used by Franco. Four primary components made up the burner: mixing manifold, flow

excitation hub, flow conditioner, and the burner tube assembly. This system also allowed for the analysis of flashback with external excitation by the means of the hub section and a 100 W speaker. High-speed video imaging was used to observe flashback behavior. The sequences of flashback were analyzed by taking images with a high-speed camera. A swirl flow combustor was used in order to capture the flame. This set up consists of an inlet manifold with static mixture, swirl burner, and an optically accessible combustion chamber. This study concluded that boundary layer flashback propensity varies nonlinearly as hydrogen content increases in the mixture. Also it was found out that external excitation has no significant effects on flashback propensity for hydrogen/carbon monoxide flames.

Flashback limits for combustion induced vortex breakdown was also studied at UTEP by Dam et al. [25].The investigation was carried out in a modular laboratory gas turbine combustor. It is composed of three configurable modules: inlet manifold, swirl burner, and an optically accessible combustion chamber. Swirl stabilized flames were analyzed at different mixture compositions where a methane air mixture was the baseline. Flashback propensity was compared by using data collected from two center body swirlers. The flame was initially stabilized inside the combustion chamber before proceeding to flashback. Particle image velocimetry (PIV) as well as proper orthogonal decomposition (POD) was used to capture instantaneous velocity information. It was concluded that flashback was seen at leaner conditions for mixtures containing higher hydrogen concentration.

Other researchers have also performed several studies to analyze flashback in combustors at atmospheric pressures. Kiesewetter et al. [38] investigated combustion induced vortex breakdown in a premix burner by using a combustion model. Their experimental set up consisted of conical swirler that is connected to an optically accessible cylindrical tube. The reactants were previously premixed before being introduced into the lines. Flashback was analyzed numerically by varying equivalence

ratio and validated experimentally. It was concluded from this analysis that vorticity changes due to the volume expansion and that CIVB flashback is governed by turbulence and chemical time scales in the vortex flow.

Kröner et al. [39] investigated flashback limits for combustion induced breakdown in a swirl burner. Flashback limits were detected by means of an optical flame sensor on a mixing tube. Experimentation was performed on a 200 kW atmospheric test rig with a multistage mixing section. The burner section contains a swirl generator that is connected to a cylindrical quartz glass tube. Flame was stabilized prior to initiating flashback where the air was decreased. Conclusions from this experiment were that CIVB is the governing mechanism for the upstream propagation of the flame and that increasing the flow velocity leads to improvements on flashback safety.

Syred et al. [40] investigated the effect of hydrogen containing fuel blends upon flashback in swirl burners. In this investigation, they described an approach to study and mitigate the effect of flashback using natural gas as a fuel. Their set up consisted of three swirl burners used to analyze flame stability limits at atmospheric conditions. It is made up of a central fuel injector that extends through the burner and it is used to produce premixed and non-premixed flames. The swirl numbers on the burners were 1.47, 1.04, and 0.8. It was concluded from this study that there are considerable variations due to the swirl number. Methane based fuels containing 30% hydrogen shows a similar behavior as that where hydrogen content is increased.

Blesinger et al. [26] investigated the influence of geometrical scaling of flashback on a swirl flame. Two types of flashback were investigated: turbulent burning along the vortex axis (TBVA) and combustion induced vortex breakdown (CIVB). A comparison of two geometrically scaled burners was performed at similar Reynolds number to observe flashback phenomena with similar swirl flow at different turbulent scales. The burner consists of a swirl generator extended by a tube that represents the mixing section. It was determined that for TBVA the recirculation zone extends into the mixing tube and

axial flame propagation is limited by quenching and for CIVB the combustion induced change is a necessary condition for axial flame propagation.

Several studies have been conducted to completely understand flashback at atmospheric conditions. Nevertheless, the next step in gas turbine design is to have a complete understanding of flashback at gas turbine operating conditions.

## 2.2 HIGH PRESSURE FLASHBACK MEASUREMENTS

Flashback has been classified into four different categories:

1. Propagation in the core flow
2. Propagation in the boundary layer
3. Propagation due to combustion induced vortex breakdown
4. Propagation due to combustion instabilities

These mechanisms have been studied thoroughly in atmospheric conditions. Nevertheless, flashback represents a big hazard for a gas turbine when it is operational. Experimentation on actual turbines has a great cost associated with it due to the damages it can cause as well as the increased safety measurements that have to be taken into consideration for it. Therefore, many facilities lean towards research in high-pressure combustors operating in conditions similar to gas turbines which can in turn provide the necessary information regarding this phenomenon.

Flashback phenomena associated with lean premixed syngas combustion has been analyzed in Switzerland at the Paul Scherrer Institut. Daniele et al. [41] experimented at gas turbine like condition to determine flashback limits and issues that may arise during operation of gas turbines. Their experimental set up consisted of an adaptation of a high pressure turbulent premixed facility that can operate at pressures of 3 MPa and temperatures of 2000 K. The combustor contains a cooled casing as well as optical access. They introduced equal volumetric parts of hydrogen and carbon monoxide, two primary components in syngas, in all experiments. Results obtained lead to the

conclusion that flashback propensity can be mitigated by reducing inlet temperature at constant pressure. In conclusion, results indicated a strong pressure dependence of flashback. Regarding mitigation, it was suggested to reduce the inlet temperature to obtain better results.

Physical Sciences Inc. [32] is also contributing to research on the next generation turbine design. They designed an optically accessible combustor that can operate at pressures of 5 MPa with preheated air that incorporates a production fuel injector. The preheated air had temperatures ranging from 400 K to 500 K. Their air supply system can be pressurized up to 17MPa and to preheat the air they use a 250 kW electric heater. In their research, they analyzed instantaneous OH planar laser-induced fluorescence in spray flames at 2MPa. The fuel used in their experiments was heptane and Jet-A. Pressures were varied for both fuels; heptane reaching up to 1.1 MPa while Jet-A flames reached those of 2 MPa. It was concluded that a reduction in soot and hydrocarbon intermediates could be attributed to the fuel injector and the preheated air.

A study on flashback and lean blow out characteristics of hydrogen/carbon monoxide/ methane mixtures was explored at Georgia Institute of Technology [42]. The combustor was experimented at various pressures, reaching up to 0.45MPa and 470 K inlet temperatures. The combustor is also optically accessible with a 7.6 cm diameter quartz tube housed in a pressure vessel. It was concluded that hydrogen compositions of less than 60 percent have a reduced effect on flashback characteristics than blowout. Fast flashback was also experienced at the highest hydrogen concentrations.

An investigation of a diffusion flame gas turbine combustor with mixtures of hydrogen and natural gas has also been conducted in Germany. Tomczak et al. [33] evaluated the performance of a gas turbine when using hydrogen rich mixtures. Their combustor is a reverse-flow multi-can combustor able to operate at pressures of 1MPa and has a performance of 15 to 24 MW. This combustor is able to operate using liquid or gaseous fuels. It was concluded that high NOx emissions are the result of using pure

hydrogen in combustion systems. It was suggested that NOx emission reduction techniques such as water or steam injection would be introduced into the design of combustion systems.

Other laboratories have also designed and tested high-pressure combustors for research. The University of Cambridge [27-28] is undertaking projects in high pressure and temperature combustion. Their high-pressure combustion facility includes an optical access test unit that can operate at pressures up to 1 MPa and temperatures up to 873 K. Their combustion section is 200 mm long and has an inner diameter shell of 135 mm with cooling air surrounding the inside of the pressure vessel. This combustor mainly operates using liquid fuels but can be accommodated for gaseous fuels as well. Optical diagnostics include planar laser induced fluorescence (PLIF), laser doppler anemometry (LDA), particle dynamics anemometer (PDA), and particle image velocimetry (PIV). Their research focuses on flame structure, soot formation and thermoacoustics of flames at gas turbine operating conditions.

The University of California Irvine [29-30] is also addressing the challenges of the next generation gas turbines. Their Advanced Power & Energy Program has established the UCI Combustion Laboratory (UCICL)that performs research in combustion of alternative and fossil fuels. The UCICL currently has two operational pressure vessels to explore component and system performance at elevated temperatures and pressures. The first vessel features high optical access, full traversing, and detailed in-situ measurements. The second vessel was designed for long duration experiments and durability evaluations. Both can maintain pressures of 1.5 MPa and temperatures of 649°C. The facilities operate using high-pressure liquid fuel or natural gas. Their research focuses on alternative fuels and emissions in a gas turbine engine.

The Department of Energy is also contributing to the development of the next generation gas turbine technology. The National Energy Technology Laboratory [31] has established a high-pressure combustion facility capable to evaluate high pressure and

temperature hydrogen combustion. Experiments are performed in combination with research in computational fluid dynamics to analyze fluid flow and combustion. The optical combustor has been design to reach pressures and temperatures of up to 2.2 MPa and 700 K respectively. It is also designed to be optically accessible in the combustor as well as in the test section. A second test rig can simulate gas turbine like conditions reaching up to 1MPa and 600 K of preheated air. Natural gas and liquid fuel is being used with a focus on hydrogen and propane in the near future. The main research focus is to evaluate emissions along with flame structure and flow field characterization.

Several advancements have been made in gas turbine technology design. Many of these have been the direct result of research on gas turbine combustors that simulate operating conditions of a gas turbine. Although flashback analysis on a gas turbine would be more beneficial, it is not feasible due to the high cost associated with it.

## 2.3 IGNITION SOURCES

There are three components needed to obtain a flame: fuel, oxidizer, and an ignition source. Ignition for hydrocarbons can be generated by an external ignition source or through auto-ignition temperature. An external ignition source, such as a flame or spark, must have sufficient energy in the form of heat to ignite the mixture. Hydrocarbon gases have minimum ignition energies between 0.1 and 1 mJ. Methane, for example, has minimum ignition energy of 0.29 mJ. Conditions such as temperature, humidity, and pressure are all factors that affect the energy in a discharge. Minimum ignition energy level increases as pressure and humidity are increased. Humidity under 25% can generally be acceptable to have a significant ignition source. The second source of ignition is exceeding the auto-ignition temperature of a hydrocarbon. Surfaces exceeding such temperatures can ignite hydrocarbon vapors. Extensive studies have proved that minimum auto-ignition temperatures must be exceeded by 200 °C in order to ignite a hydrocarbon mixture in open air. Internal combustion engines operate under both sources

of ignition. Gasoline engines usually have spark ignition or external ignition source, while diesel engines operate on adiabatic compression which is the principle of auto-ignition temperature [43].

Using an external ignition source has been studied extensively. Lewis and Von Elbe [44] studied minimum ignition energy and quenching distances hydrocarbons. Their set up consisted of spark circuit with low capacity high voltage condensers. Charge was transferred from the power unit through a resistor to the spark circuit. Electricity is delivered to a test bomb where gas is introduced and ignited. The study focused mostly on minimum energies for igniting hydrocarbon gases with various oxygen-nitrogen atmospheres for short durations. It was concluded that the energies shift toward the rich side as the number of carbon atoms is increased, as well as a similarity on the smallest minimum energy for ignition for all hydrocarbons studied.

Kono et al. [45] performed investigations on a long duration composite spark. Practical ignition systems operate with capacitance and inductance components in its electric spark. Their experiment consisted of a composite spark of a capacitance spark circuit with dc or ac discharge. The spark has a duration of 0.5 μs and it is controlled by changing the values of its resistance and capacitance. The spark electrodes are 0.3 mm diameter tungsten wire with a 30° half angle cone and for a high quenching effect a 3.0 mm diameter steel rod tipped at 45° half angle cone. For testing they filled the combustion chamber with a propane-air mixture at room temperature and atmospheric pressure and discharged 25 to 30 times to record the number of ignition occurrences. It was determined that the optimum spark duration varies from 50 to 300 μs which is directly dependent on the mixture and quenching of the electrodes.

Ptasinski and Zeglen [46] investigated methane-air mixtures by multiple capacitor discharges in Poland. Ignition tests were performed under continuous flow of the mixture at various compositions. Measurements of discharge and incendivity were recorded at various conditions. The test set up consisted of an ignition chamber with stainless steel

electrodes of 10 mm in diameter and a separation between 0-10 mm with resolution to 0.01 mm. The supply of the mixture was stopped by means of an electro-valve after ignition due to the increment in pressure. It was concluded that the probability of methane-air ignition occurrence increases with the decrease in time intervals.

Other ignition methods have been investigated as an alternative to electrical discharge for improved efficiency and reliability. Laser ignition at high temperature and pressure was investigated at the Technical University of Vienna. Weinrotter et al. [47] investigated using an Nd:YAG laser at 1064 nm and a pulse duration of 5ns. Ignition was experimented at chamber pressures of up to 25 MPa and constant volume. Initial temperature and pressure of the chamber were those of 473 K and 3 MPa. Methane, hydrogen, and air were the fuel and oxidizer used which were at an equivalence ratio of 1.9 for methane-air and an addition of 15% hydrogen for an increased peak pressure. A multi-port ignition was also implemented in order to accelerate combustion at which pressures were reduced to 50%. Also a three point ignition system was investigated that used a diffractive lens to separate the laser into three points at a distance of 5 mm. A decrease in combustion time and an increase peak pressure was observed with the addition of hydrogen. Peak pressure was approximately 12 times higher with hydrogen than without it. Multi-point ignition experiments used hydrogen-air mixtures at an equivalence ratio of 4. Peak pressures increased 7% and the time to peak pressure was reduced to approximately 50%. Investigations with three focal points had no improvement on the combustion characteristics.

Other investigations on multi point ignition were carried out by Morsy and Chung [48]. Experimentation was carried out using a single shot laser with two conical cavities to introduce the methane-air mixture. The combustion chamber was kept at a constant volume. They introduced an alternative technique for laser-induced ignition in which the unfocused laser beam irradiated into the conical cavity in the combustor wall. Multiple reflection of the laser beam along the surface permits ignition through gaseous

breakdown. Two and three point ignition could be investigated with a single shot laser using this system. The Nd: YAG laser is directed to the combustion chamber using a convex lens where the beam is reduced and redirected when it hits the conical cavity on the chamber. Laser-induced spark ignition was first investigated as baseline for comparison of experiments. A larger flame volume was observed with this laser-induced cavity ignition than with the laser-induced spark ignition. One advantage seen in using two-point ignition is that pressure rises much faster than both laser-induced cavity and spark ignition. Also, flame initiation period and combustion time are significantly decreased by this system.

Although using a laser system may increase the efficiency and reliability of ignition, the cost associated with this system is not viable when compared to a regular spark plug ignition. The laser itself may cost thousands of dollars where a simple spark plug can cost you only a few. Advancements in technology have allowed for the investigation of laser ignition and have proven its reliability, yet traditional methods will continue to be used until the cost associated with it is reduced.

# Chapter 3: Experimental Setup and Design

A laboratory scale high pressure gas turbine combustor (HPTC) was developed in order to study the effects of flame stability as well as emissions produced by unburned hydrocarbons at high pressures. The combustor is made up of three configurable modules: an inlet manifold with static mixture, swirl burner, and an optically accessible combustion chamber.

The inlet manifold allows for the methane air mixture used in the combustor to be properly mixed and stabilized. The fuel-air mixture enters the inlet manifold via five injection ports; four tangential ports used for fuel and a central port used for air. The swirl burner is housed inside the inlet cap of the combustion chamber. The combustion chamber is ignited using a diffusion flame with a methane and air mixture. The quartz windows were used for imaging analysis. Pressure inside the combustion chamber was regulated using the converging nozzle located on the end cap.

## 3.1 INSTRUMENTATION

### 3.1.1 Combustion Chamber

There are two types of flames to which the sub-sonic combustion process can be classified into: diffusion flame and lean-premixed flame. In a diffusion flame, the fuel is introduced into an environment where there is an abundance of oxidizer for mixing. Combustion takes place only where the right mixture concentration is achieved. A diffusion flame usually tends to burn slower and produce more soot due to the unburned fuel in the mixture. A second type of flame is lean-premixed where the fuel and oxidizer are mixed prior to ignition. This is done in order to achieve a lean, uniform, and complete mixture.

This combustor operates using a lean-premixed flame ignited by a diffusion flame. The chamber is constructed in a cylindrical cross-section with optical access. Three rectangular quartz windows provide optical access for the measuring

instrumentation. Three circular windows allocate for instrumentation ports or additional optical access. Operational parameters for the combustor design were those of a chamber pressure of 1.5 MPa and an operating temperature of 2400 K. This temperature was the calculated adiabatic flame temperature. The balanced equation is shown below using a 70% CO and 30% $H_2$ mixture.

$$0.7CO + 0.3H_2 + 0.5(O_2 + 3.76N_2) \xrightarrow{yields} 0.7CO_2 + 0.3H_2O + 1.88N_2$$

The adiabatic flame temperature was found using STANJAN. This in turn would be the highest temperature the combustor can be exposed to using this mixture. The combustor also has a maximum power rating of 500 kW. Figure 3.2 represents the schematic diagram of the gas turbine combustor.

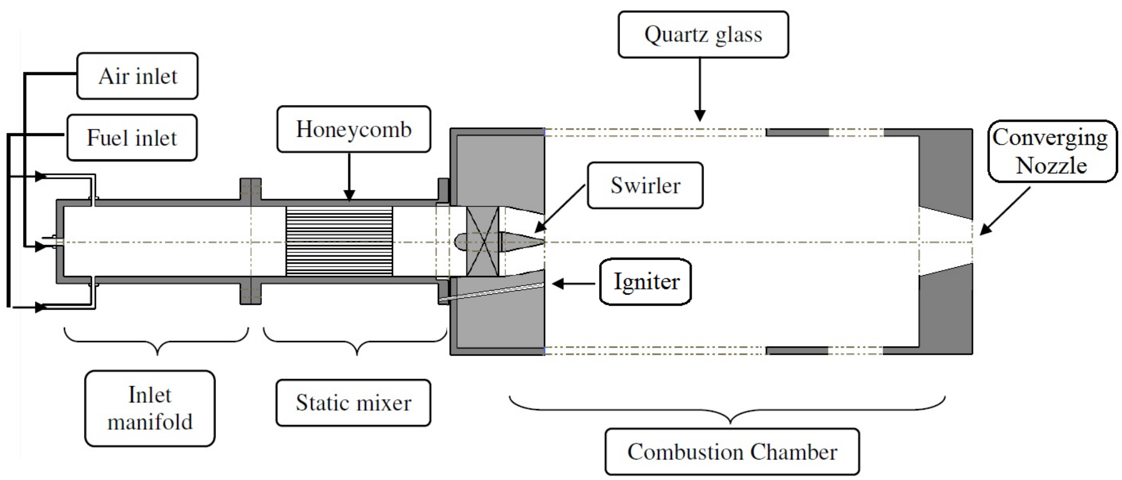


**Figure 3.1. Schematic Diagram of the Gas Turbine Combustor**

The chamber is composed of three major parts: front cap, chamber, and end cap. The front cap houses the swirler and ignition system. A center body swirler with 12 vanes and a swirl number of 0.97 was used in this study and has been previously experimented with in the atmospheric combustor. Its center body is made from stainless steel and the veins are from anodized aluminum for higher temperature resistance, see Figure 3.3 [6]. Swirling flows allow for good mixing which ensures efficient combustion. Swirl number

is defines as the flux of angular and linear momentum and it can be approximated using the following equation.

$$S = \frac{2}{3}\left[\frac{1-\left(\frac{d_h}{d}\right)^3}{1-\left(\frac{d_h}{d}\right)^2}\right]\tan\theta \qquad (3.1)$$

Where $d_h$ and d are the hub diameter and swirler diameter respectively [49-50]. The swirl number has a direct effect on the flames size, shape, stability, and combustion intensity as previous studies have proven.

**Figure 3.2. Swirler**

The combustion chamber houses three rectangular quartz windows as well as three instrumentation ports that can be also used for optical access. The wall thickness of 88.9 mm was determined by using NX Nastran Design Simulation at an operating temperature of 350 K. Using a 10 node tetrahedral mesh, results obtained showed a maximum stress of 355.08 MPa which is less than the yield strength of 575 MPa for stainless steel (SS) 410. Stress concentrations were found in the corners of the window covers and on the edges of the instrumentation ports which are the areas of maximum displacement as seen in Figure 3.4.

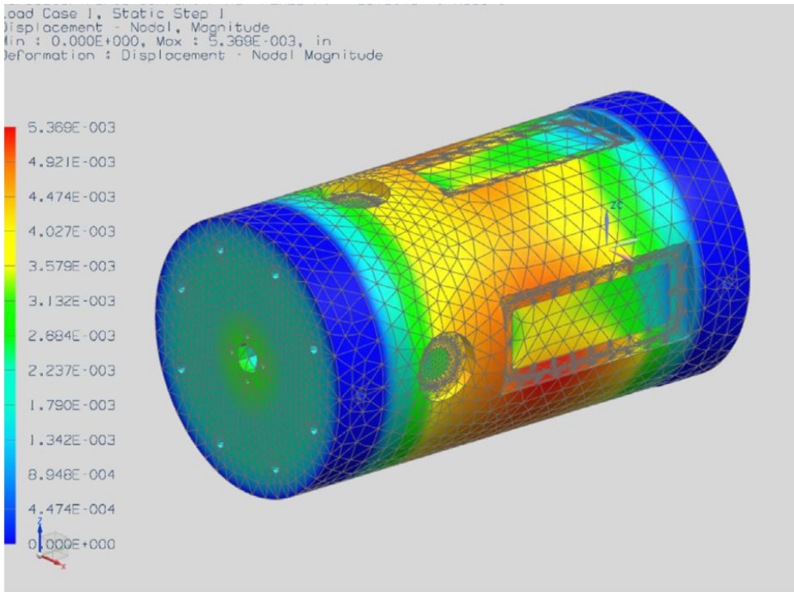


**Figure 3.3. Combustion Chamber Displacement [51]**

The wall thickness of 5.08 mm for the window covers was also found using finite element analysis (FEA). The constraints used for this analysis were placed at the bolt holes in the window cover in order to resemble the actual conditions. Temperature and pressure loads used were those of 350 K and 1.5 MPa respectively, both placed inside the window cover where the quartz windows are. Figure 3.5 demonstrates the results obtained where there is a maximum stress of 290.95 MPa, which is still below the yield strength of SS 410. Instrumentation ports were also placed in the combustion chamber to

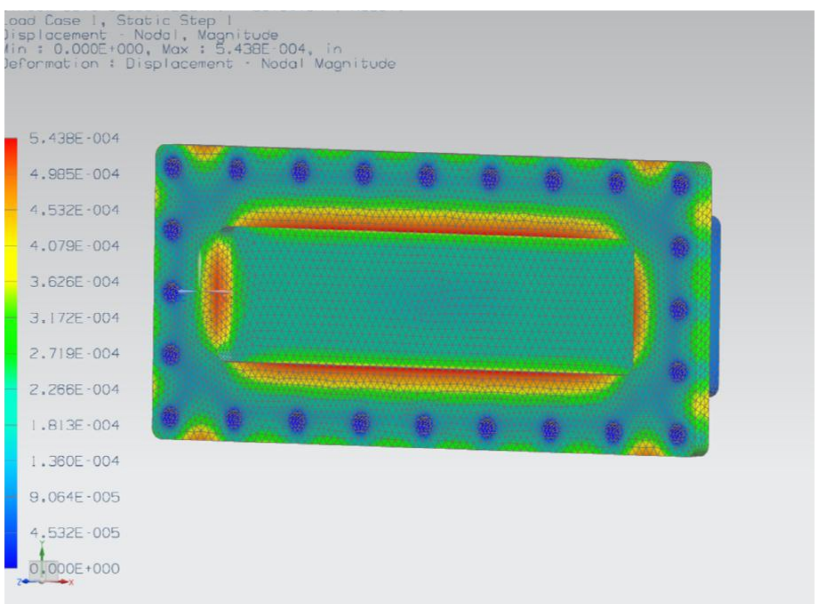


**Figure 3.4. Window Cover Displacement [51]**

allow optical access, gages, or burst disks. It is also designed to be used as an entrance for material placement for testing inside the combustor. The properties for stainless steel 410 can be found in Table 3.1. The window covers were modified to allow the user with an easier method for removal. Four threaded holes were added on the corners of the covers such that when the bolts hit the wall the window cover moves out.

**Table 3.1. Stainless Steel Properties [52]**

**Mechanical Properties**

Typical mechanical properties for grade 410 stainless steels are given in table 2.

**Table 2.** Mechanical properties of 410 grade stainless steel

| Tempering Temperature (°C) | Tensile Strength (MPa) | Yield Strength 0.2% Proof (MPa) | Elongation (% in 50mm) | Hardness Brinell (HB) | Impact Charpy V (J) |
|---|---|---|---|---|---|
| Annealed * | 480 min | 275 min | 16 min | - | - |
| 204 | 1310 | 1000 | 16 | 388 | 30 |
| 316 | 1240 | 960 | 14 | 325 | 36 |
| 427 | 1405 | 950 | 16 | 401 | # |
| 538 | 985 | 730 | 16 | 321 | # |
| 593 | 870 | 675 | 20 | 255 | 39 |
| 650 | 755 | 575 | 23 | 225 | 80 |

* Annealed properties are specified for Condition A of ASTM A276, for cold finished bar.

# Due to associated low impact resistance this steel should not be tempered in the range 425-600°C

The end cap was designed to be modular with three removable sections. A converging nozzle, nitrogen exhaust disk, and the end cap. Currently only the end cap and converging nozzle are being used in this experiment. The converging nozzle regulates the pressure drop across the combustor. The end cap is designed to close the combustion chamber and also as the link to the exhaust. (For a detailed description on the design of the combustor please refer to [51].)

### 3.1.2 Inlet Manifold

As previously discussed, this combustor operates using lean-premixed combustion. Both fuel and oxidizer are mixed in the inlet manifold prior to their entrance to the combustion chamber. It is composed of three modular sections: fuel/oxidizer mixture, static mixture, and connector to combustor. Fuel and air enter the inlet manifold in the first section which initiates the mixing. It is then passed through the static mixer, which is made up of a honeycomb that is placed inside the inlet manifold to stabilize the flow. Figure 3.1 demonstrates the honeycomb used in the combustor. The sections are united using flanges with alumina and copper gasket to seal the junctions.

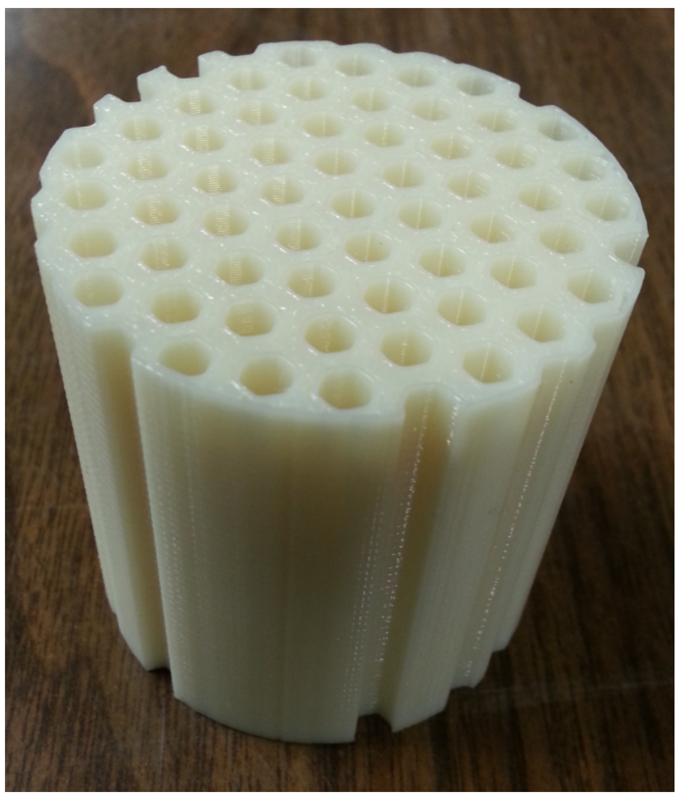

**Figure 3.5. Honeycomb**

### 3.1.3 Flow Control

The high pressure gas turbine combustor is designed to deliver carbon monoxide and hydrogen as fuel and air as the oxidizer. The schematic of the delivery system is demonstrated in Figure 3.6.

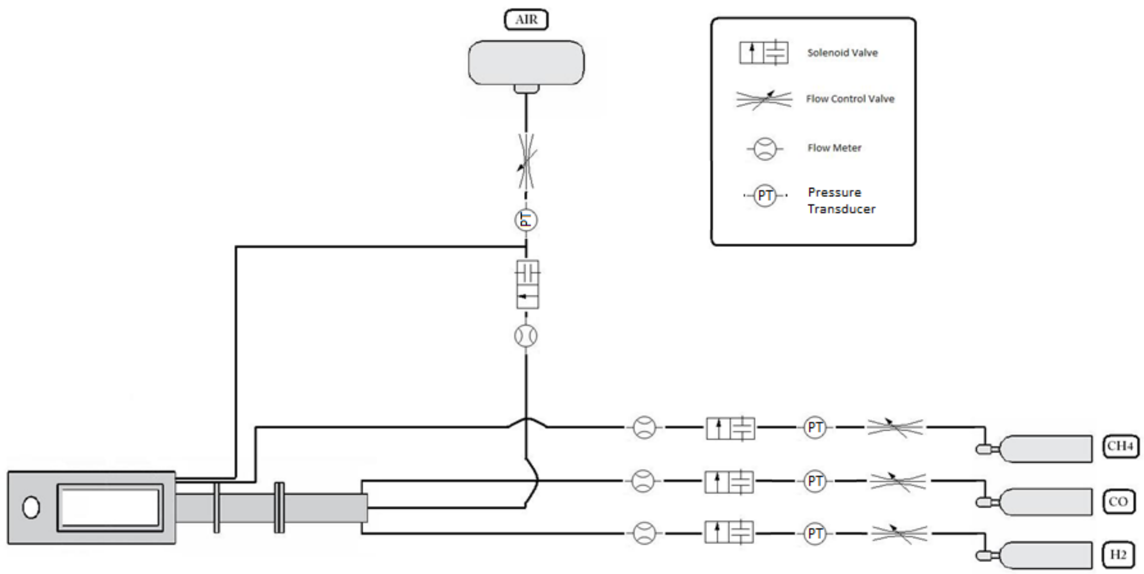


**Figure 3.6. Control System Schematic**

The solenoid valves are the model number 1314IA06T from Jefferson valves which are actuated with a 120 VAC signal and are shown in Figure 3.7. These were selected due to their pressure differential of 1550 kPa and their 1.91 cm connection. They are normally closed two way valves made of 316 stainless steel. It was required to manufacture a connection that would power up the valves. A computer power cable was split and rewired to accommodate the needs of the valves. Terminal blocks were then used to distribute the 120 VAC signal to all three valves.

**Figure 3.7. Jefferson Valve 1314 Series**

A second set of valves used were the EH2 series from KZ Valve actuated with a 12 VDC signal. They are also a two way valve operated by a motor that turn a stainless steel ball valve which regulates the flow. The valves are rated up to 6895 kPa and can be regulated with an output of 0-10 VDC. Figure 3.8 demonstrates the EH2 valve.


**Figure 3.8. KZ Valve EH2 series**

Omega flow meters were used to measure gas flow in the lines. FMA 1843-1845 were selected based on their flow measurement capacity. They require an excitation voltage of 12 VDC and provide a signal of 0-5 VDC as feedback that can be acquired in LabVIEW. Numeric displays in the valves confirm the reading that is obtained in the computer as shown in Figure 3.9. Calibration was performed for each valve reading in LabVIEW following the following formula. The flow meter outputs a certain voltage that needs to be multiplied by a correction factor and then the residual background noise must be subtracted. See Appendix B for a sample calculation.

$$Actual\ Flow = \left(x\ V * \frac{maximum\ flow\ of\ the\ mass\ flow\ meter}{maximum\ total\ output\ signal}\right) - background\ noise$$

Where *x* represents the voltage output from the flow meter. This in turn provided a value in liters per minute that can be monitored remotely without the need to see the reading in the valve. The flow meters were connected to the USB 6008 and the power supplies in order to be able to observe the flows from the graphics interface. Pins number 2-5 were used in order to power the flow meters and communicate with the computer as shown in Figure 3.10. The wiring was as follows: black – power common, red – power positive, green – 0-5 VDC common, white – 0-5 VDC output.


**Figure 3.9. Omega FMA Series 1700/1800**

| PIN | FUNCTION |
|---|---|
| 1 | Remote LCD display signal |
| 2 | 0 to 5 VDC output indication |
| 3 | 0 to 5 VDC common |
| 4 | Power supply, positive |
| 5 | Power supply, common |
| 6 | Remote LCD display reference |
| 7 | (unassigned) |
| 8 | 4 to 20 mA output indication |
| 9 | 4 to 20 mA common |

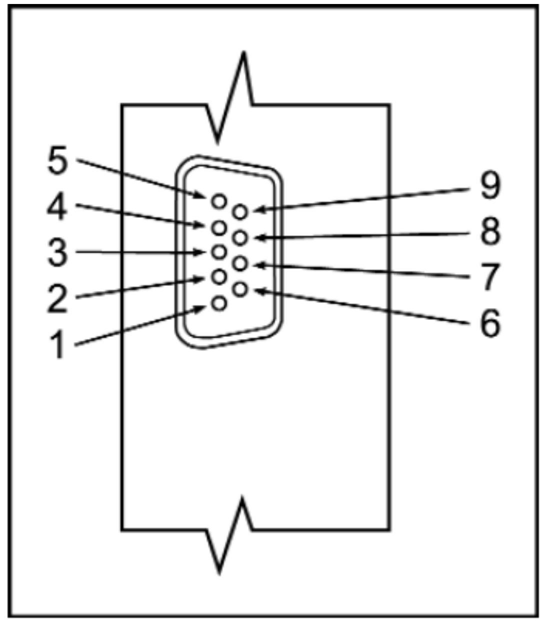


**Figure 3.10. FMA 1700/1800 Pinout**

Pressure transducers were also implemented in the system to evaluate the pressure in the lines. Omega pressure transducers PX309-300G5V were selected and require a 9-30 VDC excitation and feedback a signal from 0-5 VDC. These transducers can read pressures of up to 2068 kPa and are shown in Figure 3.11. We operate the transducers using 10 VDC and the wiring connection is shown in Figure 3.12. Please note that the ground cable from the transducer is split to two wires one which connects to the negative on the power supply and one which connects to the common in the USB DAQ.


**Figure 3.11. Omega PX309-300G5V**

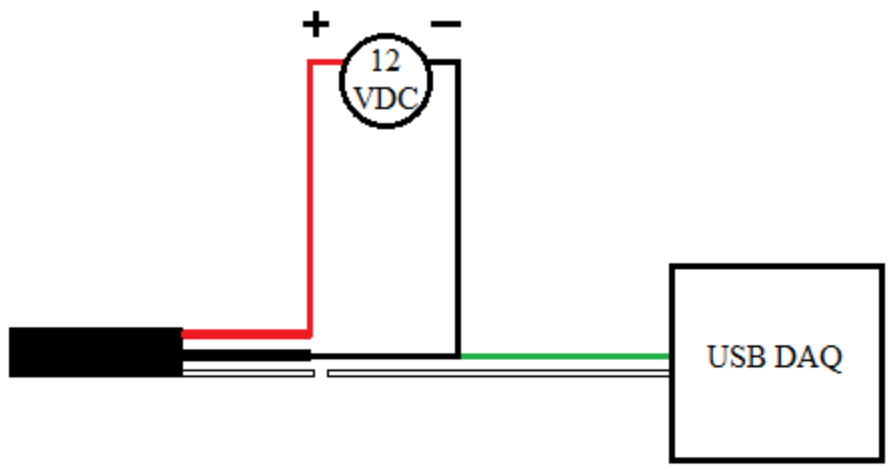


**Figure 3.12. Wiring Schematic for Pressure Transducer**

An analysis was performed in order to define what was required for the control of the flow. The requirements for each part of the instrumentation used varied and thus it was necessary to analyze the electrical characteristics to make the hardware function properly. These characteristics were summarized in Table 3.2. A minimum of 8 valves were required to control the high pressure turbine combustor; four solenoid and four proportional control valves which used both AC and DC voltages. Instrumentation used also required 0-5 VDC, 0-30 VDC, 0-10 VDC and 120 VAC to be powered up.

**Table 3.2. Electrical Characteristics of HPTC Components**

| Classification | Hardware | Electrical Characteristics |
|---|---|---|
| Control | 4 Solenoid valves | Excitation: 120 VAC |
| | 4 Proportional control valves | Excitation: 12 VDC |
| | | Output: 0-10 VDC |
| Measurement | 3 Pressure transducers | Excitation: 9-30 VDC |
| | | Output: 0-5 VDC |
| | 4 Mass flow meters | Excitation: 0-12 VDC |
| | | Output: 0-5 VDC |

Power is provided by a DC power supply unit from EXTECH Instrument model number 382270 as seen in Figure 3.13.There are two units to meet the power demand of

the instrumentation. Each unit provides a total of four outputs: two 0 to 30 V with a maximum of 5 A, one 3 to 6.5 V with a maximum of 3 A, and one 8-15 V with a maximum of 1 A.


**Figure 3.13. EXTECH Instruments 382270 Power Supply**

Wiring for the HPGTC was done via two different types of wire. The wire for the control of the solenoid valves was selected to be a gage 12 AWG stranded wire from Grainger due to the 120 VAC supply needed for the valves. The wire has a rating of 600 Volts and 20 amps. A second multi-paired wire from Mouser Electronics was used to connect the proportional valves to the DAQ. This type of wire has four gage 18 AWG wire and it is rated at 300 Volts.

The hardware components consisted of a PCI card and a USB DAQ from National Instruments (NI). The NI PCI-6521 has eight mechanical relay outputs and can output 150 Volts AC or DC. This PCI was used to control the solenoid valves with the mechanical relay outputs via LabVIEW. The USB-6008 has two 0-5 VDC analog outputs and eight ±10 Volts analog inputs. Two USB-6008 were implemented in the set up for control of the proportional valves. Both hardware components are demonstrated in Figure 3.14. The connections for both the PCI card and DAQ varied depending on their use. The valve assignment in LabVIEW was performed by following the pinouts of the corresponding hardware accessory as shown in Figure 3.15. The PCI 6521 is solely a relay card which was used to actuate the solenoid shut off valves as well as the igniter

coil. Alternatively, the USB 6008 has both analog outputs and inputs. Three analog inputs were used for the flow meters in the first DAQ as well as both analog outputs for the proportional valves. The second DAQ is used for the third proportional valve by using port AO 1.


**Figure 3.14. NI PCI-6521 and USB DAQ-6008**

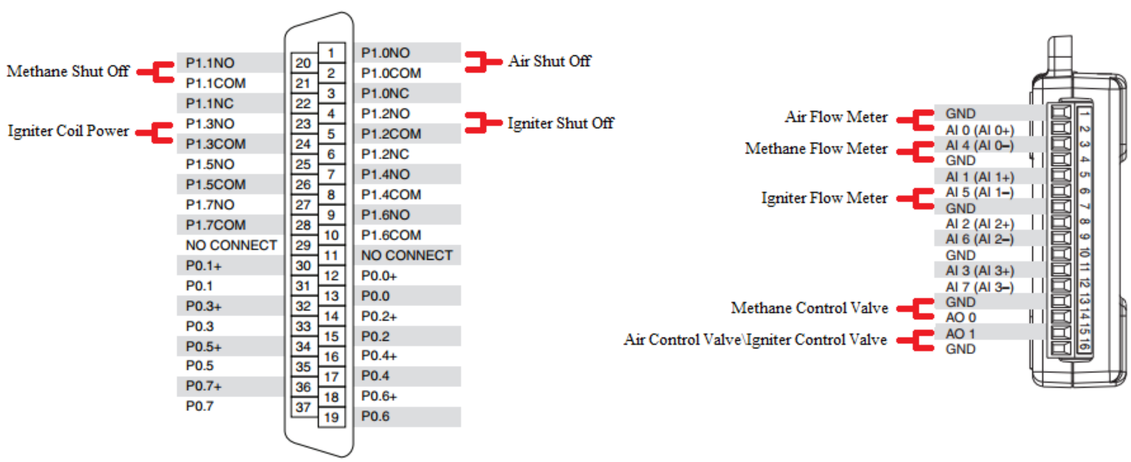


**Figure 3.15. PCI 6521 (left) and USB 6008 (right) Pinout Assignment**

All cables were routed to terminal blocks and then distributed to both USB 6008's and PCI 6521. The flow control system was used for both the igniter and the combustor. The use of actuated valves permitted remote operation as a safety precaution to not

expose the user to the risks associated with high pressure combustion. Software configuration will be discussed in section 3.1.5.

### 3.1.4 Igniter

A spark plug was modified with the purpose of providing the HPTC with a reliable and fast ignition source capable of withstanding the pressure and temperature of the HPTC environment. The spark ignition had several requirements that are as follows:

- The igniter should be able to reach the inside of the combustor without interfering with the quartz tube.
- The igniter should be able to feed methane and air as oxidizer and fuel.
- The igniter should not premix the oxidizer and fuel until it is an inch away from the combustion chamber.
- The igniter should be designed to withstand temperatures of up to 1800°C.

A concentric design was chosen in order to avoid premixing of the gases. The outer tube was chosen to have a diameter of 1.905cm while the inner concentric tube that of 1.27cm. The spark plug would then be concentric with the inner 1.27 cm tube. Housing for the spark plug was required to be manufactured given that it was not a conventional design. A 2.54cm cylinder was drilled in the middle for an opening for the spark plug. The spark plug threaded entrance had a diameter of 1.2 cm and the reducer end was that of 1.27 cm to be introduced into the igniter. Figure 3.16 demonstrates the designed housing and reducer. The reducer side was swaged to a T connector that introduces the fuel to the 1.27 cm tube. Air is introduced to the 1.905 cm tube via a cross connector which can also be used to introduce nitrogen to the line as shown in Figure 3.17.

The spark plug was modified and extended in order to meet the length of 45.72 cm. Haynes 230 was selected as the central electrode material due to its low resistivity and high melting point. The haynes 230 rod was then welded to the spark plug in order to achieve the extension needed and the ground electrode insulator was cut as shown in Figure 3.18.A holder was needed to be manufactured in order to maintain the extension electrode centered with the spark plug electrode in order to be welded. A 2.54 cm steel block was used to accommodate both the spark plug and the haynes 230. The block had two main holes: a 1.19 cm hole that was tapped for a 14 mm thread and a 0.32 cm entrance for the haynes 230; furthermore, a 0.76 gap was also drilled out to be able to weld both components It was noted that after welding the ceramic insulator inside the spark plug was broken and therefore it was needed to be filled out using resbond. Table 3.3 shows the typical properties for haynes 230. It was then needed to insulate the electrode so that the spark could be carried to the outside electrode. Ceramic thermocouple insulator from Omega was selected to insulate the electrode due to its high temperature resistance.

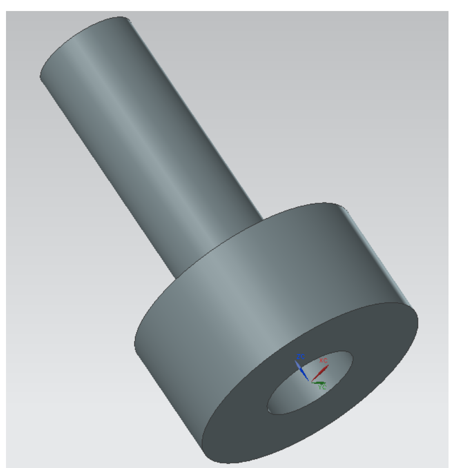

**Figure 3.16. Housing Designed for Spark Plug**

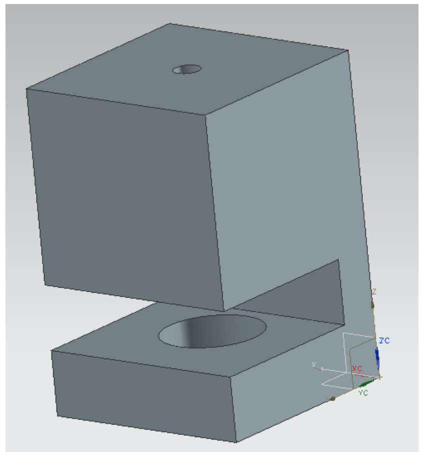

**Figure 3.17. Holder used for the Welding Process**

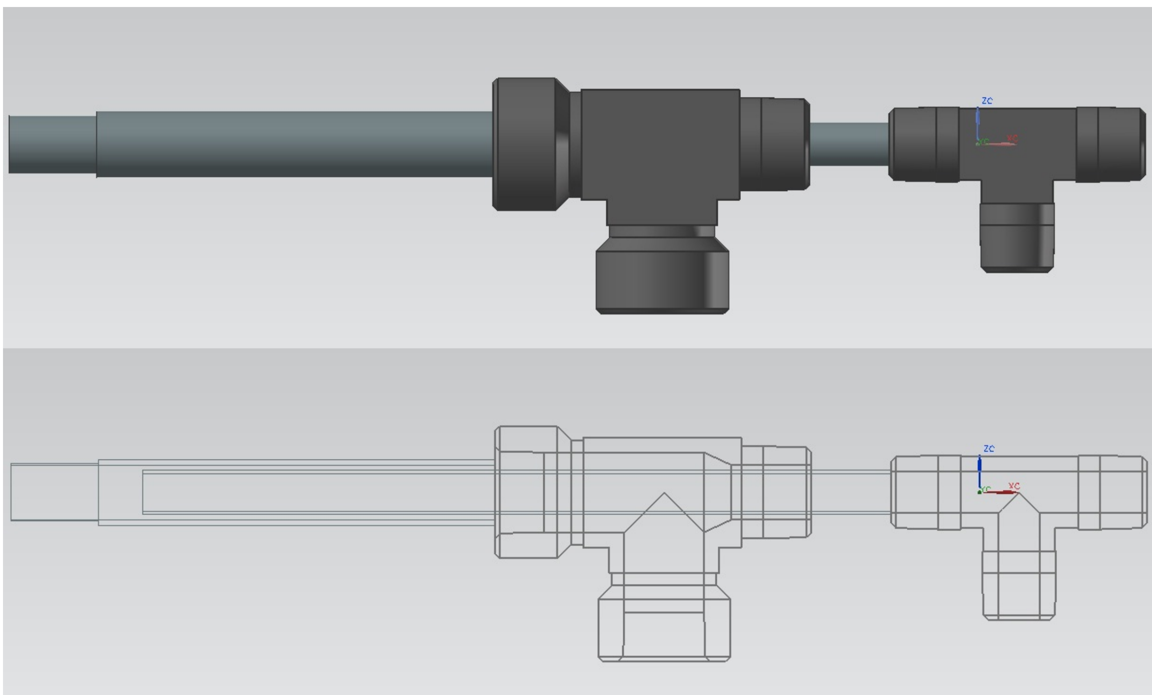

**Figure 3.18. Design of Igniter**

## Table 3.3. Typical Properties for Haynes 230 [53]

| | Temperature, °F | British Units | Temperature, °C | Metric Units |
|---|---|---|---|---|
| Density | Room | 0.327 lb/cubic in | Room | 9.05 g/cubic cm |
| Melting Range | 2350-2510 | | 1290-1375 | |
| Electrical Resistivity | Room | 49.2 miohm-in. | Room | 125.0 microhm-in. |
| | 200 | 49.5 | 100 | 125.8 |
| | 400 | 49.8 | 200 | 126.5 |
| | 600 | 50.2 | 300 | 127.3 |
| | 800 | 50.7 | 400 | 128.4 |
| | 1000 | 51.5 | 500 | 130.2 |
| | 1200 | 51.6 | 600 | 131.2 |
| | 1400 | 51.1 | 700 | 130.7 |
| | 1600 | 50.3 | 800 | 129.1 |
| | 1800 | 49.3 | 900 | 127.1 |
| | -- | -- | 1000 | 125.0 |
| Thermal Diffusivity | Room | 3.8 x 10(-3) $in^2$/sec. | Room | 24.2 x 10(-3) $cm^2$/sec. |
| | 200 | 4.1 | 100 | 26.8 |
| | 400 | 4.7 | 200 | 29.9 |
| | 600 | 5.2 | 300 | 32.9 |
| | 800 | 5.6 | 400 | 35.7 |
| | 1000 | 6.1 | 500 | 38.5 |
| | 1200 | 6.5 | 600 | 41.9 |
| | 1400 | 6.7 | 700 | 43.0 |
| | 1600 | 6.7 | 800 | 43.2 |
| | 1800 | 7.3 | 900 | 44.4 |
| | -- | -- | 1000 | 48.2 |
| Thermal Conductivity | Room | 62 BTU-in./$ft^2$hr.-°F | Room | 8.9 W/m-K |
| | 200 | 71 | 100 | 10.4 |
| | 400 | 87 | 200 | 12.4 |
| | 600 | 102 | 300 | 14.4 |
| | 800 | 118 | 400 | 16.4 |
| | 1000 | 133 | 500 | 18.4 |
| | 1200 | 148 | 600 | 20.4 |
| | 1400 | 164 | 700 | 22.4 |
| | 1600 | 179 | 800 | 24.4 |
| | 1800 | 195 | 900 | 26.4 |
| | -- | -- | 1000 | 28.4 |
| Specific Heat | Room | 0.095 Btu/lb.-°F | Room | 397 J/Kg-K |
| | 200 | 0.099 | 100 | 419 |
| | 400 | 0.104 | 200 | 435 |
| | 600 | 0.108 | 300 | 448 |
| | 800 | 0.112 | 400 | 465 |
| | 1000 | 0.112 | 500 | 473 |
| | 1200 | 0.134 | 600 | 486 |
| | 1400 | 0.140 | 700 | 574 |
| | 1600 | 0.145 | 800 | 595 |
| | 1800 | 0.147 | 900 | 609 |
| | -- | -- | 1000 | 617 |
| Mean Coefficient of Thermal Expansion | 70-200 | 7.0 microin/in.-°F | 25-100 | 12.7 x 10(-6) m/m-°C |
| | 70-400 | 7.2 | 25-200 | 13.0 |
| | 70-600 | 7.4 | 25-300 | 13.3 |
| | 70-800 | 7.6 | 25-400 | 13.7 |
| | 70-1000 | 7.9 | 25-500 | 14.0 |
| | 70-1200 | 8.1 | 25-600 | 14.4 |
| | 70-1400 | 8.3 | 25-700 | 14.8 |
| | 70-1600 | 8.6 | 25-800 | 15.2 |
| | 70-1800 | 8.9 | 25-900 | 15.7 |
| | -- | -- | 25-1000 | 16.1 |

It is made of mullite type ceramic which can withstand temperatures up to 1650°C. Resbond was also used to attach the insulators to the spark plug. Figure3.19 demonstrates the components of the spark plug and Figure 3.20 is the complete assembly of the igniter.

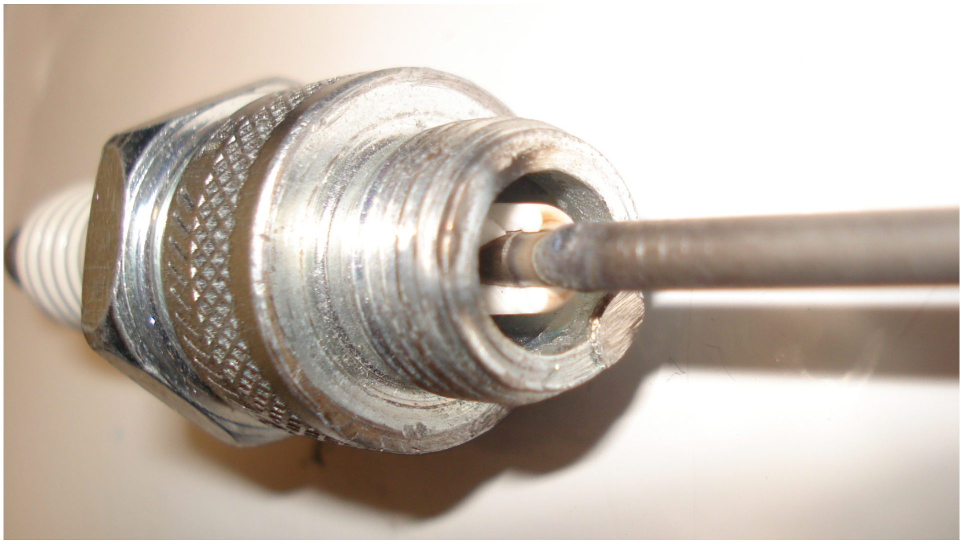

**Figure 3.19. Spark Plug Weld**

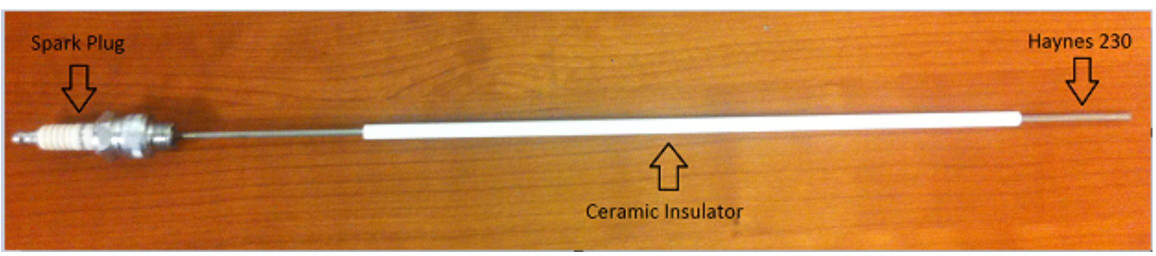


**Figure 3.20. Spark Plug Components**

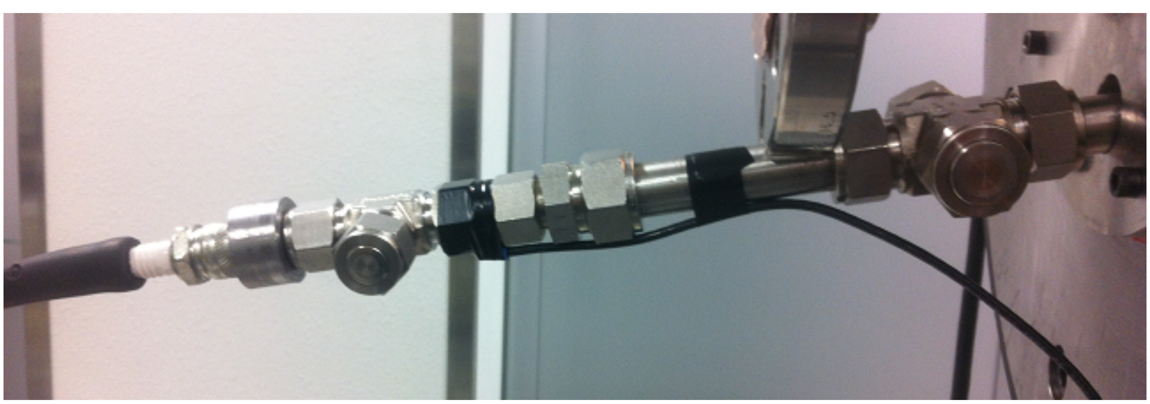

**Figure 3.21. Igniter Assembly**

Modifications had to be made on the front cap in order to accommodate an entrance for the ignition system. A 1.67 cm hole was drilled 3.81 cm center to center from the main combustion line to allow a threaded entrance for the ignition system. The entrance port was made at a 10° angle in order for the igniter flame to hit the main combustion line. In addition, the 10° angle allowed for no interference of the ignition system with the quartz tube port. Figure 3.21 demonstrates the modifications made to the front cap.

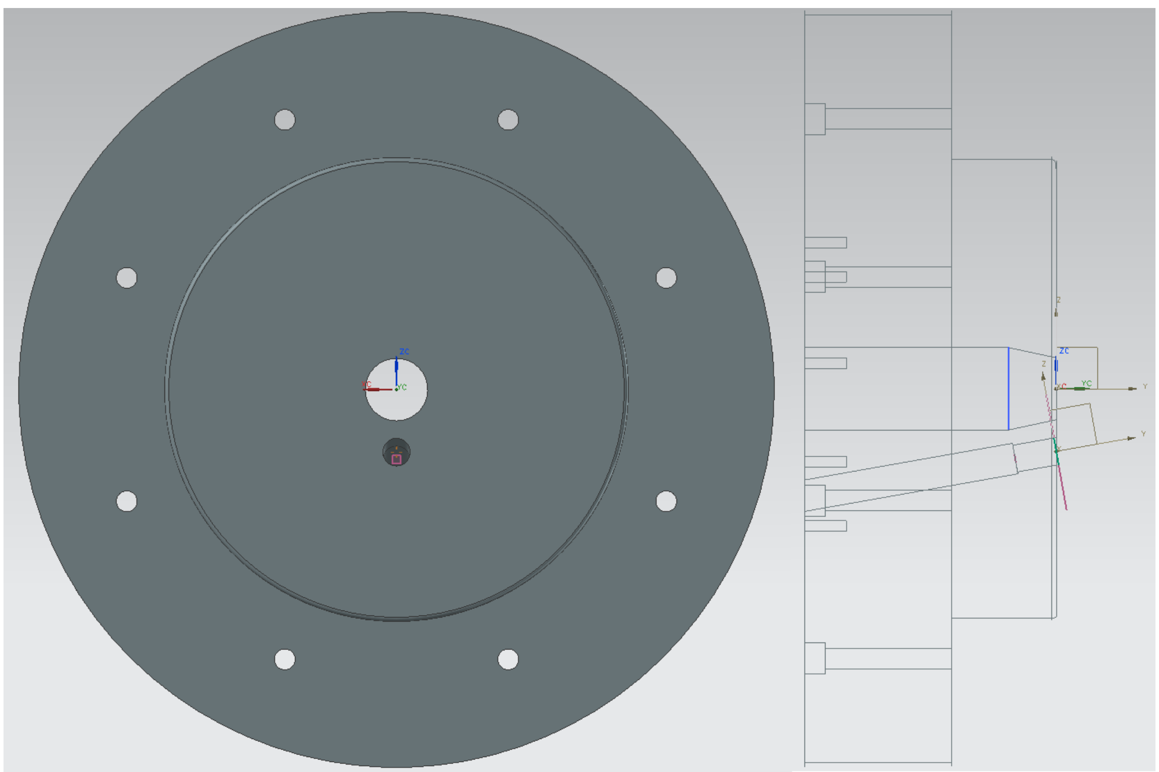

**Figure 3.22. Modifications Made to the Front Cap**

Configuration of the hardware components was performed following the manufacture and assembly of the igniter. MSD 8247 multi-spark coil was selected to create the discharge needed for the spark plug. This coil needs a frequency of 100 Hz and a 5 V input; these are provided using a signal generator and a 12 V battery. The four pin connector was selected in order to accommodate all the components needed. Figure 3.22 demonstrates the MSD 8247 and its connection pin out.

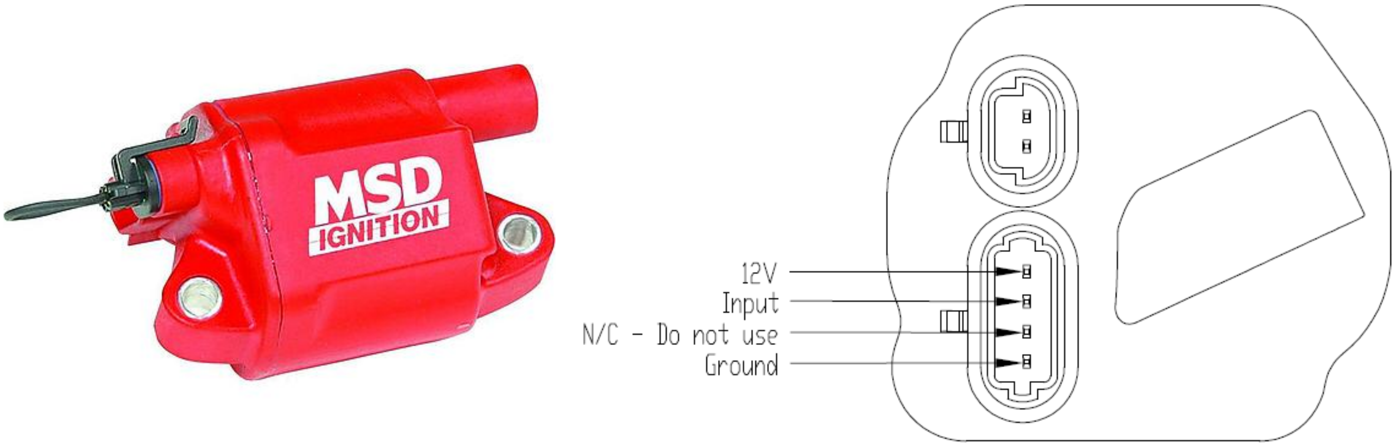


**Figure 3.23. MSD 8247 and Connection Pin Out**

Wiring was done using the Mouser Electronics 18 AWG cables as follows:

- Red – 12 V battery positive to 12 V in coil
- White – Coil input to PCI 6521 to signal generator
- Green – Coil ground to 12 V battery negative
- Black – 12 V battery negative to spark plug ground

The negative battery connector was also grounded to the power supplies in order to avoid any undesired current. Figure 3.23demonstrates the battery connector with all its components. The two green cables are used as ground and each one connects to one power supply for safety purposes.

BK Precision 4012A signal generator was used to generate the 100 Hz frequency needed for the coil and it is shown in Figure 3.24. A square signal was sent via a transistor-transistor logic (TTL) channel that outputs a mean of 2.4 V. It is important to connect only to the TTL channel because the output channel gives 14 V which can burn the coil. Also, the coil will not turn on unless the TTL 5V signal is sent via LabVIEW; therefore, the user has control over the TTL signal and thus control over the coil ignition. The Bayonet Neill-Concelman (BNC) cable was cut at one end in order to connect the positive and negative wires. The 12 V battery was used mainly to provide the current needed for the spark plug. The configuration of the software components will be discussed in section 3.1.5.

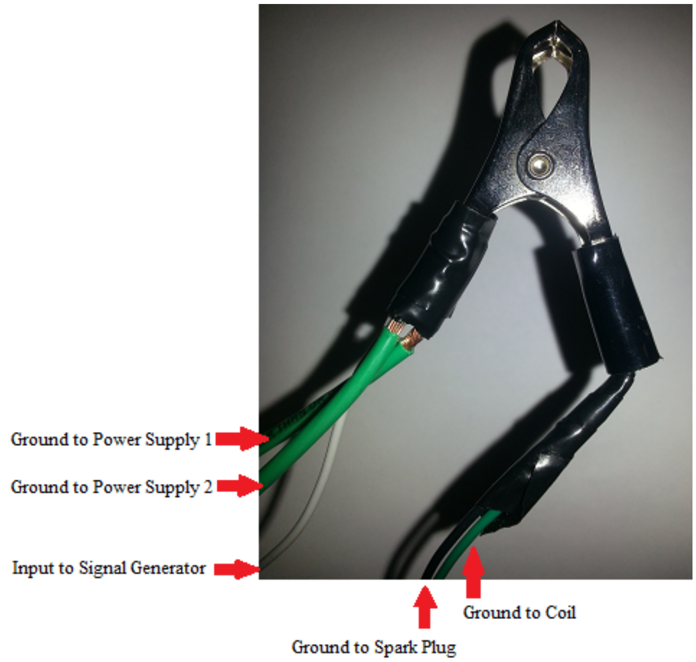


**Figure 3.24. Negative Battery Connector**


**Figure 3.25. BK Precision 4012A Signal Generator**

### 3.1.5 Integration of Components

Software configuration in LabVIEW was performed after all the hardware set up was completed. LabVIEW provides the user with a graphical interface and permits remote operation and monitoring. Both USB DAQ and PCI card were configured using the DAQ Assistant tool from LabVIEW. The configuration for the PCI 6521 card is shown in Figure 3.25. As previously discussed, this card controls the solenoid valves for the fuel and air lines for both the combustor and igniter. Each solenoid valve is normally closed and needs to be actuated in order to be opened.

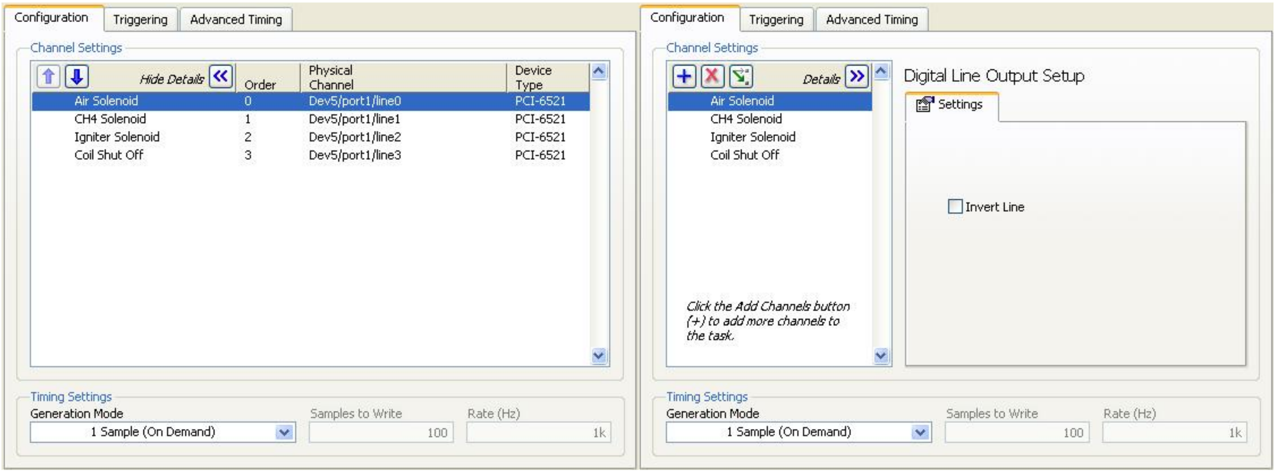


**Figure 3.26. PCI 6521 Configuration**

Figure 3.26 demonstrates the configuration for USB 6008 DAQ 01, which controls the air and methane proportional valves; in addition, the three flow meters are also controlled using this DAQ. This DAQ has five input channels that are available to use. Figure 3.27shows the configuration for the second USB 6008 DAQ 02. This DAQ controls the remaining proportional valve used for the igniter. Furthermore, this DAQ also has eight input channels available as well as one analog output channel. Both USB 6008 had a signal output range from 0-5 Volts with a terminal configuration of RSE and on demand samples.

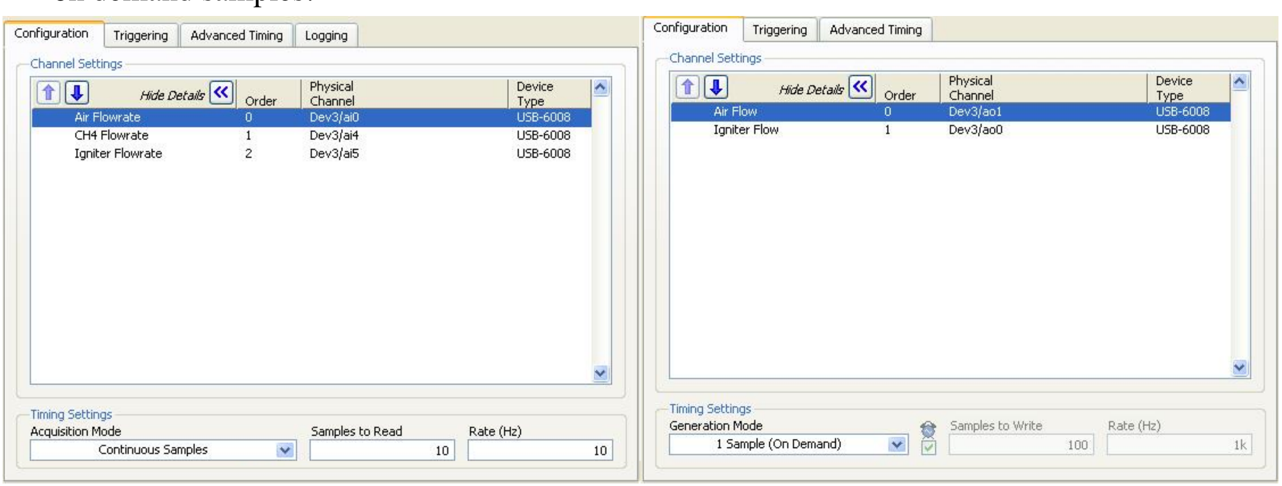


**Figure 3.27. USB 6008 DAQ 01 Configuration**

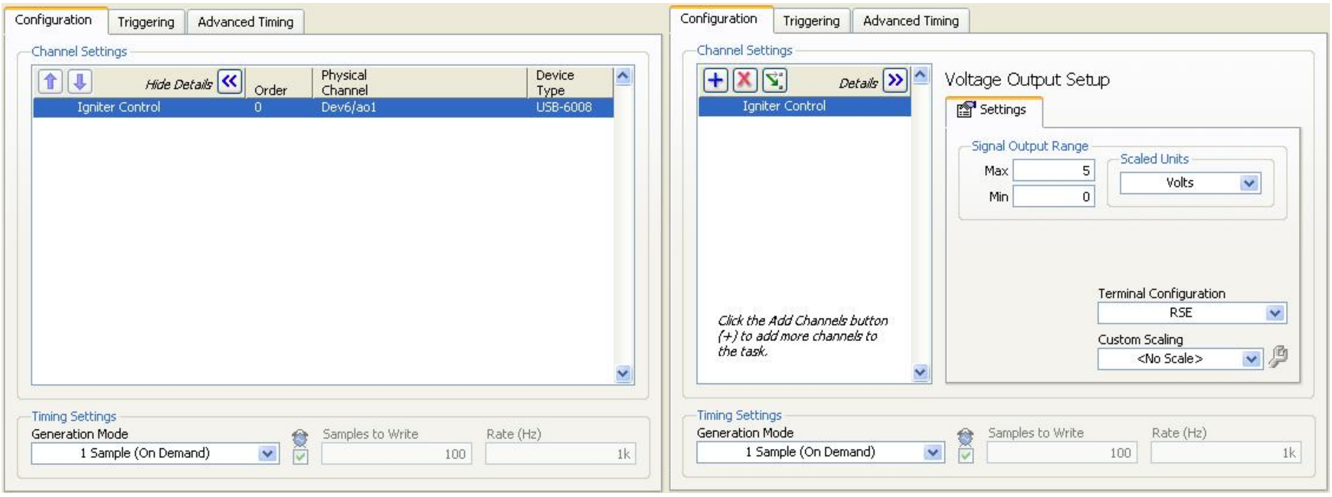


**Figure 3.28. USB 6008 DAQ 02 Configuration**

Configuration of the graphic interface was initiated once the hardware components were integrated into LabVIEW. All controls and sensors are integrated in the same window to facilitate inspection and control of the experiment. Flow control can be regulated by modifying the voltage on the proportional control valves from 0-5 volts. The solenoid valves have to be actuated in order for the line to be opened. A green light in the panel indicates that the valve is open and flow can go through. Figure 3.28 demonstrates the graphic interface panel for the high pressure turbine combustor. Data was recorded using the “Write to Measurement File” tool in LabVIEW. Data is saved in a series of files and includes date and time of testing. This data can then be viewed and analyzed in Excel. Data are saved according to the samples to write and rate which can be modified in the configuration of the input data located at the DAQ Assistant tool.

A relay card diagnostics lets the user know which lines are still open; furthermore, it also informs the user about the igniter coil status. A green light indicates the relay is on and functioning. All logic is placed inside a while loop which repeats the sequence until the stop button is activated. The logic circuit programmed was divided into three parts: proportional valves, data, and solenoid valves. The proportional valves are controlled using a numeric controller which then is converted into dynamic data for the DAQ. Figure 3.29 demonstrates the logic for the proportional valves.

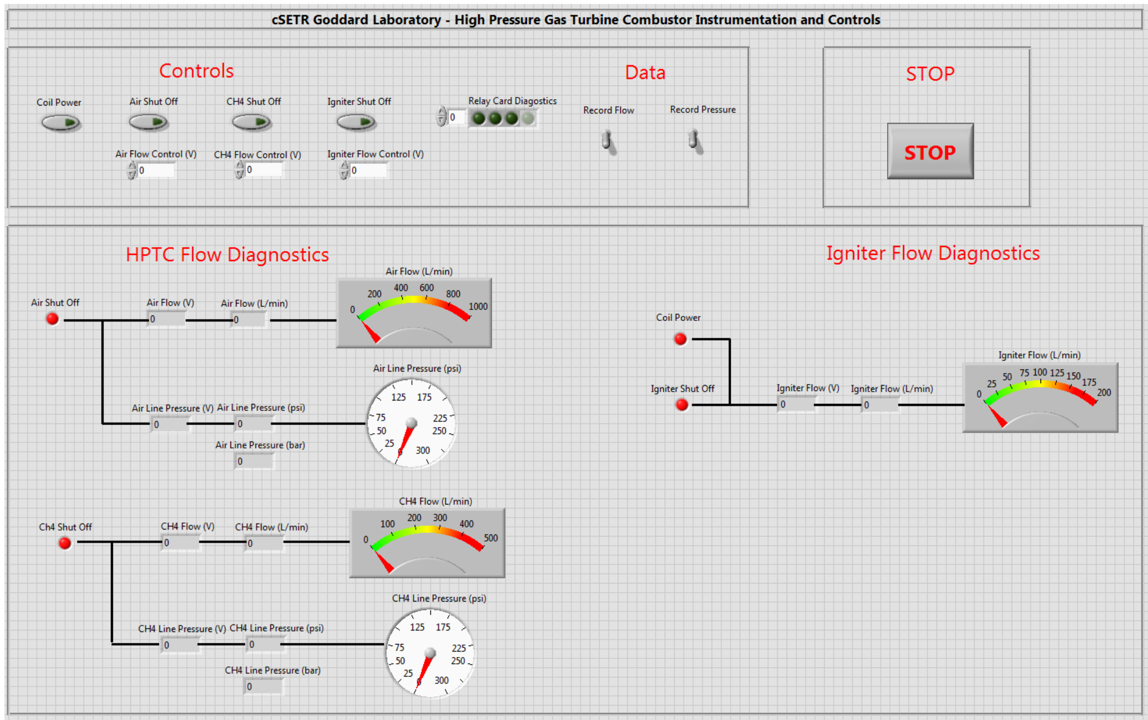


**Figure 3.29. Graphic Interface Panel for the HPTC**

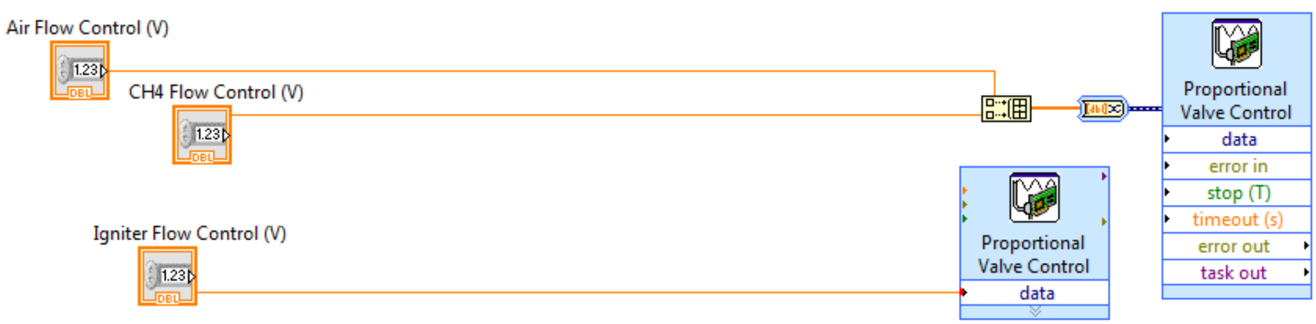


**Figure 3.30. Proportional Control Valves Logic**

Data is acquired and recorded using the first USB 6008 DAQ. The output signal is acquired by the DAQ from the instrumentation and is visually represented in the graphic interface panel. The signal comes in as a voltage, which then needs to be changed to a L/min reading by applying the actual flow formula. A series of indicators lets the user know the status of the flow both graphically and numerically. All data is recorded in L/min and limited by the samples and rate. Figure 3.30 demonstrates the logic for Data Acquisition and Recording.

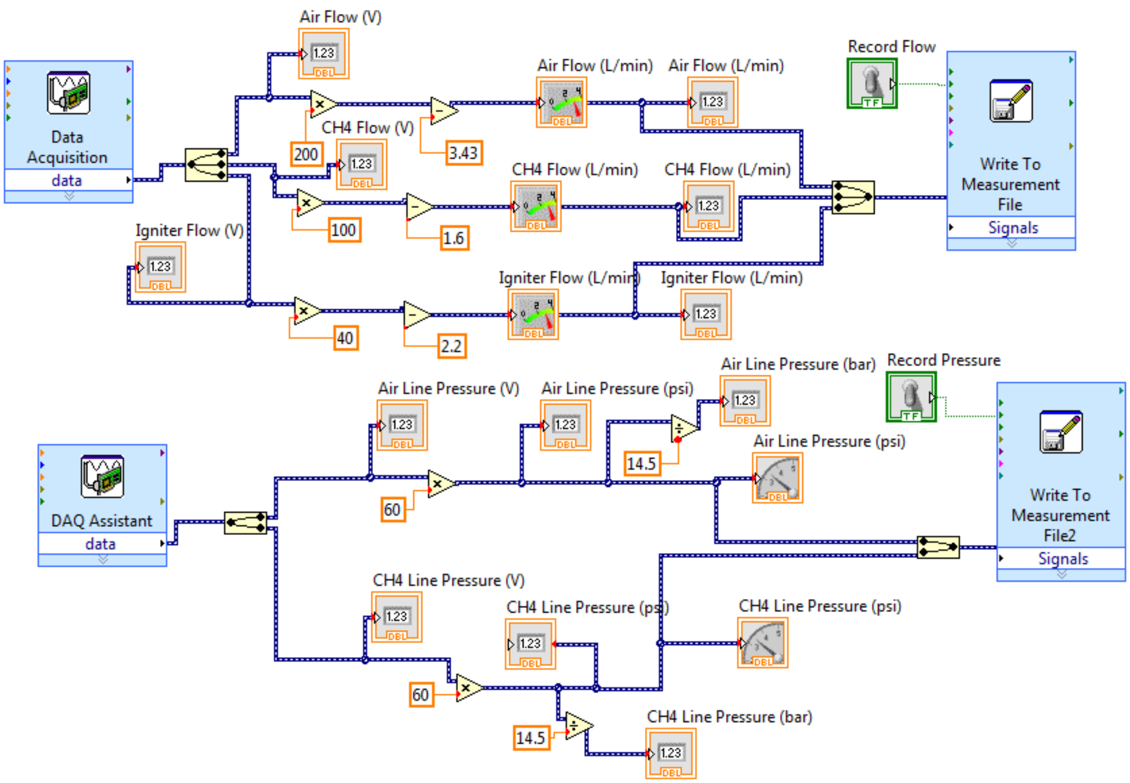


**Figure 3.31. Data Acquisition and Recording Logic**

The solenoid valves were controlled using switches. The signal from all the buttons was sent into an array prior to being delivered to the DAQ. The relay diagnostics was programmed after the array as an indicator to visually inspect the channel that was being used. Figure 3.31 demonstrates the logic for the solenoid valve control.

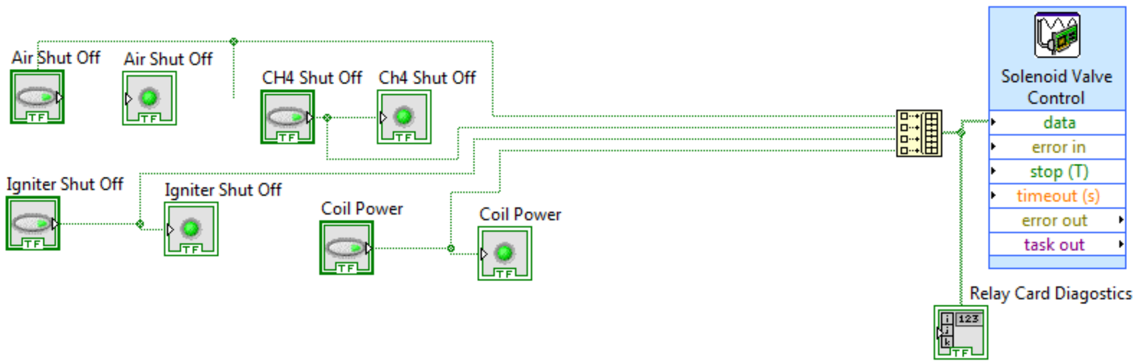


**Figure 3.32. Solenoid Valve Control Logic**

Figure 3.32 demonstrates the USB 6008 and PCI 6521 as they are adapted to the control system as well as the power supplies used. The first terminal block is just for the ground cable to not be left unconnected, the next three terminal blocks to the left distribute the 120 V to the positive lines, the next three distribute the 120 V to the negative lines. The 12 terminal blocks to the left of the PCI card are used for the proportional valves power and data output. The 12 terminal blocks next to those are used for the power and output of the flow meters. And the last nine are used for the power and output of the pressure transducers.

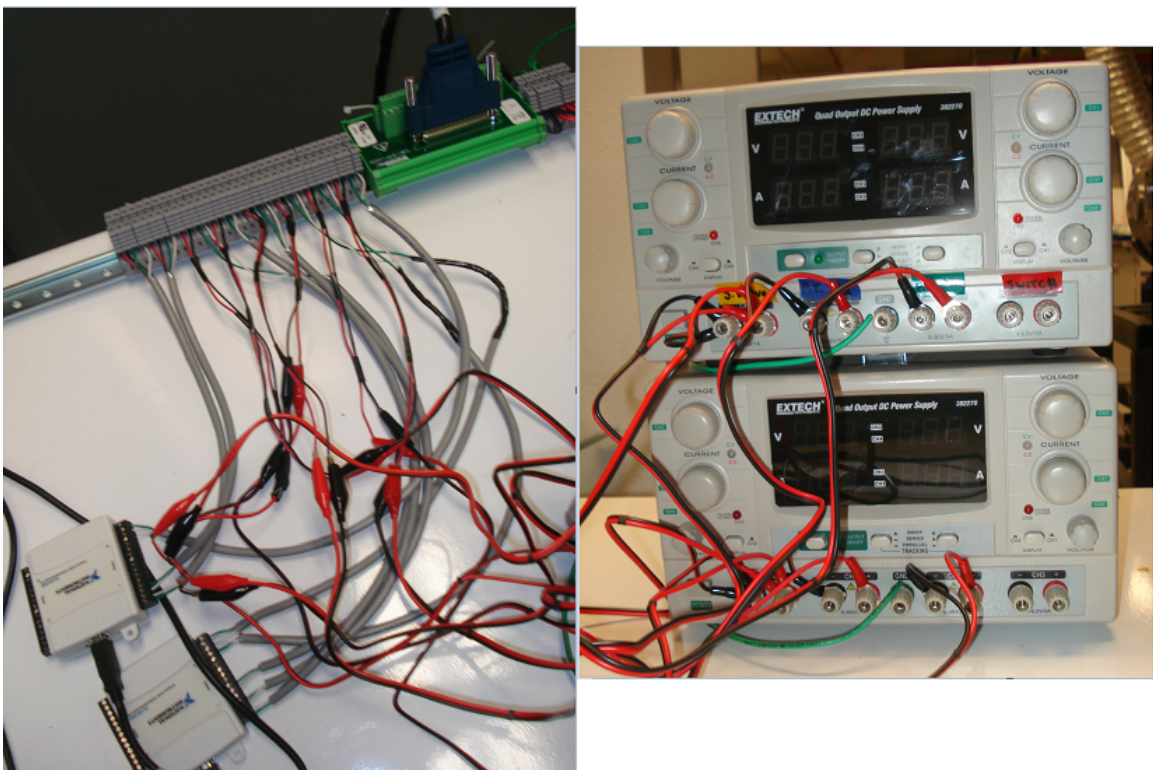


**Figure 3.33. Adaptation of PCI and USB DAQ (left) with Power Supplies (Right)**

The valves are placed in a cart to make them portable in case the set up needs to be moved to another location. This cart houses both the valves and the ignition system components; signal generator and 12 V battery. Figure 3.33 shows the valves as they are

placed in the cart. The final assembly of the HPTC can be seen in Figure 3.34. Here all instrumentation was connected and was ready for testing.

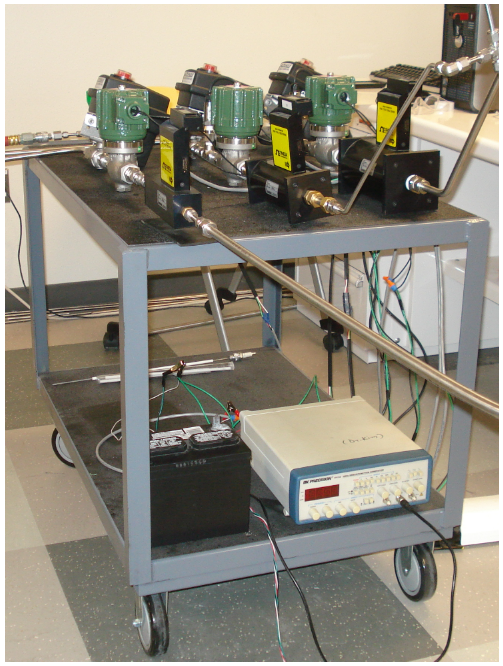

**Figure 3.34. HPTC Valves in Cart**

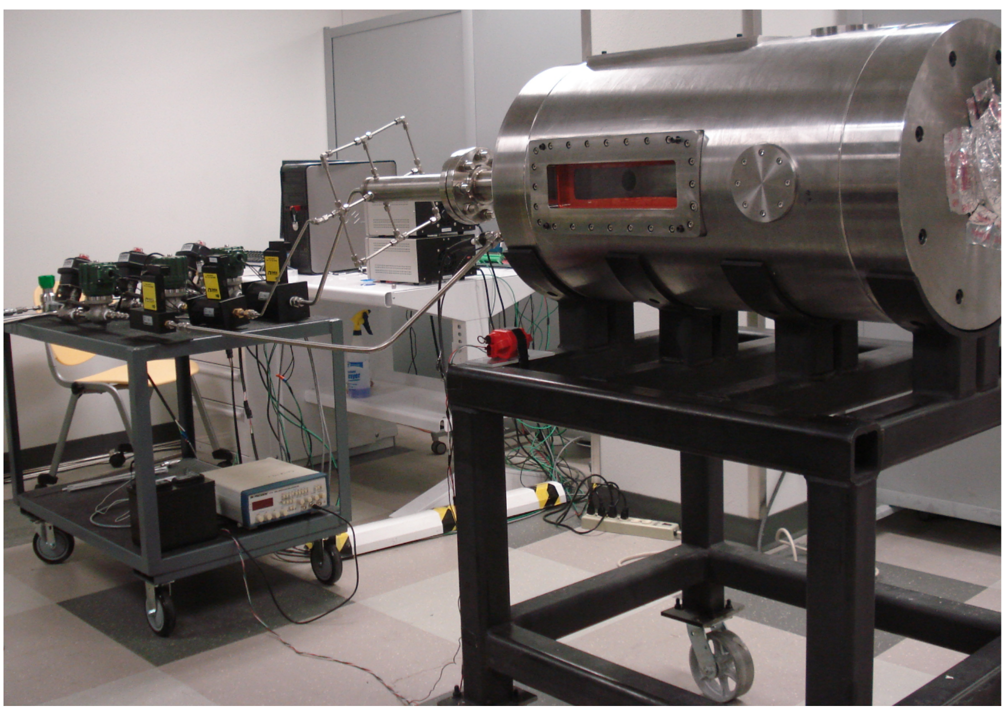

**Figure 3.35. High Pressure Gas Turbine Combustor Full Assembly**

### 3.2 CALCULATIONS

The choked flow diameter was needed to be calculated in order to determine the correct pipe size needed. This was obtained using the stagnation mass flow rate at Mach 1 as shown by the equation below.

$$\dot{m}_{max} = A^* P_0 \sqrt{\frac{k}{RT_0}} \left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}} \quad [3.2.1]$$

Where $\dot{m}_{max}$ is the maximum flow rate needed, $A^*$ is the choke area, $P_0$ is stagnation pressure, k is the specific heat ratio of the gas, R is the gas constant, and $T_0$ is the stagnation temperature. The stagnation temperature and pressure were calculated using the following formulas. T is the static temperature and P is the static pressure.

$$T_0 = \left(1 + \left(\frac{k-1}{2}\right) * Ma^2\right) * T \quad [3.2.2]$$

$$P_0 = \left(1 + \left(\frac{k-1}{2}\right) * Ma^2\right)^{\frac{k}{k-1}} * P \quad [3.2.3]$$

Solving for diameter we obtain the following equation.

$$D_{choke} = \sqrt{\left(\frac{4*\dot{m}_{max}}{\pi * P_0}\right)\left(\frac{1}{\sqrt{\frac{k}{RT_0}}}\right)\left(\frac{1}{\frac{2}{k+1}^{\frac{k+1}{2(k-1)}}}\right)} \quad [3.2.4]$$

The density of the gas varied with the fluctuation in pressure and thus it was needed to calculate the diameter at the 1500 kPa needed. Table 3.4 demonstrates the results obtained at atmospheric pressure and at 1500 kPa. The flow rates needed were obtained from previous calculations performed by Jesus Nunez and Sudipa Sarker [51].

**Table 3.4. Choke Diameter**

| Substance | D at atmospheric pressure (cm) | D at 1500 kPa (cm) |
|---|---|---|
| CO | 1.26 | 0.36 |
| Air | 1.41 | 0.54 |
| $N_2$ | 1.08 | 0.98 |
| $H_2$ | 0.47 | 0.13 |

With this it was concluded that a minimum pipe diameter of 1.91 cm was needed in order to not choke the line for the current set up. The inner diameter of the pipe selected is that of 1.68 cm which allows the flow to not be choked at 1500 kPa.

A test matrix was formulated in order to run the initial test experiments. The balanced chemical equation for stoichiometric combustion of methane air mixture is as follows.

$$CH_4 + 2(O_2 + 3.76N_2) \xrightarrow{yields} CO_2 + 2H_2O + 7.52N_2$$

Therefore, a result of 17.1 is obtained by calculating the stoichiometric air fuel ratio of methane. The test matrix shown in Table 3.5 provides the L/min needed for both methane and air in order to maintain the equivalence ratio at 1.

**Table 3.5. Ignition Test Matrix**

| (A/F) stoic | Volume Flow rate of CH4 (LPM) | Volume Flow rate of CH4 (m3/s) | Mass Flow rate of CH4 (kg/s) | Volume Flow rate of air (m3/s) | Mass Flow rate of air (kg/s) | Volume Flow rate air (LPM) | Conversion factor for CH4 (LPM) |
|---|---|---|---|---|---|---|---|
| 17.1 | 10 | 1.67E-04 | 1.08E-04 | 1.59E-03 | 1.85E-03 | 95.11 | 7.50 |
| 17.1 | 11 | 1.83E-04 | 1.19E-04 | 1.74E-03 | 2.04E-03 | 104.62 | 8.25 |
| 17.1 | 12 | 2.00E-04 | 1.30E-04 | 1.90E-03 | 2.23E-03 | 114.13 | 9.00 |
| 17.1 | 13 | 2.17E-04 | 1.41E-04 | 2.06E-03 | 2.41E-03 | 123.64 | 9.75 |
| 17.1 | 14 | 2.33E-04 | 1.52E-04 | 2.22E-03 | 2.60E-03 | 133.16 | 10.50 |
| 17.1 | 15 | 2.50E-04 | 1.63E-04 | 2.38E-03 | 2.78E-03 | 142.67 | 11.25 |
| 17.1 | 16 | 2.67E-04 | 1.73E-04 | 2.54E-03 | 2.97E-03 | 152.18 | 12.00 |
| 17.1 | 17 | 2.83E-04 | 1.84E-04 | 2.69E-03 | 3.15E-03 | 161.69 | 12.75 |
| 17.1 | 18 | 3.00E-04 | 1.95E-04 | 2.85E-03 | 3.34E-03 | 171.20 | 13.50 |
| 17.1 | 19 | 3.17E-04 | 2.06E-04 | 3.01E-03 | 3.52E-03 | 180.71 | 14.25 |
| 17.1 | 20 | 3.33E-04 | 2.17E-04 | 3.17E-03 | 3.71E-03 | 190.22 | 15.00 |

The test matrix can be modified to the desired equivalence ratio needed which provides the volume flow rate for methane air that is needed.

# Chapter 4: Results

All testing is conducted at the Center for Space Exploration Technology Research (cSETR). Safety procedures require a minimum of two persons to begin testing; the test operator and the safety operator. The test operator follows the instructions from the safety operator and is in charge of the control system and provides feedback to the safety operator. In turn a safety operator overviews the experiment to prevent any hazard that may occur. The control set up is demonstrated in Figure 4.1.

**Figure 4.1. HPTC Control Set Up**

There were three stages to evaluate the system's performance: functional testing, pressure testing, and ignition testing. Leak testing was performed prior to beginning the system's evaluation using air. This ensured that the combustor will not release any gases during combustion. All testing was performed following the experimental procedure outlined in Appendix A.

## 4.1 Functional Testing

All instrumentation in the HPTC was tested for functionality in this section. The proportional valves were operated by changing the voltage from 0-5 and from 5-0 one by one. All solenoid valves were opened and closed one at a time. The reading on the pressure transducers was checked to show 0 kPa on both methane and air lines. Furthermore, all mass flow meters were verified to have a reading of 0 L/min. The system had to be grounded to the 120 V socket in order to prevent any unwanted current discharge. The ignition coil was checked for functionality as well by making sure there was a spark when it was actuated. Finally all valves were actuated at the same time to make sure the system would be operational.

## 4.2 Pressure Testing

Two different types of pressure testing were performed on the HPTC. First was the air pressure line which was tested to the maximum pressure of the current compressor of 758kPa. Leaks were checked in the combustor and the lines to ensure a proper delivery. The pressure transducer readings were verified to show 758kPa. Additionally, the methane line was evaluated using a pressure of 207kPa. Similarly, the line was checked for leaks as well as the pressure transducer reading to show 207 kPa. The methane in the line was introduced into the combustion chamber, diluted and purged using air.

## 4.3 Ignition Testing

The main purpose of this test is to maintain a reliable and stable flame in the HPTC. Initial testing began with the igniter outside the combustion chamber. This was done to confirm that it would work inside the combustor. Only the methane line was connected using a flow rate of 1 L/min while the spark plug was actuated to obtain a flame. A stable diffusion flame was obtained in the igniter while varying the flow from 1 to 5 L/min.

Testing began inside the combustion chamber once a stable flame was obtained on the external experiment. The same procedure was followed inside the combustion chamber and first was to obtain a stable flame on the igniter. This was achieved using 1 L/min on the line which provided a diffusion flame long enough that reached the main line as shown in Figure 4.2.

**Figure 4.2. Igniter Flame in HPTC**

Air was needed to be introduced to the chamber once a stable flame was obtained inside the combustor. The air valve was open to the desired initial flow of 60 L/min for air and as expected the pilot flame blew out. Therefore, a flow rate of 5 L/min was used in the igniter to obtain a stable flame when introducing the air flow. Figure 4.3 demonstrates the pilot flame with air in the main line. Furthermore, methane was

introduced to the main line at 9 L/min at which a stable flame was observed on the main line. The pilot flame was then turned off in order to observe the reliability of the flame as seen in Figure 4.4.

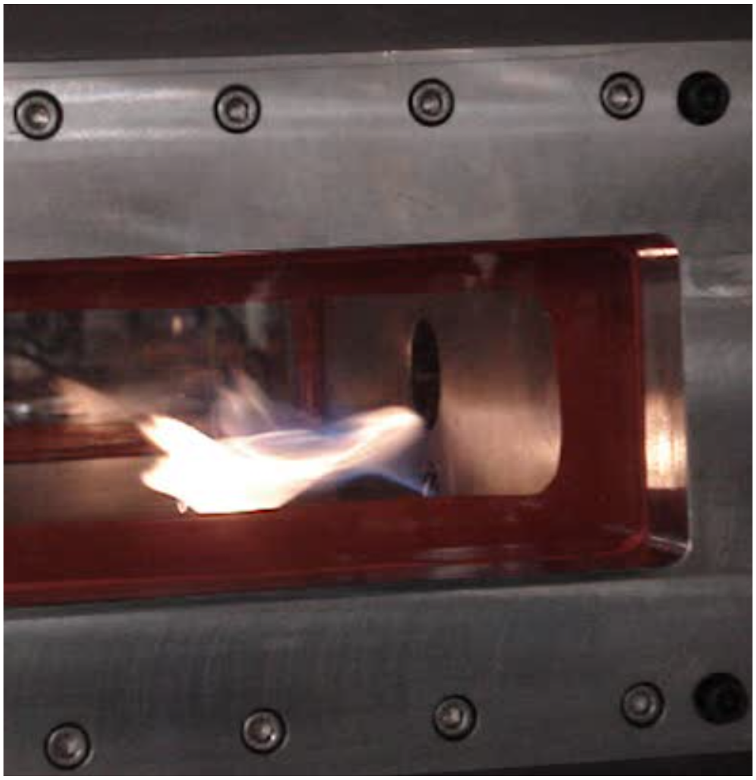

**Figure 4.3. Pilot Flame with Air**

Table 4.1 demonstrates the flow rates obtained at ignition of the HPTC. Mixture ratio is the air to fuel ratio present during combustion. Complete combustion occurs when the amount of air provided burns all the fuel which in turn is known as stoichiometric mixture. The stoichiometric air to fuel mixture ratio for methane air is 17.1 and thus this would be a mixture ratio of 1. Equivalence ratio is the ratio of actual air to fuel mixture ratio (AFR) to stoichiometry. See Appendix B for both mixture ratio and equivalence ratio calculation example.

**Table 4.1. Ignition Flow Rates**

| Air Mass Flow Rate (L/min) | CH4 Mass Flow Rate (L/min) | Mixture Ratio (A/F) | Equivalence Ratio |
|---|---|---|---|
| 45 | 9 | 9 | 0.53 |
| 54 | 6 | 16.2 | 0.95 |
| 60 | 8 | 13.5 | 0.79 |
| 60 | 9 | 12 | 0.70 |

Having an equivalence ratio value of less than one signifies that combustion is lean and there is more oxidizer than needed for complete combustion; Burning rich means that there is more fuel than needed for complete combustion. A common lean premixed flame can be observed as a blue flame while a rich flame is observed to be yellow. The line pressures before opening the lines are shown in Table 4.2. The line pressures returned to 1 psi after opening the solenoid valves and thus no premixing can be obtained in the lines due to overpressure. An example from the data recorded can be seen in Figure 4.5. Data logging was done at 10 samples per channel under the current set up.

**Table 4.2. Ignition Line Pressures**

| Air Line Pressure (kPa) | CH4 Line Pressure (kPa) | Igniter Line Pressure (kPa) |
|---|---|---|
| 138 | 69 | 69 |
| 138 | 69 | 69 |
| 207 | 103 | 103 |
| 552 | 103 | 103 |

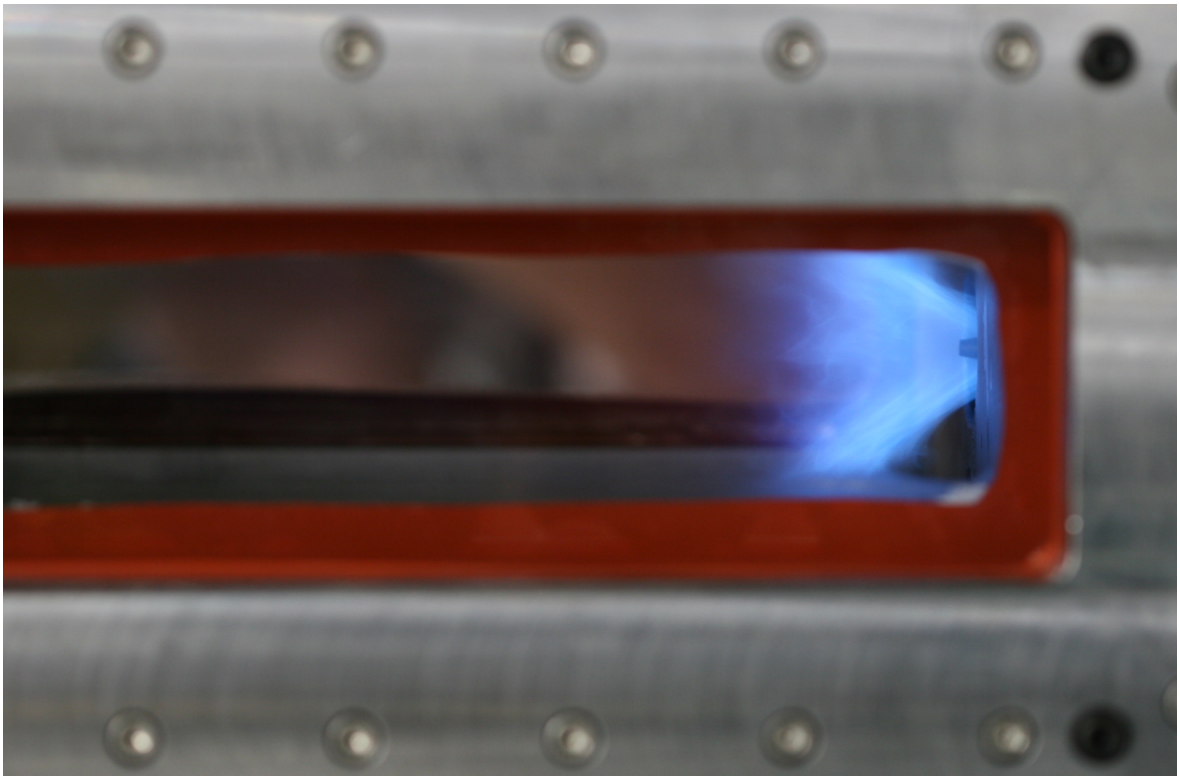

**Figure 4.4. Stable Flame in Main Line**

| | | | | |
|---|---|---|---|---|
| LabVIEW Measurement | | | | |
| Writer_Version | 2 | | | |
| Reader_Version | 2 | | | |
| Separator | Tab | | | |
| Decimal_Separator | . | | | |
| Multi_Headings | Yes | | | |
| X_Columns | No | | | |
| Time_Pref | Absolute | | | |
| Operator | cavaldez3 | | | |
| Date | 11/25/2012 | | | |
| Time | 12:51.9 | | | |
| ***End_of_Header*** | | | | |
| | | | | |
| Channels | 3 | | | |
| Samples | 10 | 10 | 10 | |
| Date | 11/25/2012 | 11/25/2012 | 11/25/2012 | |
| Time | 12:51.9 | 12:51.9 | 12:51.9 | |
| Y_Unit_Label | Volts | Volts | Volts | |
| X_Dimension | Time | Time | Time | |
| X0 | 0.00E+00 | 0.00E+00 | 0.00E+00 | |
| Delta_X | 0.1 | 0.1 | 0.1 | |
| ***End_of_Header*** | | | | |
| X_Value | Air Flowrate | CH4 Flowrate | Igniter Flowra | Comment |
| | 48.98951 | 8.170691 | 0.04041 | |
| | 48.98951 | 8.170691 | 0.448662 | |
| | 48.98951 | 8.170691 | 0.448662 | |
| | 51.030354 | 8.170691 | 0.448662 | |
| | 51.030354 | 8.170691 | 0.04041 | |
| | 51.030354 | 7.150013 | 0.04041 | |
| | 48.98951 | 8.170691 | 0.448662 | |
| | 48.98951 | 8.170691 | 0.04041 | |
| | 48.98951 | 8.170691 | 0.448662 | |
| | 51.030354 | 8.170691 | 0.448662 | |

| | | | |
|---|---|---|---|
| LabVIEW Measurement | | | |
| Writer_Version | 2 | | |
| Reader_Version | 2 | | |
| Separator | Tab | | |
| Decimal_Separator | . | | |
| Multi_Headings | Yes | | |
| X_Columns | No | | |
| Time_Pref | Absolute | | |
| Operator | cavaldez3 | | |
| Date | 11/25/2012 | | |
| Time | 12:51.7 | | |
| ***End_of_Header*** | | | |
| | | | |
| Channels | 2 | | |
| Samples | 10 | 10 | |
| Date | 11/25/2012 | 11/25/2012 | |
| Time | 12:51.7 | 12:51.7 | |
| Y_Unit_Label | Volts | Volts | |
| X_Dimension | Time | Time | |
| X0 | 0.00E+00 | 0.00E+00 | |
| Delta_X | 0.1 | 0.1 | |
| ***End_of_Header*** | | | |
| X_Value | Voltage_0 | Voltage_1 | Comment |
| | 1.340476 | 1.383882 | |
| | 1.340476 | 1.383882 | |
| | 1.340476 | 1.383882 | |
| | 1.340476 | 1.383882 | |
| | 1.340476 | 1.383882 | |
| | 1.340476 | 1.383882 | |
| | 1.340476 | 1.383882 | |
| | 1.340476 | 1.383882 | |
| | 1.340476 | 1.383882 | |
| | 1.952621 | 1.383882 | |

**Figure 4.5. Data Logging Sample**

# Chapter 5: Summary and Future Work

The design, development, and integration of the control and ignition systems for the High Pressure Gas Turbine Combustor were completed. Ignition testing was also performed in order to observe the reliability of both systems. It is important to know that experimentation at high pressures requires a deep understanding of combustion in order to be able to observe flashback and flame stability. A deep understanding of heat transfer, fluid dynamics, instrumentation and control system is also required prior to testing at high pressures using the HPTC. The safety of the operators is ultimately the most important aspect of any project. Therefore, practicing safe testing techniques is of vital importance for the project.

In summary, this work presents the following:

- A remotely controlled system has been developed at the Center for Space Exploration Technology Research for the High Pressure Gas Turbine Combustor; this system provides the user with automated testing with the capabilities to test using Syngas or other types of fuels.
- This system allocates for different types of testing with its instrumentation ports as well as its optical accessibility.
- This system is also modular and allows for modifications to be integrated as well as having the capability to be integrated into the cSETR's Goddard Laboratory bunker control system.
- Data Recording can be executed simultaneously when performing an experiment and logged by test date and time.
- The development of the HPTC provides the capabilities to experiment at 1.5 MPa and temperatures of up to 2400 K.

Improvements are needed in the control system in order to be able to have better precision. A new DAQ is needed with the capability of at least 4 analog outputs from 0-

10 VDC in order to fully control the proportional valves. Also, a regulator for the air line is needed in order to not observe the fluctuation in pressure that is given by the current compressor. The integration of thermocouples and pressure transducers in the combustion chamber would also benefit this project and can be easily integrated into the current DAQs. A better battery is also needed since the spark plug discharges the current one at a fast rate. Also, a monitor system for the operators to be able to observe the flame from the control station is suggested such as a live camera feed or the implementation of mirrors. Finally, modifications to the end cap must be made in order to be able to open the chamber without trouble such as those performed on the window covers.

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# Appendix A

Procedural Actions: QC

| # | Required Actions | Expected Results | Action Upon Adverse Result | ☒ |
|---|---|---|---|---|
| 1 | Prepare test matrix | known flow rates | Review test matrix | ❑ |
| 2 | Make sure all required equipment is in the lab | experiment will go as planned | obtain equipment and recheck | ❑ |
| 3 | Make sure a leak test has been performed prior to experimentation | no leaks present | mitigate leaks | ❑ |
| 4 | Open exhaust vent | exhaust gases can vent | check vent | ❑ |
| 5 | Alert others your test will begin | prevention of hazards for others | Alert others test will begin | ❑ |
| 6 | Turn on power for equipment | all valves and instrumentation will be on | check power instrumentation | ❑ |
| 7 | Allow flow meters to stabilize | Flow can be measured correctly | check flow meters | ❑ |
| 8 | Open CH4 tank for methane line | CH4 enters the line | check tank | ❑ |
| 9 | Connect air line | Air enters the line | check line | ❑ |
| 10 | Open CH4 tank for igniter line | CH4 enters the line | check tank | ❑ |
| 11 | Connect 12 V battery to ignition coil | power will be given to coil | check battery voltage | ❑ |
| 12 | Run Labview program | instrumentation can now be | check labview logic | ❑ |
| 13 | Adjust proportional valve for air and igniter to desired open position | allow flow to enter the lines | check proportional valves | ❑ |
| 14 | Check pressure transducers | determine the desired pressure | adjust proportional valves | ❑ |
| 15 | Open the main air line (solenoid valve) | allows air into the combustor | check air line | ❑ |
| 16 | Close the main air line | stops the air flow in the combustor | check air line | ❑ |
| 17 | Open Igniter line (methane) - Solenoid Valve | allows fuel onto the igniter | check igniter line | ❑ |
| 18 | Actuate coil until flame is stable | igniter turns on | check coil and spark plug | ❑ |
| 19 | Turn off coil once flame is stable | spark plug turns off | check coil | ❑ |
| 20 | Start recording data | gather data | check labview logic | ❑ |
| 21 | Open the main air line | allows air into the combustor | check air line | ❑ |
| 22 | Adjust proportional valve for methane line | methane enters the line | check methane line | ❑ |
| 23 | Open methane line ( Solenoid Valve) | methane enters the combustion | check methane line | ❑ |
| 24 | Adjust proportional valve to obtain a stable flame | stable flame in combustor | adjust proportional valves | ❑ |
| 25 | Shut off igniter | stops igniter flame | check igniter line | ❑ |
| 26 | Shut off methane | stops main flame | check methane line | ❑ |
| 27 | Shut off the methane tank (igniter) | igniter turns off | check tank | ❑ |
| 28 | Shut off the methane tank (main) | no flow can pass | check valve/Labview | ❑ |
| 29 | Open methane and igniter lines to relieve the pressure on lines | methane is vented | check tanks | ❑ |
| 30 | Purge gases with air | lets gases go out the exhaust | check exhaust | ❑ |
| 31 | Shut off air | stops air in combustor | check air line | ❑ |
| 32 | Return proportional valve to 0 V on igniter after no flow is seen | combustor turns off | check tank | ❑ |
| 33 | Shut off solenoid valve on igniter line | no flow can pass | check valve/Labview | ❑ |
| 34 | Return proportional valve to 0 V on air line | no flow can pass | check valve/Labview | ❑ |
| 35 | Shut off solenoid valve on air line | no flow can pass | check valve/Labview | ❑ |
| 36 | Return proportional valve to 0 V on main methane line after no flow is seen | no flow can pass | check valve/Labview | ❑ |
| 37 | Shut off solenoid valve on main methane line | no flow can pass | check valve/Labview | ❑ |
| 38 | Stop recording data | data is saved | check labview logic | ❑ |
| 39 | Stop labview logic | program stops | check labview logic | ❑ |
| 40 | Disconnect air line | no air on line | check line | ❑ |

Project: High Pressure Gas Turbine Combustor
Test/Experiment: Ignition Test

# Appendix B

**Mixture and Equivalence Ratios**

$$AF = \frac{\dot{m}_{air}}{\dot{m}_{fuel}}$$

Knowing the volume flow rates of air and methane from the experiment we can determine the actual mass flow rate of air and methane with the following equations. A conversion from L/min to $m^3$/s is needed for the volume flow rate.

$$\dot{m}_{air} = \dot{V}_{air} * \rho$$
$$\dot{m}_{fuel} = \dot{V}_{fuel} * \rho$$

The air fuel ratio can now be calculated knowing the mass flow rates for both air and methane. From this and knowing that the stoichiometric mixture ratio for methane is 17.1 the equivalence ratio can now be calculated.

$$\phi = \frac{AFR_{actual}}{AFR_{stoich}}$$

For example,

Known: $\dot{V}_{air} = 60\ LPM$, $\dot{V}_{fuel} = 8\ LPM$, $\rho_{air} = 1.17\ \frac{kg}{m^3}$,$\rho_{fuel} = 0.65\ \frac{kg}{m^3}$

We can obtain: $\dot{V}_{air} = 0.001\ \frac{m^3}{s}$, $\dot{V}_{fuel} = 0.000133\frac{m^3}{s}$, $\dot{m}_{air} = 0.00117\ \frac{kg}{s}$,$\dot{m}_{fuel} = 0.0000867\ \frac{kg}{s}$

And thus, the mixture ratio would be:

$$AF = \frac{0.00117}{0.0000867} = 13.5$$

And the equivalence ratio:

$$\phi = \frac{13.5}{17.1} = 0.79$$

**Choked Flow**

Using the following equation:

$$D_{choke} = \sqrt{\left(\frac{4 * \dot{m}_{max}}{\pi * P}\right)\left(\frac{1}{\sqrt{\frac{k}{RT}}}\right)\left(\frac{1}{\frac{2}{k+1}^{\frac{k+1}{2(k-1)}}}\right)}$$

With the values known:

$\dot{m}_{max} = 0.08193\ \frac{kg}{s}$,P=1500000 Pa, k=1.4, R=287$\frac{m^2}{s^2K}$, T=293 K

Substituting these values into the equation and solving we obtain,

$$D_{choke} = \sqrt{\left(\frac{4 * 0.08193\ \frac{kg}{s}}{\pi * 1500000\ Pa}\right)\left(\frac{1}{\sqrt{\frac{1.4}{287\frac{m^2}{s^2 K} * 293\ K}}}\right)\left(\frac{1}{\frac{2}{1.4+1}^{\frac{1.4+1}{2(1.4-1)}}}\right)} = 0.0202\ m = 2.02 cm$$

**Flow Meter Calibration**

$$Actual\ Flow = \left(x\ V * \frac{maximum\ flow\ of\ the\ mass\ flow\ meter}{maximum\ total\ output\ signal}\right) - background\ noise$$

The calibration for a 1000 LPM flow meter with an output signal of 5V would be as follows:

$$Background\ noise = 2\ LPM$$

$$Actual\ Flow = \left(x\ V * \left(\frac{1000\ LPM}{5\ V}\right)\right) - 2\ LPM$$

Where x is the signal output in voltage from the flow meter as shown without the correction factor. Background noise would be shown on the graphics interface to which you would subtract the value.

# Vita

Carlos Alejandro Valdez attended the University of Texas at El Paso (UTEP) in August 2006 for the first time seeking a Bachelor of Science in Mechanical Engineering under a merit scholarship. He obtained a second scholarship, the Shiloff Family foundation scholarship, after his first semester. He graduated in 2010 and was given the opportunity to work at the Center for Space Exploration Technology Research (cSETR) doing research and continuing his education. He entered the graduate program at UTEP in January 2011 working under Dr. Ahsan Choudhuri and Dr. Norman Love. This opened up the opportunity to be a Mickey Leland Fellowship recipient working at the National Energy Technology Laboratory for the Department of Energy.

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