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Dedication

I dedicate this work to my mother and my grandparents whose sacrifices made this possible. I received nothing but love and support from my family and I owe all my success to them. I am eternally grateful for everything they have done for me.

Quiero dedicar este tesis a mi madre y mis abuelos que por medio de sus sacrificios pudo ser esto posible. Yo siempre e recibo nada mas que amor y apollo de mi familia y les debo todo me exito a ellos. No les puedo dar suficientes gracias por todo lo que han echo pro mi.

DESIGN OF A FEED SYSTEM FOR AN OXY-METHANE HIGH PRESSURE COMBUSTOR

by

JORGE ARTURO ROSERO, B.S. Mechanical Engineering

THESIS

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Abstract

With growing concern over the effects that fossil fuels are having on the environment and the expected increases in energy demand in the coming decades, it is becoming increasingly more important to find cleaner and more efficient ways to generate energy. Natural gas has grown in popularity in the last decade thanks to a drastic drop in price and its lower carbon emissions compared to coal. With enough natural gas reserves in the United States to last over 90 years, natural gas is expected to be a large part of the future energy outlook.

Increased demand from growing populations also pushes for the need of cleaner more efficient energy sources and oxy-methane high pressure combustion could be a possible solution. Oxy-methane high pressure combustion has the potential to produce energy more efficiently due to the elevated temperatures from using 100% oxygen and is also cleaner than normal methane-air combustion. Using oxy-methane at high pressure can also be beneficial as fuels behave differently at different pressure ranges. To further develop the use of oxy-methane in large-scale power generation efforts it is important to conduct research using oxy-methane at different pressure ranges to pursue higher efficiencies.

This thesis focuses on the design of a feed system for a 20 [bar] high pressure combustor that will operate with oxy-methane to test the efficiency of oxy-methane at high pressures. This research will be used as a stepping stone in the development for higher pressure systems to continue the study of oxy-methane at high pressure. The methodology used when designing a feed system for high pressure applications including calculations, design requirements, and part selection are discussed.

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Chapter 1: Introduction and Background

1.1 ENERGY

Due to major breakthroughs in natural gas extraction techniques there has been a significant decrease in the cost of natural gas power generation. In the last 8 years, natural gas prices have seen an approximate decrease of 76% from $13 per million [BTU]s to $3 per million [BTU]s [1]. This dramatic decrease in price has caused a major shift in the United States away from coal with many coal firing plants being shut down. Another added benefit of using natural gas as opposed to coal is that natural gas produced approximately half the carbon emissions [2], making it a much cleaner alternative. With close to 2.5 trillion cubic feet of proven natural gas reserves in the U.S. the country has enough natural gas to last 93 years [3]. Currently, natural gas which is primarily made up of methane, provides 33% of the U.S. energy needs [4] and it is expected to continue to be a major source of energy for decades to come. However, increased population size and an increase in standard of living means that future energy demand is expected to be much higher than that of today. Current predictions say that by the year 2040 that world energy demand is projected to increase by 48% [5], which is why it is increasingly important to find new sources of energy as well as improve the efficiency of current energy producing methods. Although renewable sources such as wind and solar have become increasingly popular in the last few years, the technology and infrastructure for these energy sources is still not able to meet our current energy needs. In 2015, wind and solar provided only 5.3% of the U.S. energy demand [4], which is still too small a number to be considered a viable replacement for fossil fuels. With natural gas providing such a sizable percentage of our energy and renewable resources still decades away from being a suitable replacement, even a small increase in efficiency in energy production using natural gas could prove extremely helpful in meeting the increased demand.

One possible solution to this problem could be oxy-fuel combustion. All combustion processes require two sources: a fuel and an oxidizer, and most of the power stations used today use air as the oxidizer. Air only contains approximately 21% oxygen which can severely limit the effectiveness of power stations as the maximum temperature that can be achieved is much lower compared to using 100% oxygen. This lower temperature reduce the power output that can be produced by a thermodynamic process which is one of the reasons most industrial power stations are only 30% to 60% efficient [6]. Using pure oxygen as the oxidizer in power generation would allow for much higher temperatures to be achieved, potentially increasing the overall efficiency of the system.

1.2 POLLUTION EMISSIONS

In recent years, there have been growing concerns of the effects that global warming is having on the planet. An overwhelming majority of climate scientist agree that increased greenhouse gas emissions such as CO2 are responsible for the rapid global temperature rise observed in recent decades. Figure 1.1 shows how CO2 emissions have increased since the 1850s.

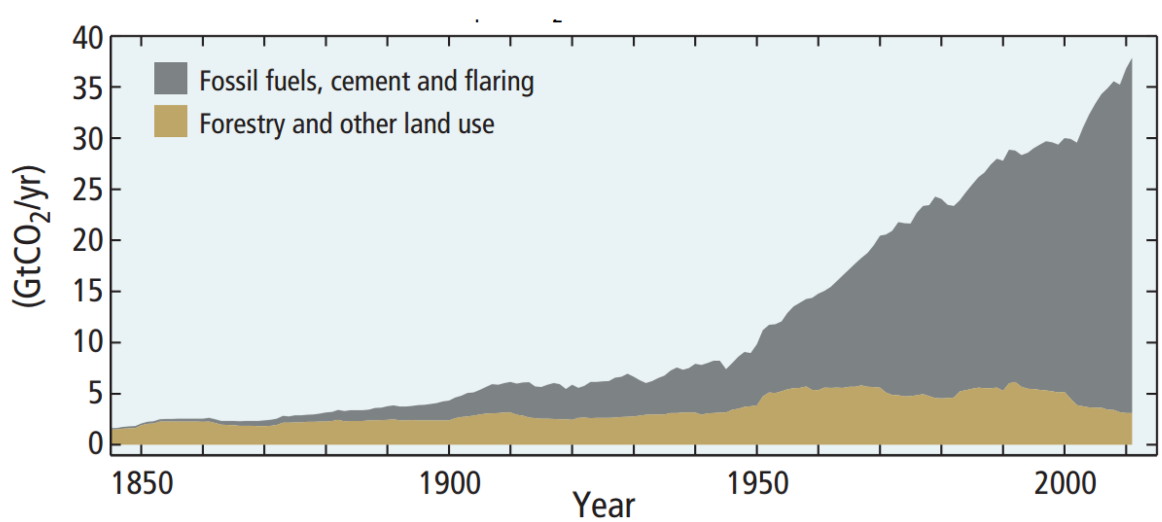


Figure 1.1 - Global Anthropogenic CO2 Emissions [7]

This increase in greenhouse gas emissions has caused a rapid increase in Earth's surface temperature. From the year 1880 to 2012 the global surface temperature has risen by an average of 0.85 [°C] as shown in figure 1.2.

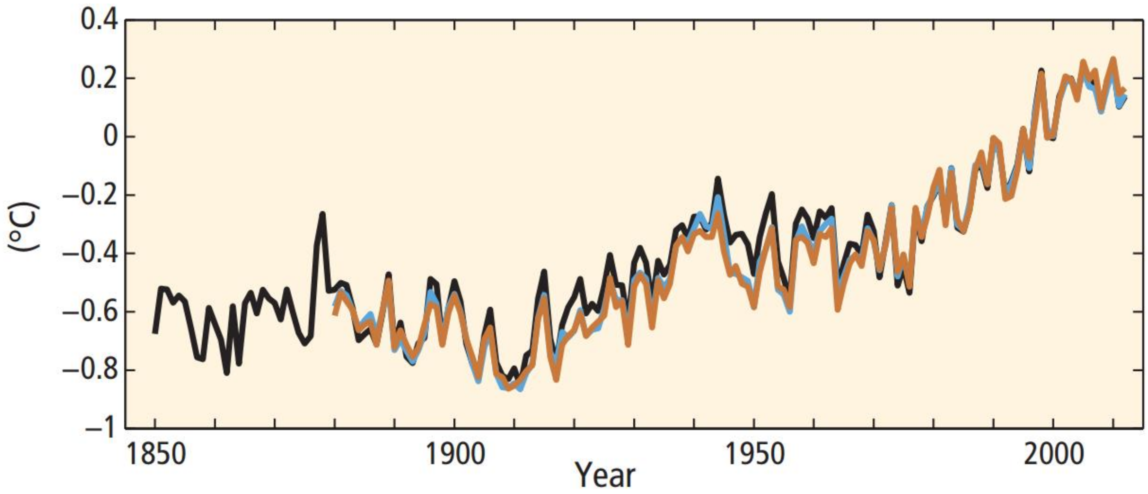


Figure 1.2 - Globally Averaged Combined Land and Ocean Surface Temperature [7]

Some of the repercussions of this temperature rise include a warming of the oceans, shrinking of the ice sheets, rise in sea levels, acidification of the oceans, and the destruction of various eco systems [7]. If we wish to stop the effects of global warming it is important to find alternative ways of power generation that can reduce the amount of pollution emissions and using 100% oxygen has the potential to generate lower pollution emissions compared to conventional energy generation methods.

1.3 Mission and Purpose

The University of Texas at El Paso's (UTEP) Center for Space Exploration Technology Research (cSETR) has been conduction high pressure combustion research for many years,

conducting experiments using synthesis gas and magnetohydrodynamic (MHD) power generation. Recently the center has partnered with Air Liquide, a world leader in the gas industry who shares the center's passion for experimental power generation research. The lab's current goal is to demonstrate continuous combustion using an oxy-methane fuel at high pressures to test the possibilities for oxy-fuel combustion power generation.

The main objective of this project is to use a combustor currently at the cSETR which was designed to operate at a max pressure of 15 [bar] with a fuel and oxidizer mixture of hydrogen/carbon monoxide and air and modify it to operate at a higher pressure of 20 [bar] using a mixture of pure oxygen and methane. This is a power generation research effort which unlike rockets is required to operate for a much longer time frame. We wish to demonstrate that the combustor is capable of operating continuously for a period of two hours at a pressure of 20 [bar] with a fuel input 500 [kW] as we believe the higher pressure and fuel input could lead to higher efficiencies. The project will require several major changes to the design including a new feed system, injector, electrical control system, removal of quartz windows, addition of a cooling system, addition of carbon dioxide, as well as a relocation to a new testing facility in Fabens, TX. For the purposes of this thesis only the design of the new feed system will be discussed.

This first demonstration, currently scheduled for August of 2017 aims to show continuous oxy-fuel combustion at a pressure of 20 [bar] (290 [psi]) with a mass flowrate of 0.01 [kg/s] of methane for a period of two hours. If this test is successful, the center will pursue studies involving higher pressures such 100 [bar] and 300 [bar] combustors as this is an area where very limited research exists today.

Chapter 2: Literature Review

2.1 COMBUSTION

Combustion is defined as rapid oxidation that generates heat and it is an extremely integral part of what made us the civilization we see today. Combustion has allowed us to take chemical energy trapped inside natural resources found in our planet and transform that energy into heat. That heat can then for countless applications such as heating a home, running an engine, launching a rocket, or turning a turbine to generate power. With approximately 64 percent the energy produced today coming from combustion sources such as coal and natural gas [4], combustion is a vital part of our everyday lives.

Combustion is typically divided up into two modes: flame and non-flame. The flame mode is further broken down in to premixed or non-premixed (diffusion) flames. Figure 2.1 shows the difference between a premixed

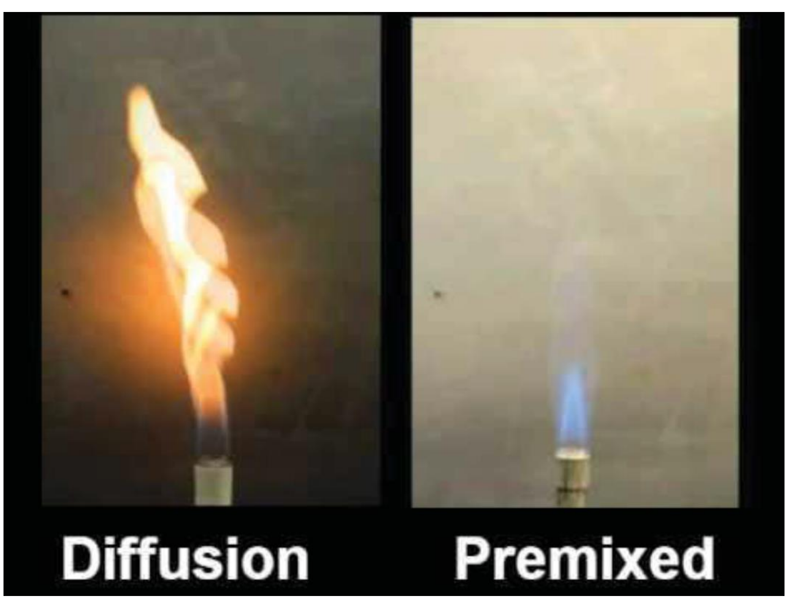


Figure 2.1 - Diffusion vs Premixed Flames

For both these flames combustion can occur in three possible ways: stoichiometric, lean or rich. Stoichiometric combustion is the condition in which the exact amount of oxidizer needed to burn a quantity of fuel is used. If more than the stoichiometric amount of oxidizer is used then the mixture is considered to be fuel lean, and vice versa. If less than the stoichiometric amount needed is used the mixture is said to be fuel rich [8].

In combustion, it is useful to have a number that allows you to easily know whether a combustion is lean, rich or stoichiometric and this is known as the equivalence ratio (Φ). The equivalence ratio is simply the ratio of the stoichiometric oxidizer to fuel ratio to the actual oxidizer to fuel ratio being used. If a fuel mixture has an equivalence ratio $\Phi > 1$, then this is a rich mixture. An equivalence ratio $\Phi < 1$ would mean the mixture is lean and an equivalence ratio $\Phi = 1$ means that the mixture is exactly stoichiometric [8].

Depending if the flame is premixed or diffused and whether the mixture is fuel rich or lean, this can have dramatic effects on how the flame behaves. After ignition, there are four possible outcomes for the flame's behavior. The ideal case is having a fully anchored flame as shown in Figure 2.2

Figure 2.2 - Fully Anchored Flame [9]

The flame could also be partially anchored where the flame may act stable but there is a slight separation between the flame and the port in a phenomenon called lift-off as shown in Figure 2.3.

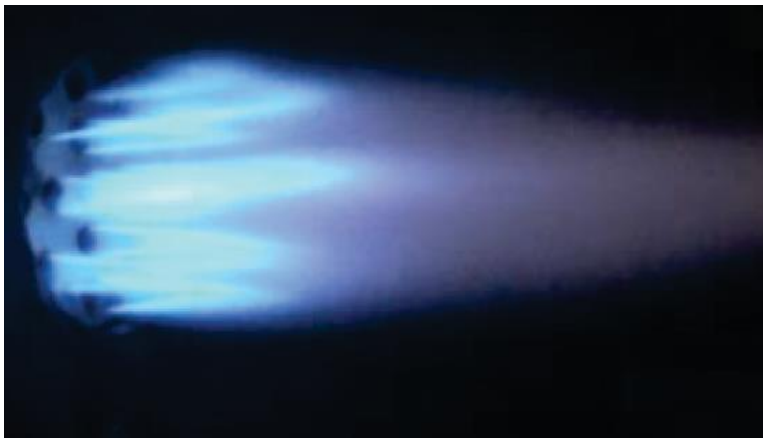


Figure 2.3 - Partially Stable Flame (Lift-Off) [9]

One important parameter that can also affect flame behavior is the laminar flame speed (S_L), which is the speed at which a flame will propagate through a mixture of unburned reactants. Essentially, the flame has a velocity at which it will burn through the reactants. In order to keep a stable flame the velocity of the feed gases must be equal to the velocity of the flame speed. If the velocity of the gases is too fast it will cause the flame to blowout as shown in Figure 2.4.

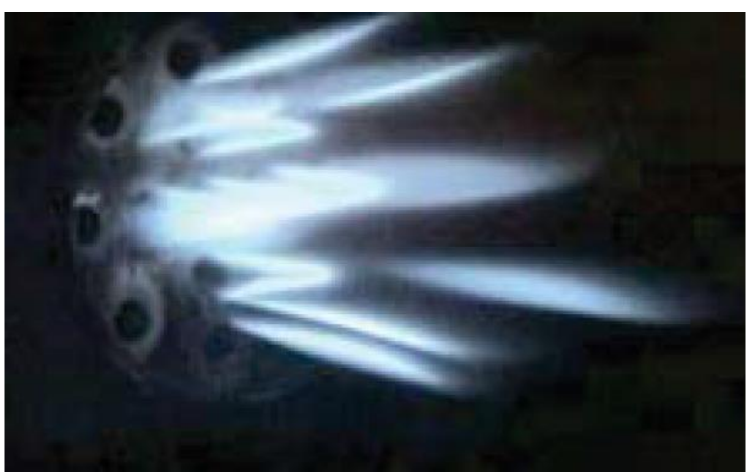


Figure 2.4 - Flame Blowout [9]

In a premixed flame experiment where the flame speed is higher than the velocity of the reactants it is possible for the flame to propagate against the steam of gases towards this gas source in a phenomena called flashback. Flashback can be a very dangerous safety hazard when conducting experiments as it can ignite the entire gas supply causing damage to the equipment, the facility and personnel. For this reason it is vital for a flashback arrestor to be installed to safeguard against this issue when dealing with a premixed flame system. Figure 2.5 shows the flashback phenomena in more detail.

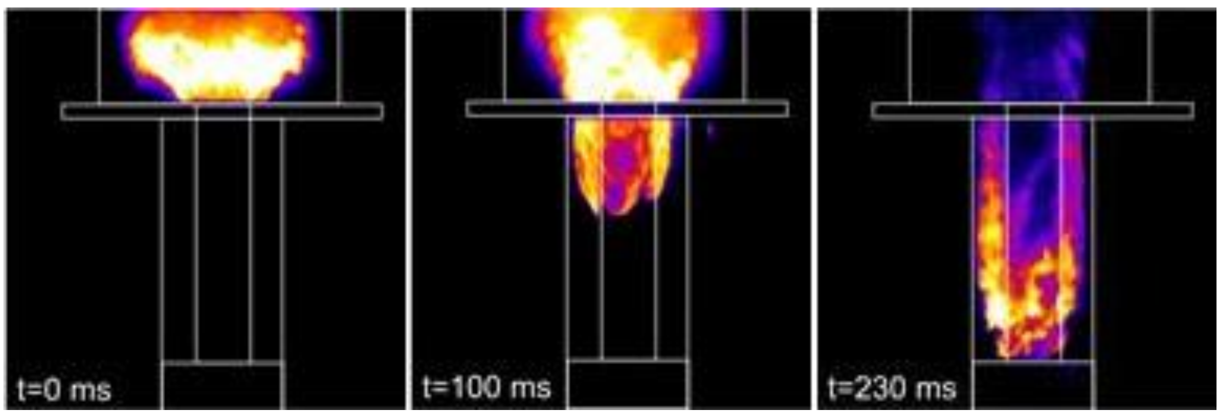


Figure 2.5 - Flashback

2.2 HIGH PRESSURE COMBUSTION

High pressure combustion has several different applications, from rocket engines to airplane turbines to power plants all of which play a vital role in our society today and in the future. When it comes to power generation, the study of high pressure combustion systems in extremely important because the combusting characteristics change at higher pressures and could potentially lead to better efficiencies. Research into high pressure combustion systems could potentially lead the way to developing the technology that will power the world in the future.

Several different institutions are currently conduction high pressure combustion research such as the University of California Irvine Combustion Laboratory (UCICL), the Penn State High

Pressure Combustion Lab, the Clean Combustion Research Center, the Cambridge University High Pressure Combustion Lab, along with many others. Among those institutions, the University of Texas at El Paso's Center for Space Exploration Technology Research (cSETR) has also focused greatly on high pressure combustion research since 2010. The combustor currently in the laboratory can operate at pressures of 15 [bar] and temperatures of 2400 [K]. It is also optically accessible to allow for clear view of the combustion process inside the chamber. Figure 2.6 shows the high pressure combustor facility used in the experiments.

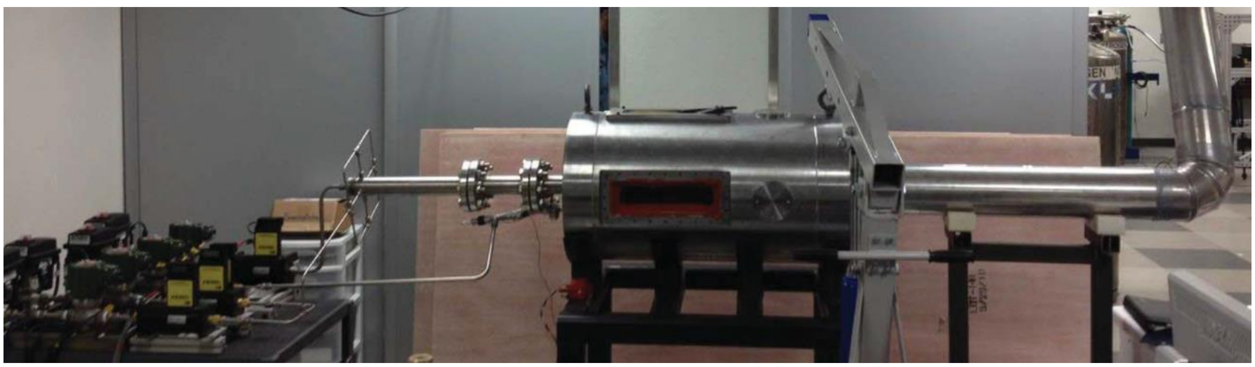


Figure 2.6 - cSETR High Pressure Combustor Facility

The latest research conducted at this facility tested the flame stability of a synthesis gas (syngas) as it could potentially be used as an alternative form of power generation. Syngas has some interesting attributes that make it an appealing potential power source. Syngas can be extracted from coal which the U.S. has in abundance and could potentially be much cleaner that using coal. However, one of the major challenges of using syngas for power generation is that it is more unstable than common fuel sources used today. The gas is composed primarily of hydrogen and carbon monoxide, and it is its high hydrogen content makes it so unstable.

The syngas was tested at different bulk velocities, gas compositions and equivalence ratios to try and determine the stability of syngas. The results of the study were able to successfully show a clearly defined stability region for syngas at several combinations of equivalence ratios, bulk

velocities and gas compositions. This tells us that syngas does indeed have the potential to be a viable fuel for power generation.

High pressures can have a large effect on how fuels behave when burned and continuing to conduct research into high pressure power generation systems is vital for the development of new power generation techniques.

2.3 Oxy-Fuel Combustion

As mentioned earlier, all combustion processed require a combination of a fuel and an oxidizer. Currently, almost all power generated at combustion power plants is done using air as the oxidizer which only contains approximately 21% oxygen. In the search for more efficient power generation methods, some have turned to using pure oxygen as the oxidizer as this would greatly increase the temperature of the combustion process and has the potential to achieve higher efficiencies.

Oxy-fuel combustion also has the potential to reduce pollution emissions. Coal-fired power plants have done CO2 capture attempts such as CO2 sequestration [10] to try and reduce greenhouse gas emissions. CO2 sequestration is done by collecting the exhaust gases after combustion and then pumping the CO2 back into the ground thus not adding any CO2 into the atmosphere. However, using air as the oxidizer has caused a problem with these efforts. Air contains approximately 79% nitrogen which then mixes with the other combustion gases creating nitrous oxides [NOx]. In order to capture the CO2 the nitrogen must first be extracted from the flue gas before the CO2 can be captured and redeposited. When using pure oxygen as the oxidizer there is no nitrogen in the mixture meaning the products would almost completely be composed of CO2 and H20, making the extraction of CO2 much easier. This could in theory create an emissions free power generation system.

Although much exciting research is being conducted using oxy-methane a literature review showed that there is a lack of research on high pressure oxy-methane combustion. Given that pressure plays a major role in the characteristics of a combustion process it is important to test the effects of oxy-methane combustion at high pressures as it may reveal some new opportunities for future power generation technologies.

Chapter 3: Design Methodology

3.1 Feed System Description

In this chapter, the process used in designing a feed system for a high pressure oxy-methane combustor will be discussed. For clarification, a description of what the feed system is and what it intends to accomplish is given next. For combustion systems, a feed system is simply the mechanism used to deliver substances from the source to the combustion chamber at precise quantities in order to achieve ignition. Feed systems come in many different forms depending on the system but they all share the same characteristics such as having a method to measure pressure and flowrates as these are vital to achieve ignition.

3.2 Design Requirements

The main methodology used in the design of this feed system is taken from the NASA Systems Engineering Manual [11]. This system consists of taking high level project goals and stakeholder expectations and turning them into system requirements. The sections that follow illustrate the requirements used in the design of the feed system.

3.2.1 High Pressure Combustor

To better determine the requirements of the feed system it is important to first understand the requirements of the system as a whole. Figure 3.1 shows an image of the high pressure combustor to be modified.

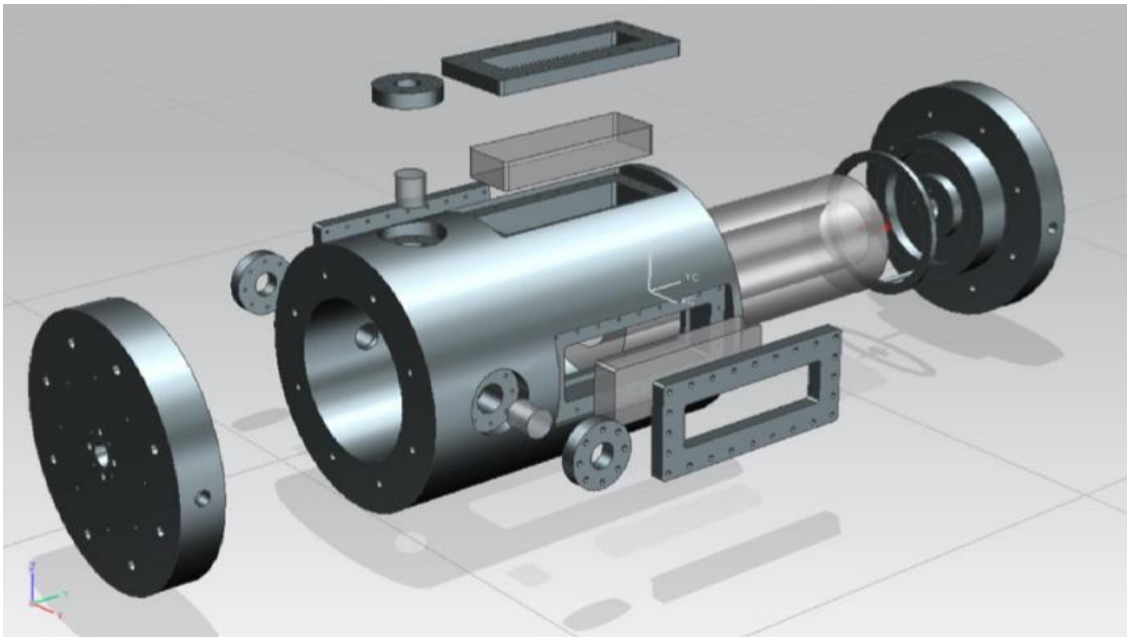


Figure 3.1 - High Pressure Combustor

As discussed in Chapter 1, the main mission of the project is to deliver a high pressure combustor that can operate at a pressure of 20 [bar] for a period of two hours with a power input of 500 [kW] using a fuel mixture of oxygen and methane by August of 2017. These system requirements were then placed in a system requirements document to have clear documentation of all aspects of the project. The full requirements document can be found in the Appendix section. Table 3.1 shows the first five items in the requirements document.

Table 3.1 - Combustor Requirements

1.	The combustor shall operate at a pressure of 20 [bar]
2.	The combustor shall use a power input of 500 [MW]
3.	The combustor shall use a fuel mixture of oxygen and methane
4.	The combustor shall demonstrate continuous safe combustion for a period of 2 hours
5.	The combustor shall demonstrate the above by August 2017

3.2.2 FEED SYSTEM

The objective of the feed system is to transport substances from one location to another and it must do this safely and consistently. To do this the system must have a method to control and measure flows. The system must also be able to collect data after running an experiment which is why a data acquisition system must also be incorporated.

To ensure the system operates safely a few other key factors must be considered. Before a test can be run it is important to always run a leak test and for this reason it is important that a valve or some other method of sealing off the end of the system is put in place. To ensure repeatable testing conditions the system should be purged after each test so a purge system should be put in place. This system is being made for a combustion process and thus is carrying combustible fluids. It is very important to ensure that the oxidizer and the fuel never come in contact with each other aside from testing, so the purge system should be designed in a way such that each line gas source can be purged individually. All the derived design requirements pertaining to the feed system are shown in Table 3.2.

Table 3.2 - Feed System Requirements

6.	The feed system shall have a method to control and measure flowrates
7.	The system shall be able to provide reliable test results
8.	The system shall have a data acquisition system
9.	Each line shall have a seal for leak testing
10.	The feed system shall have a way to purge each line individually

3.2.3 LENGTH

As the pressure requirement for the modified combustor exceeds the pressure restrictions currently in the Center for Space Exploration Technology Research facility the combustor is being moved to a new testing facility in Fabens TX. Figure 3.2 shows the current drawings for the construction of this new facility.

Figure 3.2 - Fabens Facility

The Fabens testing facility will have three different testing rooms each for different research experiments. All three rooms are 24 [ft] by 24 [ft] as shown in Figure 3.3.

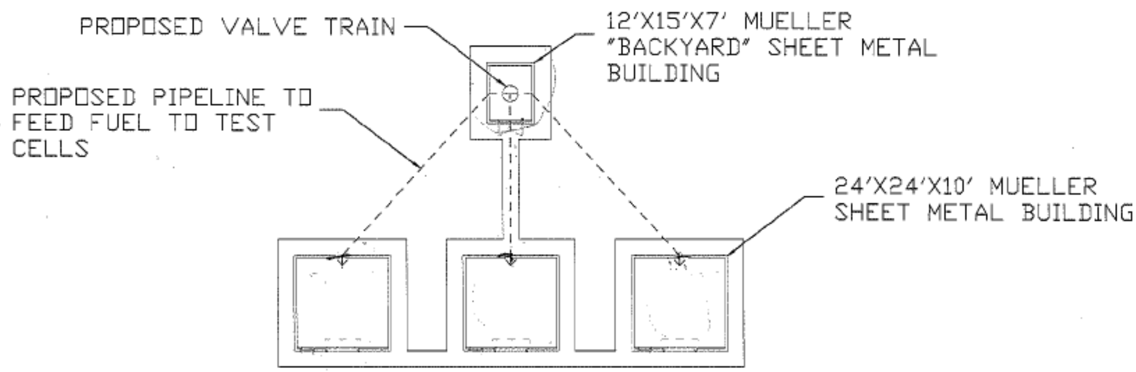


Figure 3.3 - Testing Rooms

Figure 3.4 shows a building next to the top of the three testing rooms that will be used to house high pressure tanks of different gases. These gas tanks connect to a valve train that connects to the back of each testing room meaning the source of the high pressure gases is located at the rear of the room.

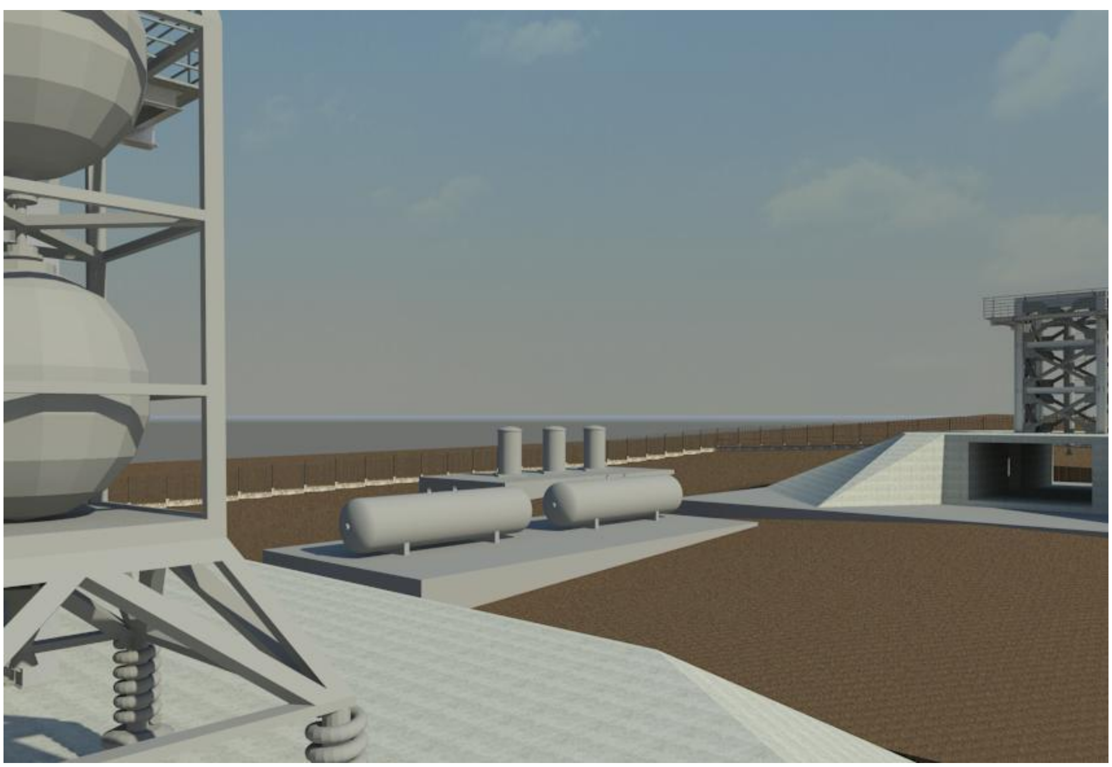


Figure 3.4 - Storage Tanks

After the equipment is relocated to the new facility it will be placed in the location that gives the most flexibility during testing. For this reason, it was decided to place the combustor in the middle of the testing room. The orientation of the combustor was also chosen as it would be best to have the exhaust of the combustor pointed towards the large garage style door in the front of the building. This would allow for the exhaust gases produced during the experiment to be easily released from the room as shown in Figure 3.5.

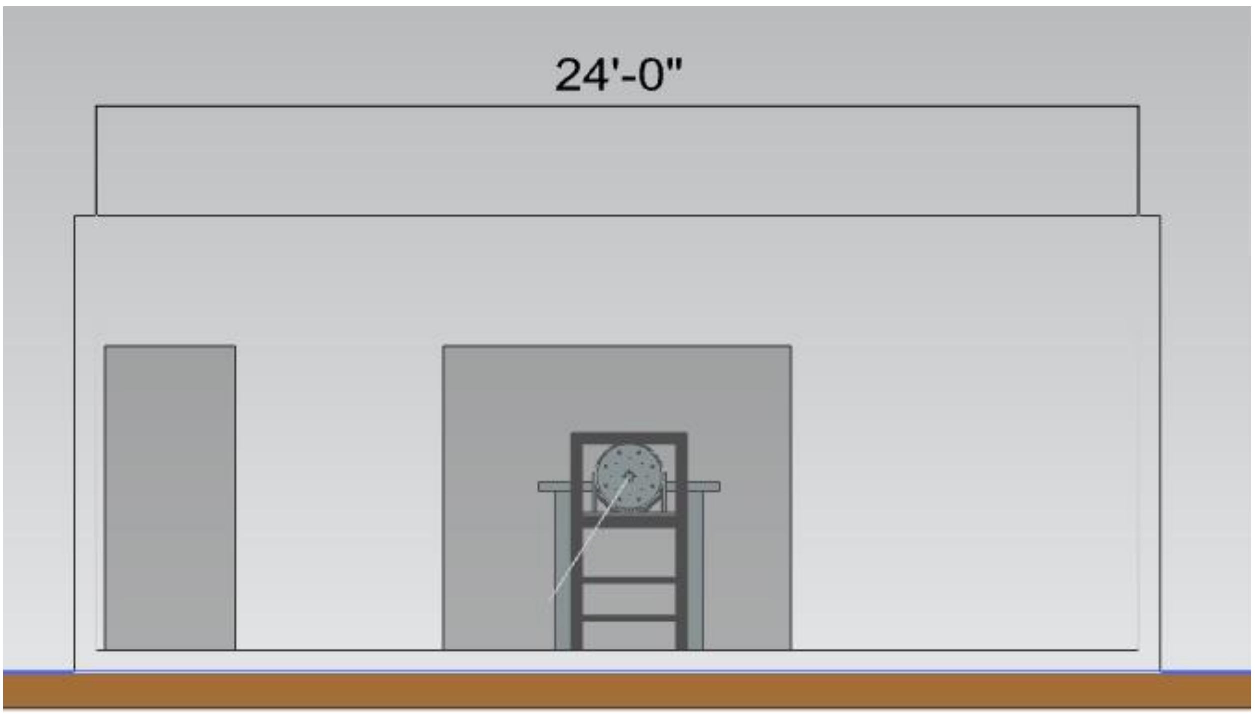


Figure 3.5 - Exhaust Exit

With the location of the gas source, the combustor location and the combustor's orientation fixed this sets the max length requirement for the feed system. Figure 3.6 shows the length from the rear of the room to the inlet of the combustor at 70 [in] which is the allowable total length of the feed system.

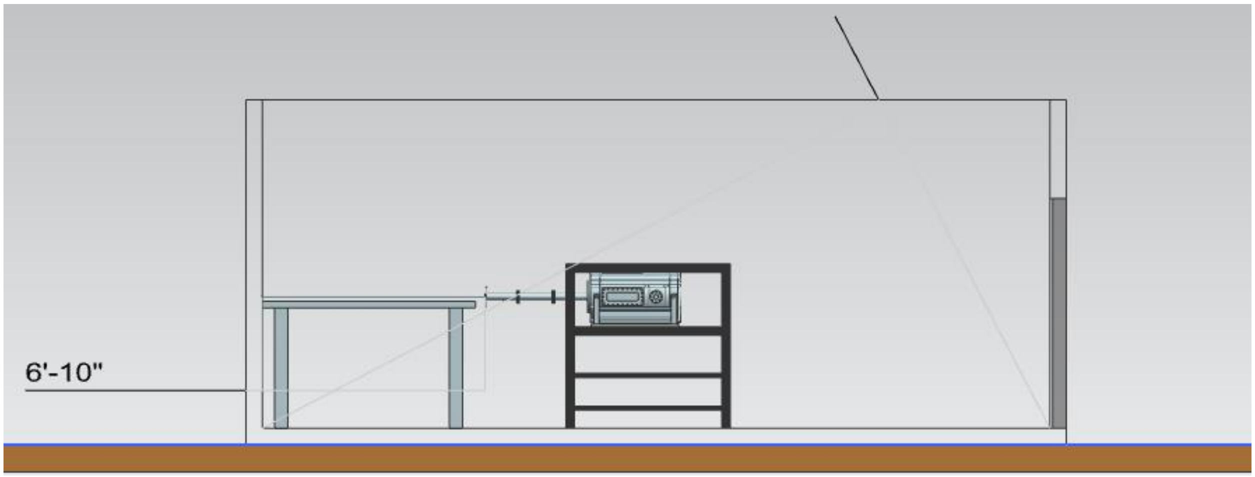


Figure 3.6 - Combustor Location

As this inlet section of the combustor will be replaced this adds 50 [in] to allowable distance giving a max length requirement of 120 [in]. Table 3.3 shows the derived length requirements for the system.

Table 3.3 - Length Requirements

11.	The high pressure combustor shall be located in the Fabens TX testing facility
12.	The high pressure combustor shall be positioned in the center of the room
13.	The high pressure combustor exhaust shall face the garage door
14.	The max length of the feed system shall be 120 [in]

3.2.4 FLUID AND FLOW

The mass flowrate for methane is set by the power input of 500 [kW] by this equation.

$$Power\ Input = 500\ kW = \dot{m}_f(LHV)$$

LHV is the lower heating value of the fuel which is discussed in more detail in the combustion section. The lower heating value of methane is 50,000,000 [J/kg] [12] meaning a mass flow rate of 0.01 [kg/s] is needed to meet this requirement as shown below.

$$500\ kW = \dot{m}_f \frac{kg}{s}\left(50E6\ \frac{J}{kg}\right) \rightarrow \dot{m}_f = 0.01\frac{kg}{s}$$

To determine the mass flowrate of oxygen first an equivalence ratio [Φ] must be chosen. For this project, an equivalence ratio of 1.14 was chosen as this is the equivalence ratio that yields the highest theoretical adiabatic flame temperature for methane [13] as shown in Figure 3.7.

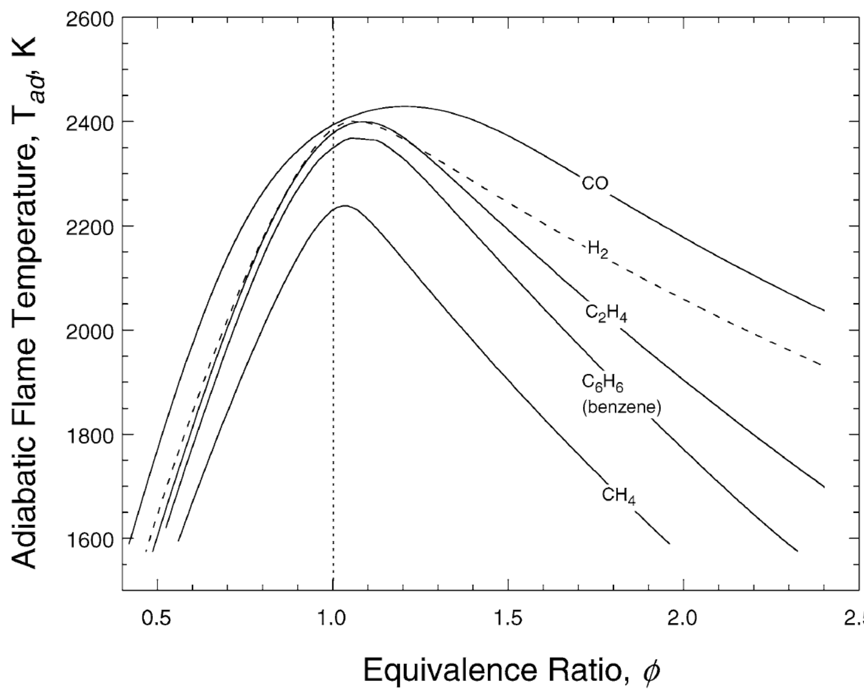


Figure 3.7 - Adiabatic Flame Temperature vs Equivalence Ratio [13]

It is also beneficial to have a rich fuel mixture as opposed to lean because having more fuel than oxygen will help relieve the highly corrosive effects of oxygen. Using the equivalence ratio and the mass flowrate of methane the mass flowrate of oxygen can be derived as shown below.

$$\varphi = \frac{\frac{O}{F}\ stoic}{\frac{O}{F}\ act}$$

$$\frac{O}{F}\ stoic = \frac{2\ kmol\left(32\ \frac{kg}{kmol}\right)}{1\ kmol\ \left(12\ \frac{kg}{kmol} + 4\ \frac{kg}{kmol}\right)} = \frac{64\ kg}{16\ kg} = 4$$

12

$$\Phi = \frac{4}{\frac{O}{F}\ act} = 1.14 \rightarrow \frac{O}{F}\ act = 3.508$$

$$\dot{m}_o = \dot{m}_f * 3.508 = 0.01\ \frac{kg}{s} * 3.508 \rightarrow \dot{m}_o = 0.03508\frac{kg}{s}$$

Using NASA's CEA software, the adiabatic flame temperature of oxy-methane is 3500 K which exceeds the max temperature of the combustor set at 2400 K. To address this problem CO2 will be added to the flow stream which will reduce the temperature while keeping the fuel mixture rich. Figure 3.8 shows how the adiabatic flame temperature of oxy-methane lowers at different concentrations of CO2.

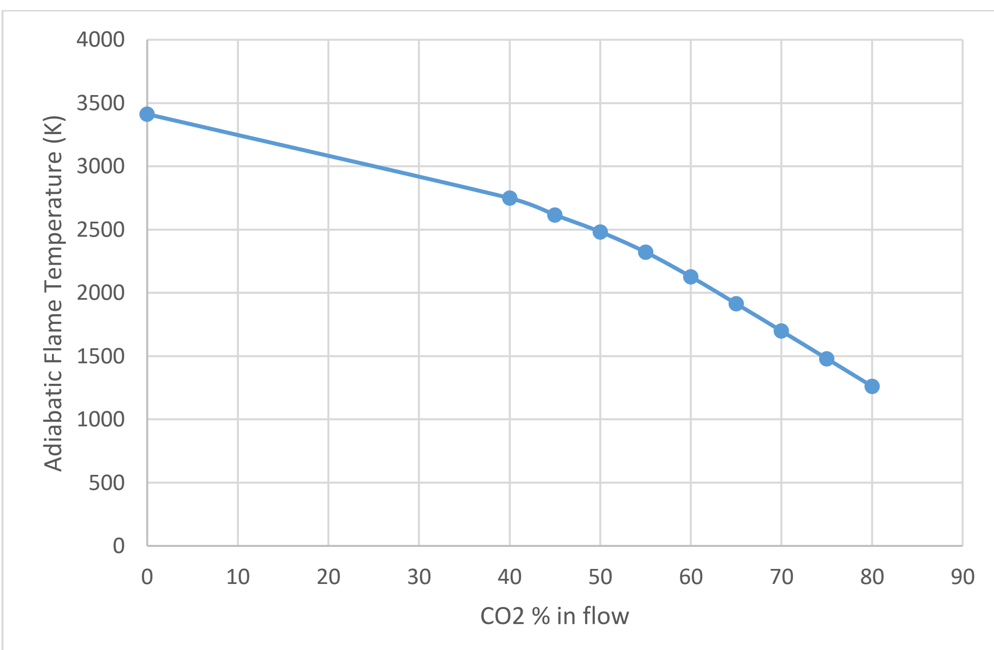


Figure 3.8 - Adiabatic Flame Temperature vs CO2 Concentration

An experimental study showed that the Upper Explosive Limit (UEL) of CO2 diluted oxy-methane was 65% [15] thus this is maximum amount of CO2 that can be used while keeping the ability to ignite. The mass flowrate of CO2 with oxy-methane at 65% dilution by mole fraction was calculated as shown below.

$$0.65 = \frac{moles_{CO2}}{moles_{CO2} + moles_{CH4} + moles_{O2}}$$

$$moles_{CH4} = \frac{mass}{molar\ mass} = \frac{10\ g}{16.04\ g/mol} = 0.623$$

$$moles_{O2} = \frac{mass}{molar\ mass} = \frac{35.08\ g}{31.99\ g/mol} = 1.097$$

$$0.65 = \frac{moles_{CO2}}{moles_{CO2} + 0.623 + 1.097} \rightarrow moles_{CO2} = 3.194$$

$$3.194\ moles_{CO2} = 0.14\ kg/s$$

It is important to note that when purchasing equipment most vendors don’t use mass [kg/s] or [LPM] but instead they use standard liters per minute (SLPM). [SLPM] are used to standardize flowrates because as gases are compressible their density changes. [SLPM] calculate the volumetric flowrate at standard conditions which are (0 [°C] and 1 [atm]). The conversion of the mass flow rate in [kg/s] to [LPM] is given below.

$$\left(\frac{0.01\ \frac{kg}{s}}{19.104\ \frac{kg}{m^3}\ (20°C, 400\ psi)}\right) \rightarrow \frac{m^3}{s} \rightarrow \frac{1000\ L}{1\ m^3} \rightarrow \frac{60\ s}{1\ min} = 31.41\ LPM$$

The only difference in converting from [SLPM] rather than [LPM] is that you divide the mass flowrate by the density at standard conditions instead of the system of the system's conditions as shown below.

$$\left(\frac{0.01\ \frac{kg}{s}}{0.717\ \frac{kg}{m^3}\ (0°C, 1\ atm)}\right) \rightarrow \frac{m^3}{s} \rightarrow \frac{1000\ L}{1\ m^3} \rightarrow \frac{60\ s}{1\ min} = 836.82\ SLPM$$

The flowrates in [kg/s] and [SLPM] are shown in Table 3.4.

Table 3.4 - Gas Flowrates

Gas	Flowrate [kg/s]	Flowrate [SLPM]
Methane	0.1	837
Oxygen	0.03508	1474
Carbon Dioxide	0.14	4266

It should be noted that the flowrates for oxygen and especially carbon dioxide are extremely high, this is important as most flowmeters sold commercially have a max rating of 1000 SLPM. Table 3.5 shows the flowrates for CO2 required to achieve different percent dilutions.

Table 3.5 - Percent Dilution and SLPM

Percent Dilution (CO2)	Flowrate [SLPM]
5	**121**
10	**255**
15	**405**
20	**574**
25	**766**
30	**985**
35	**1237**
40	**1531**
45	**1880**
50	**2297**
55	**2807**
60	**3446**
65	**4267**

Table 3.6 shows the derived flow requirements for the system.

Table 3.6 - Flow Requirements

15.	The mass flowrate of methane shall be 0.01 [kg/s]
16.	The equivalence ratio of the mixture shall be 1.14
17.	The mass flowrate of methane shall be 0.03508 [kg/s]
18.	The mass flowrate of carbon dioxide shall be 0.14 [kg/s]

3.2.5 PRESSURE

The pressure requirements can be broken down into three main parts i) the max pressure of the system ii) delivery pressure and ii) the maximum allowable pressure drop in the system. The delivery pressure has already been established as 20 [bar] or 290 [psi] but the max pressure and maximum allowable pressure drop are very difficult to determine at this point of the project. These requirements are dependent on two very important pieces of equipment i) the tank and ii) the injector which are still in the process of being purchased or designed. The tank pressure is crucial as it allows this gives the maximum pressure the system can experience the injector also plays a major role as it can induce a very large pressure drop.

As both of these items have not yet been determined, assumptions were made to continue with the design process. From literature, it was found that a pressure drop of 20% of chamber pressure was a good starting point for injector design [14]. If the chamber pressure requires a pressure of 290 [psi] then the injector should be expected to produce close to 60 [psi] of pressure drop.

The tank will be assumed to have a minimum pressure of 350 [psi] and a max pressure of 400 [psi] with a safety factor of 1.25. This is a very crucial assumption as it will dictate the entire rest of the design. At this design pressure the system should be capable of operating at pressures as high as 400 [psi] but it may also be the case that a much lower pressure tank is being used in which case pressure drop becomes a major concern.

Using the 1.25 safety factor the design pressure of the system is set at 500 [psi], meaning all components must have a minimum pressure rating up to that pressure. The system will also be designed to have a low pressure drop (30 [psi] or less) to help give the system more flexibility for lower pressure tanks. Table 3.7 shows the derived pressure requirements for the system.

Table 3.7 - Pressure Requirements

19.	The feed system shall have a maximum operating pressure of 500 [psi]
20.	The feed systems shall have no more than 30 [psi] of pressure drop

3.2.6 TEMPERATURE

Although this is a combustion process and the temperature inside the combustor will be extremely high, the gases will be delivered as cold flow and the feed system itself is not expected to vary much from room temperature. For this reason, the temperature requirement for the feed system is 68 [°F] ± [20°]. Table 3.8 shows the derived temperature requirements for the system.

Table 3.8 - Temperature Requirements

21.	The feed system shall operate within a temperature range of 48 [°F] to 88 [°F]

3.2.7 MATERIAL

There is one main thing to consider when it comes to the materials of components and that is compatibility. Some valves may only work with oil or water and some materials may react when they come in contact with a fluid. For our purposes, we can consider all three gases to be inert gases and thus materials should be chosen that are designed to operate with inert gases. As a general guideline, it is always preferable to use highly available materials as they are generally cheaper and reliable but this is not necessarily a requirement. Table 3.9 shows the derived material requirements for the system.

Table 3.9 - Material Requirements

22.	The materials for all components of the feed system shall be compatible with inert gases

3.2.8 SAFETY

Arguably the most important requirement is that the system can be operated safely to protect the facility and the students that will be conducting these experiments. Since this is a high pressure combustion process it is best to be able to control the system remotely from a safe location which means that the components must be able capable of remote control. A safety kill-switch should also be installed. This switch will seal off all fuel sources and immediately conduct a purge in case of an unwanted ignition.

The biggest safety concern comes from the possible unintended mixing of the fuel and oxidizer. It is imperative that the system not allow these two fluids to be mixed as this is a serious safety hazard. Another possible failure mode could be the over pressurization of the system and therefore safety relief valves should be installed. Table 3.10 shows the derived safety requirements for the system

Table 3.10 - Safety Requirements

23.	The systems shall be able to be controlled remotely from a safe location
24.	The system must not allow the mixture of the fuel and oxidizer before the combustion chamber
25.	Each feed line must have a pressure relief valve

3.3 DESIGN PROCESS

The design process was started by making a simple schematic using Visio software showing what was fixed in the system. At the time, there were only three features that were known. The high pressure combustor that will be used, the location of the testing facility, and the location of three pressure regulated gas tanks (one for each gas). The purpose of the feed system is to act as the link between the fuel source and the combustor as shown in Figure 3.9. Figure 3.10 shows a legend for all the symbols used in schematics in this thesis.

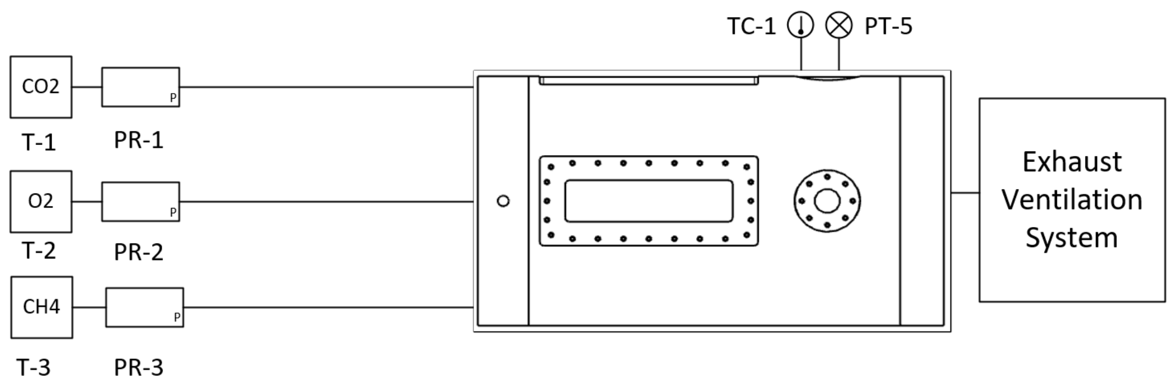


Figure 3.9 - Design Iteration 1

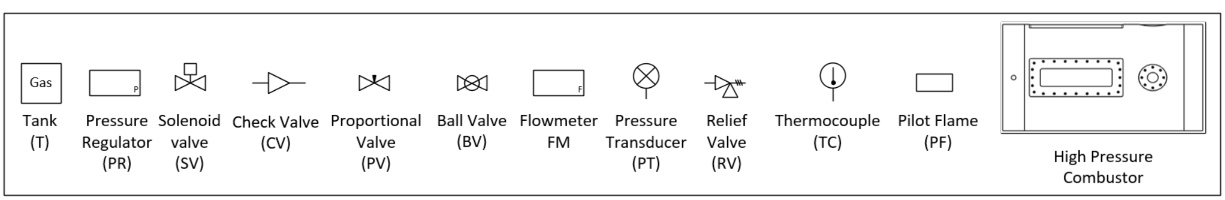


Figure 3.10 - Legend

Next the purpose of feed system was considered. The combustion process requires for the gases to be delivered at specific flowrates and thus the feed system must be able to do two things, measure and regulate the flow through the system. To do this a flowmeter was added to each line which allows the flow to be measured. To regulate the flow there are several possibilities such as

a needle valve, but this would not allow for the system to be operated remotely which is why proportional valves were used as shown in Figure 3.11.

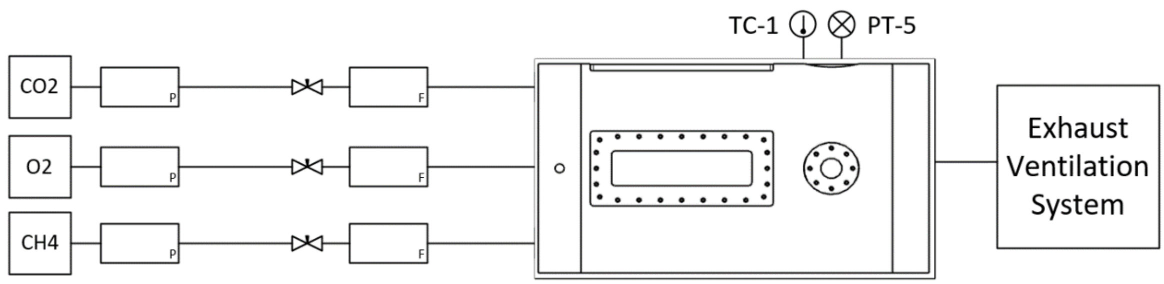


Figure 3.11 - Design Iteration 2

Once the gases are delivered an ignition source is needed to start the combustion process. The combustor has a built-in port to allow for a pilot flame to be lit as the source of ignition. However, the pilot flame also requires a fuel source for ignition. Since the system is already using methane as a fuel source, it was decided to use this methane to also light the pilot flame. The methane light was split in order to provide a fuel source for the pilot flame as shown in Figure 3.12.

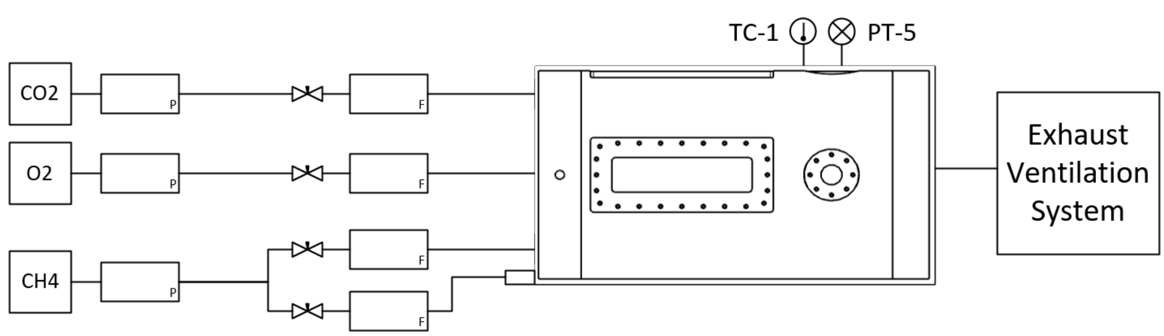


Figure 3.12 - Design Iteration 3

Although in theory all the components needed to deliver and ignite the fuel mixture are already in place, with the current system it is not possible to run the experiments safely. A solenoid

valve was added to the beginning of each fuel line to allow for the supply of gas to be cut off in the case of an emergency. Pressure relief valves were also added to each feed line to protect the system and personnel from over pressurization in the line. The addition of pressure transducers was also done to be able to monitor the pressure during testing and to be able store pressure data using a data acquisition system.

Another important aspect to running an experiment is leak testing. Leak tests must be performed before all experiments and leak test cannot be run without pressurizing the line. A ball valve was added to the end of each line to remedy this issue. Ball valves were chosen as they are significantly cheaper than solenoid valves and there is no need for the valves to be actuated. Leak testing is performed by pressurizing the line and visually inspecting the line for leaks using leak detecting fluid. This means that a member of the team must be present to perform the test and this person can simply close the valve manually. The addition solenoid valves, pressure relief valves, pressure transducers, and ball valves is shown in Figure 3.13.

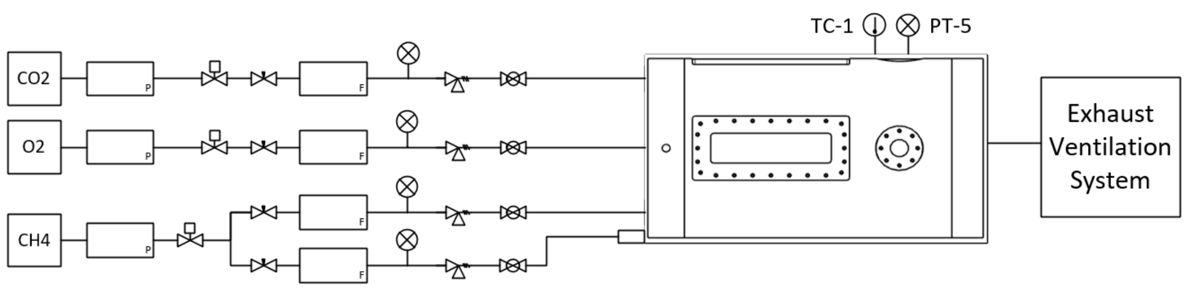


Figure 3.13 - Design Iteration 4

When designing this feed system, it was important to consider how the test will be conducted. For the experiments the testing order will be such that the pilot flame will be lit first, then each gas will be introduced one at a time. The purpose of lighting the pilot flame first is to avoid the situation where the pilot flame doesn't ignite allowing the fuel and oxidizer to build up in the combustion chamber creating the possibility of an explosion in the combustion chamber. Splitting the lines no longer allowed for the pilot flame to be lit first so a solenoid valve was added

before each methane line as shown in Figure 3.14. The solenoid before the pilot flame line will be used to turn off the pilot flame after ignition has taken place.

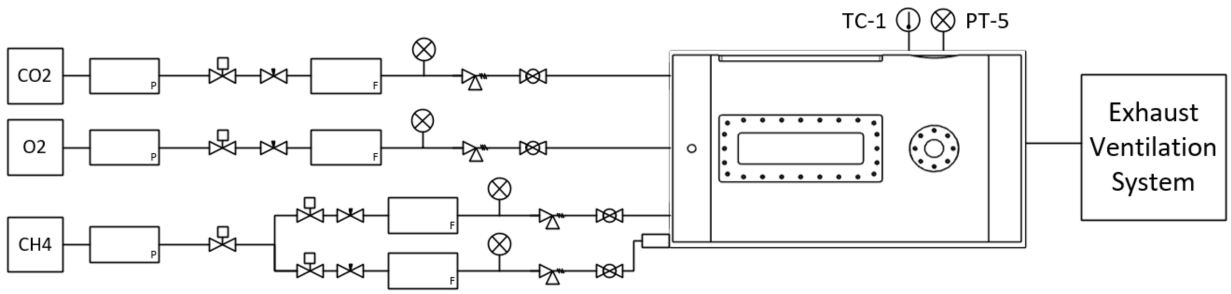


Figure 3.14 - Design Iteration 5

For combustion testing, there are essentially two ways to conduct a test, hard start or soft start. A hard start is where all the gases in the fuel mixture are delivered and ignited at the same time, which can be dangerous and unpredictable. A soft start introduces each gas one at a time slowly building up pressure and temperature, which is why this method was chosen over a hard start. Since all the feed lines now have a valve that can be actuated remotely and independently this makes a soft start possible.

Between each test the all lines must be purged using an inert gas. Since the system already incorporates CO2 for dilution this can be used for purging as well. A key point to considered when designing the purge system is that all lines must be capable of being purged independently. As mentioned earlier it is imperative that the oxidizer and the fuel are never mixed unless they intend to be ignited which is why purging each line independently of each other is so important. A connection between the three lines was made to allow for CO2 to purge the lines as shown in Figure 3.15.

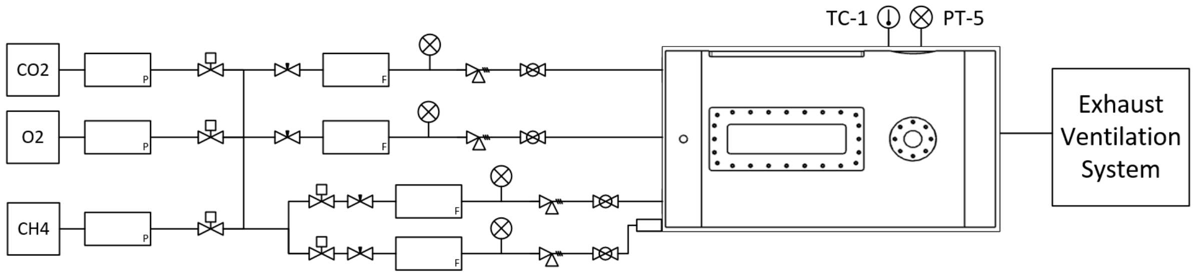


Figure 3.15 - Design Iteration 6

Making this connection can be very dangerous as this links the fuels source and the oxidizer source. To ensure the gases never meet, two solenoid valves were added in between the lines to keep the three lines separate while allowing for the lines to be purged. Figure 3.16 shows the addition of the two solenoid valves to the purge lines.

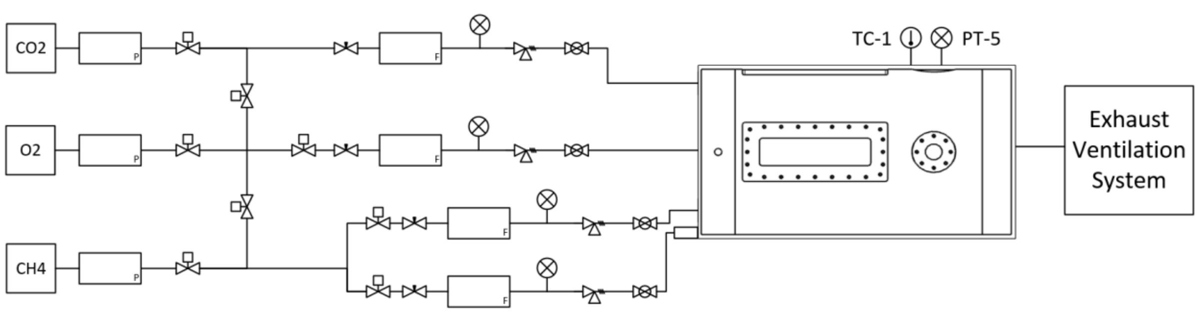


Figure 3.16 - Design Iteration 7

Although the solenoid valves should keep all three gases separated, the possibility of someone leaving one or both solenoid valves open after a purging procedure was considered. As an extra precautionary method a one-way valve (check valve) was incorporated before each solenoid valve. They were place before the solenoid instead of after so that the check valve will act as a safety mechanism in case the solenoid valve is left open and not as the primary method of keeping the gases separate. Figure 3.17 shows the proposed feed system after incorporating the check valves.

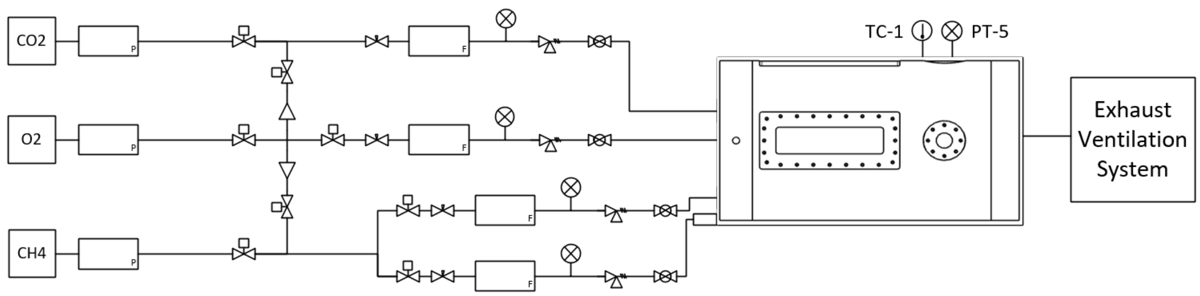


Figure 3.17 - Design Iteration 8

Lastly, the possibility of an unwanted fire occurring in the combustor caused by possible equipment failure or human error was considered. In this situation, the best course of action is to do an immediate purge of the combustor. Using CO2 is a great method to put out fires; however, purging directly through the injector is not best solution as the outlet is extremely small and it may take too long to put out a fire. A separate emergency purge line was incorporated into the schematic that will be used solely in the case of an unwanted fire. A solenoid valve was placed at the beginning of the line to stop CO2 from going in the line during testing. A solenoid was chosen because it will be connected to a kill-switch which will close all other solenoid valves in the system while opening only the valve to the emergency purge line. This should stop all gases from entering the combustion chamber while simultaneously putting out a fire. This kill-switch can also be used at any time to stop flow into the combustor as flowing CO2 into the combustor poses no real threat. Figure 3.18 shows the addition of the emergency purge line to the schematic and Figure 3.19 shows the action taken when the emergency kill-switch is pressed. In this figure, red valves are closed and green valves are open.

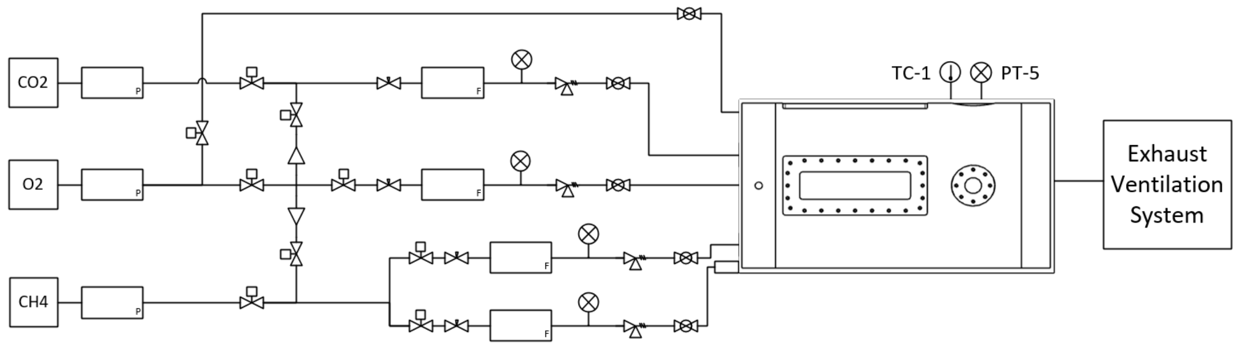


Figure 3.18 - Design Iteration 9

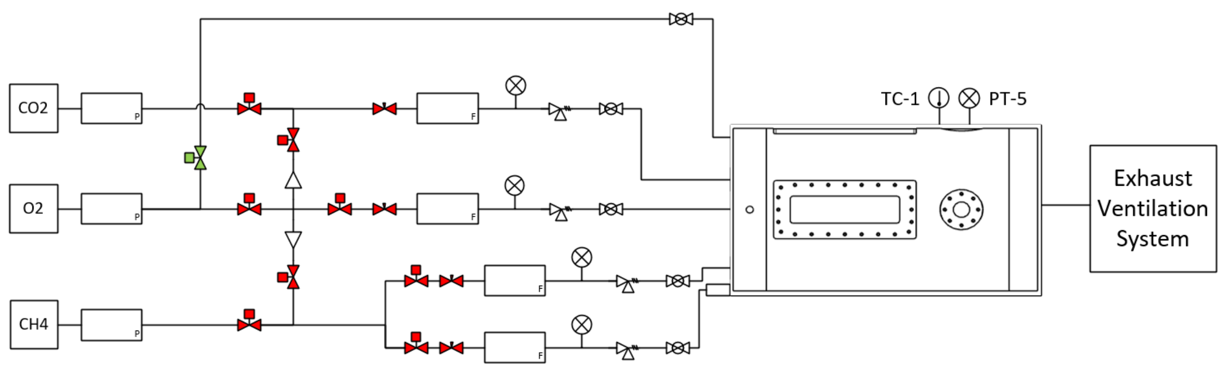


Figure 3.19 - Emergency Purge Procedure

Chapter 4: Final Design

4.1 System Schematic

Figure 4.1 shows the final schematic that will be followed when fabricating the feed system.

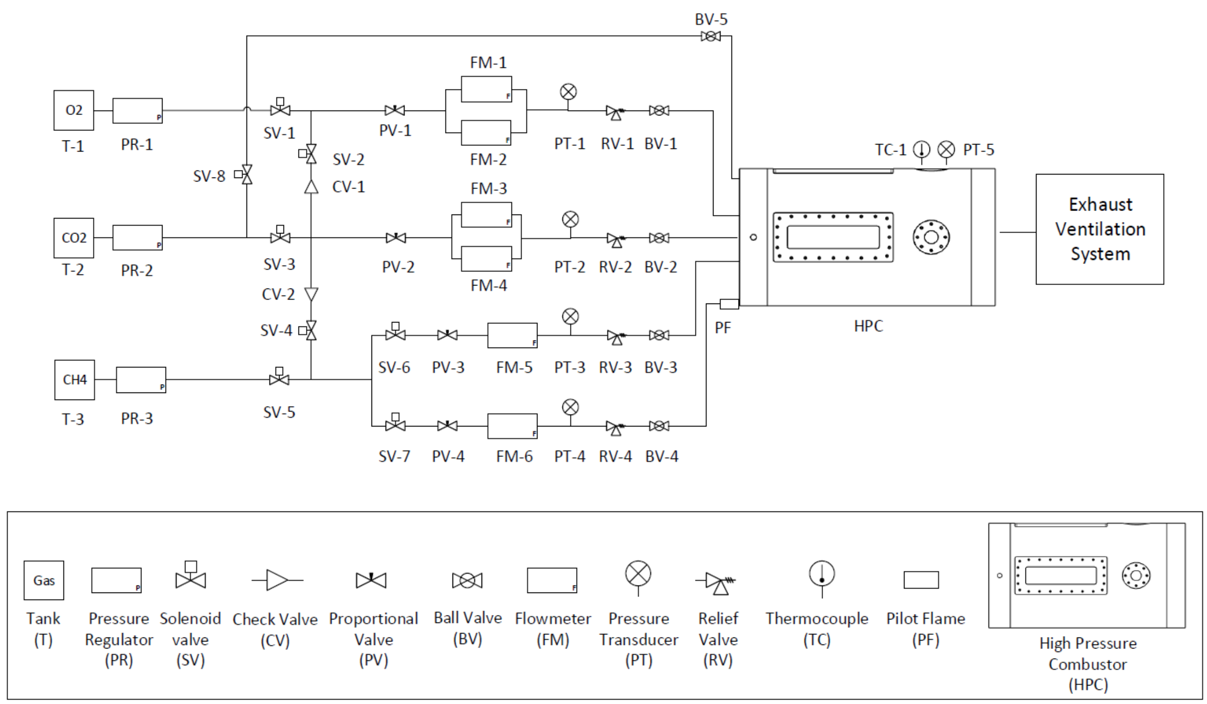


Figure 4.1 - Final System Schematic with Legend

4.2 CAD Model

To help better illustrate how the feed system will look and be assembled a 3D model was built using SolidWorks software shown in Figures 4.2 through 4.4.

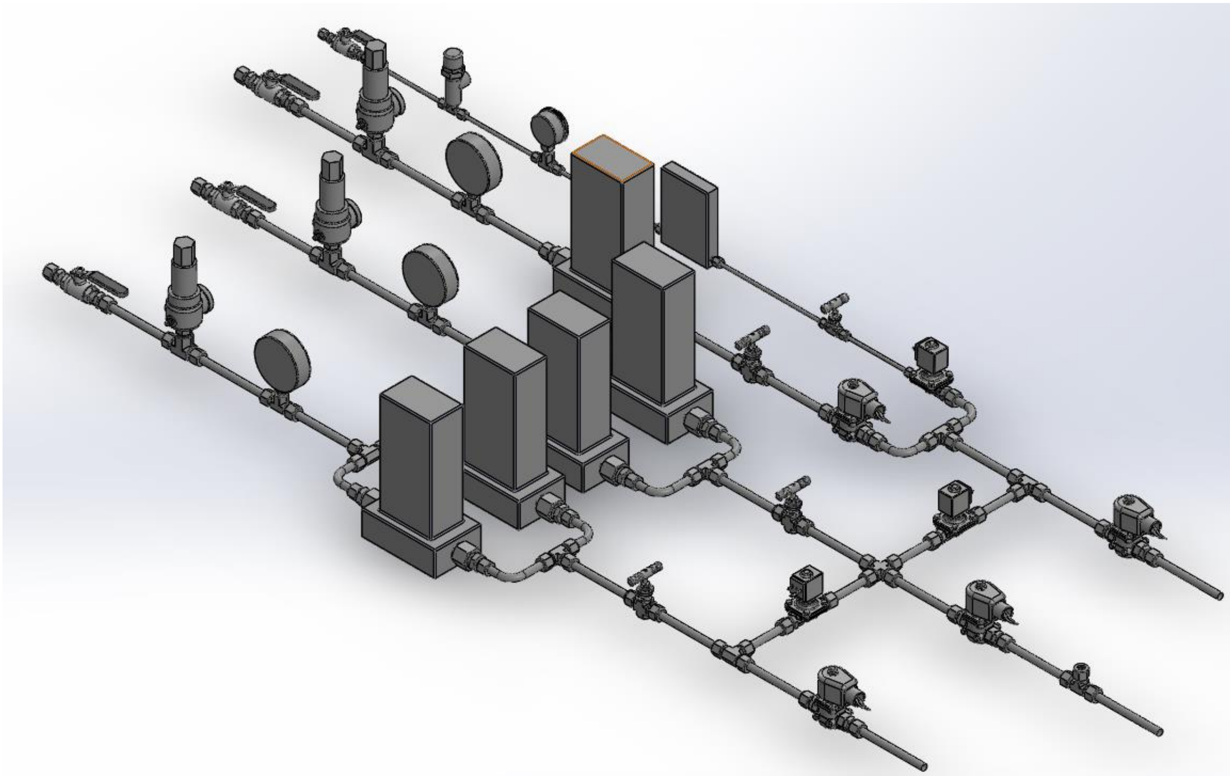


Figure 4.2 - SolidWorks Model (Isometric View)

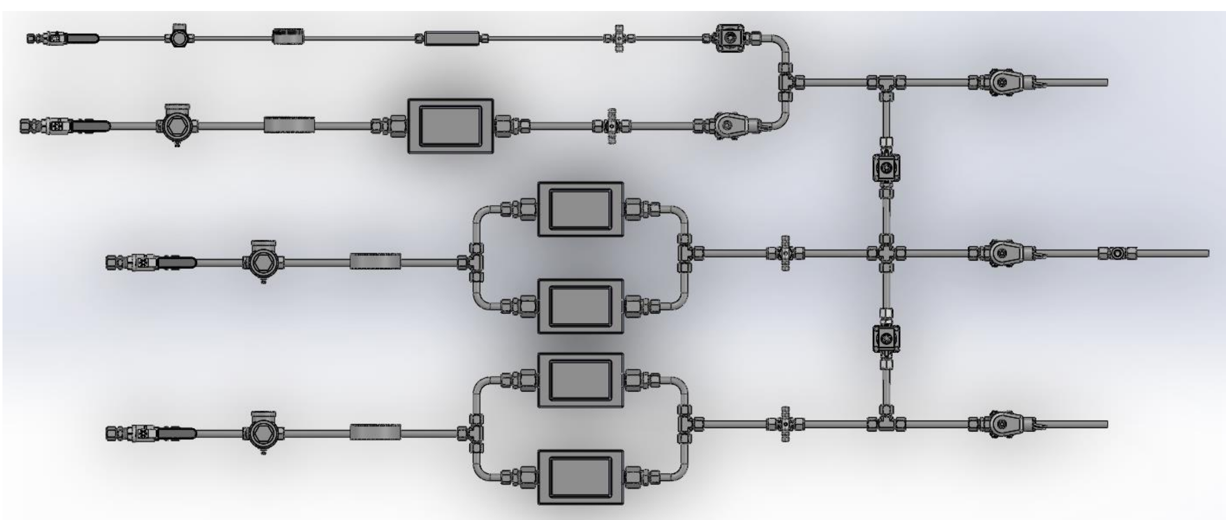


Figure 4.3 - SolidWorks Model (Top View)

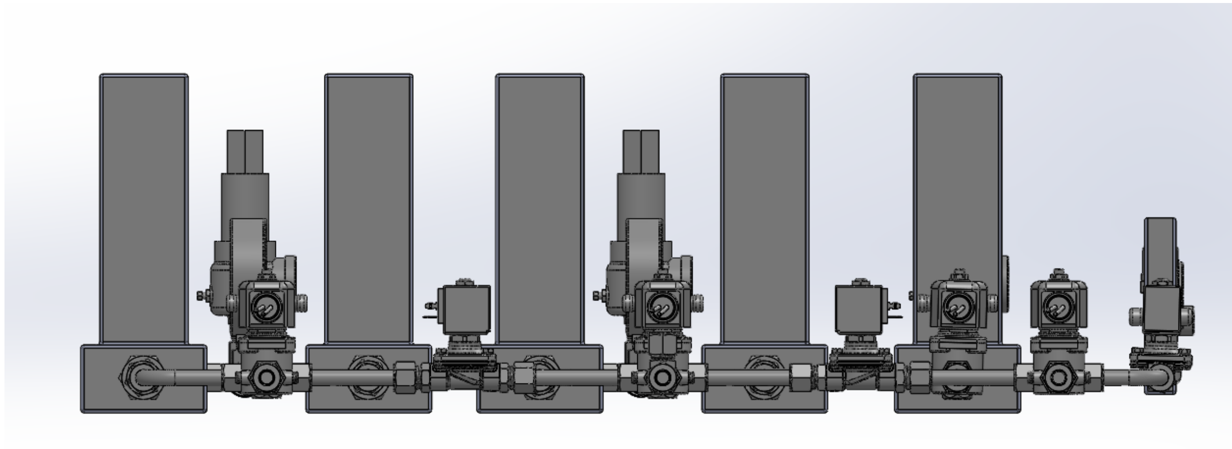


Figure 4.4 - SolidWorks Model (Front View)

All the parts for this model were obtained from the McMaster website with the exception of the flowmeters which will be purchased from Omega. The Omega website did not have a CAD model for their flowmeters available so a flowmeter was drawn using the dimensions found on the website. available on the Omega website.

4.3 LOCATION

Figure 4.5 shows a rendering of image of what the Fabens facility may look like.

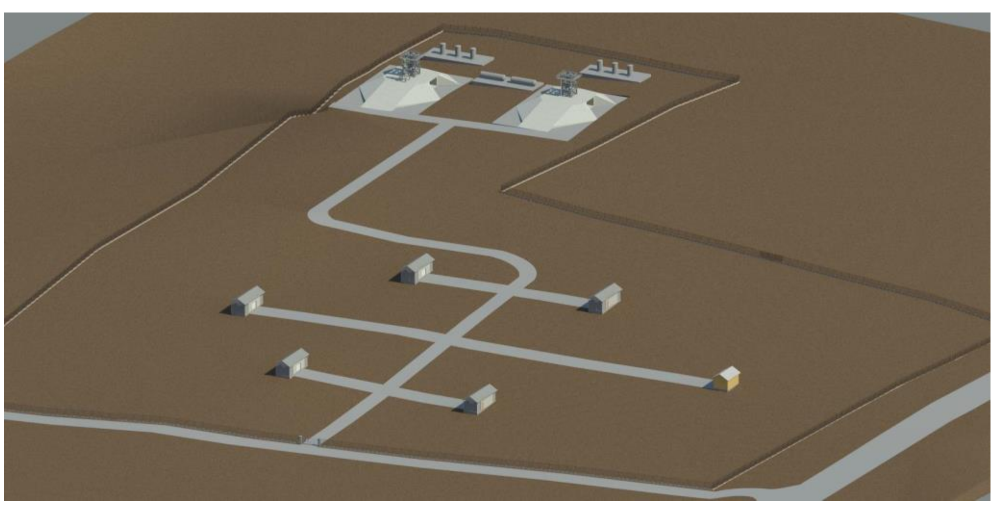


Figure 4.5. Fabens TX, Facility Rendering

Figure 4.6 shows an isometric view testing room with the high pressure combustor located in the center of the room.

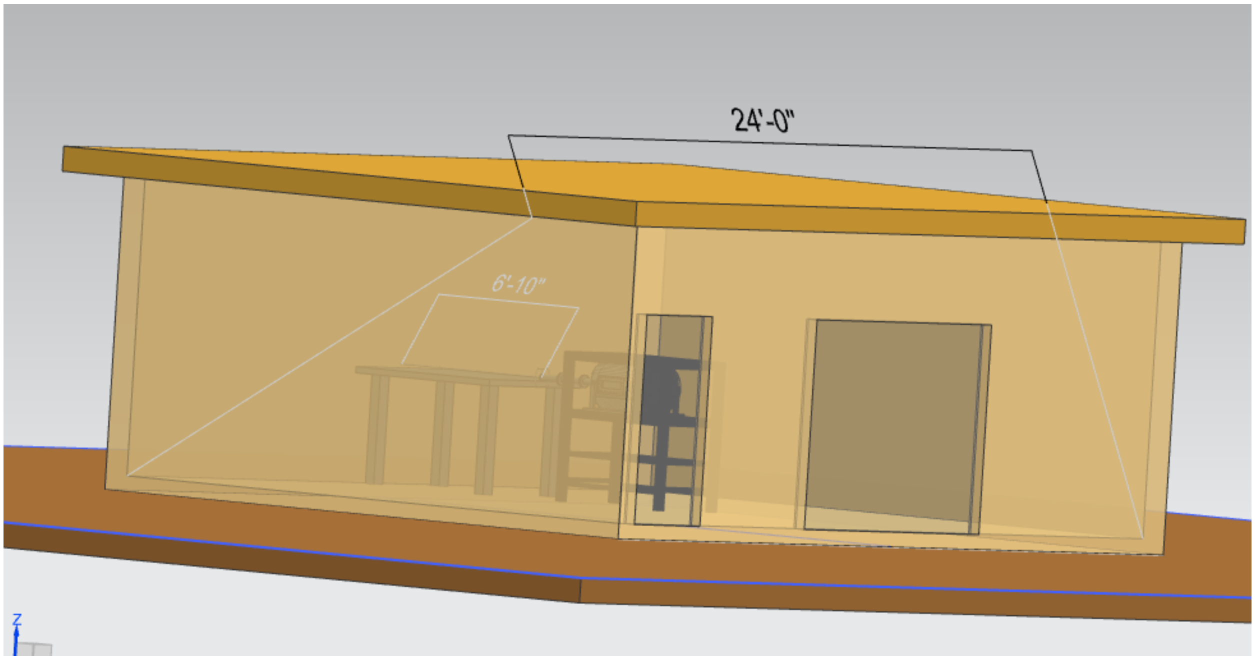


Figure 4.6 - Testing Room (Isometric View)

The system has a maximum length of 94 [in] which is well below the 120 [in] maximum length requirement. All the tubing between components are 6 [in] long but this is subject to change when the system is being built.

4.4 Part Selection

This section will show each part that was selected for the final feed system design along. A detailed explanation to why each part was chosen is also given.

4.4.1 TUBING

For the tubing material two possible choices were considered, stainless steel 304 and stainless steel 316. This is due to their very high popularity for these types of applications. Both are extremely common tubing materials that can be purchases from multiple vendors and come in various outer diameters and wall thicknesses. Although either choice would have been appropriate stainless steel 316 was chosen as it has slightly better corrosive resistance.

For the outer diameter, there were four diameters that were considered 1/4, 3/8, 1/2, and 3/4 [in]. These are all standard diameters inlet sizes making them extremely popular and easy to find. The leap was made from 1/4 [in] to 3/8 [in] instead of considering is 5/16 [in] as it would have made it much more difficult to find the correct size component. Almost all components that will go on the system can be found in these diameters and there are plenty of fittings to choose from. Their small size also makes them to very malleable which can save time in the assembly process.

To narrow down the choices, a simplified pressure drop calculation was conducted to determine if some of the smaller diameters had significantly more pressure drop and thus could not be used. The equations used to determine the pressure drop are discussed in detail in the Pressure Drop Calculations section. Table 4.1 shows the tube sizes along with the pressure drop calculated.

Table 4.1 - Tubing Pressure Drop

Tube Outer Diameter [in]	Wall thickness [in]	Pressure Drop [psi]
1/4	0.01	110.62
3/8	0.01	11.35
1/2	0.02	2.94
3/4	0.035	0.39

The gas used was CO_2 as it has the highest flow rate and is expected to have the highest pressure drop. A pressure of 320 [psi] and 68 [°F] was used to determine the density of the gas and a length of 120 [in] was used. 320 [psi] was chosen as it is the lowest tank pressure expected and 120 [in] was chosen as it is the maximum length requirement of the system and more pressure drop will be seen in a large distance than a small distance. The smallest wall thickness offered for each tube diameter was considered as these have the largest cross-sectional area and thus will have less pressure drop.

The low-pressure requirement was used instead of the high pressure limit because of the affect that pressure has on the density and velocity of a fluid.

Gases are compressible, meaning their density change with pressure. As the pressure increases the density increases. The mass flow rate equation is given below where ρ is density, A is area, and V is velocity. It can be seen that as density rises the velocity of that flow will decrease, if density decreases the velocity of the fluid must increase.

$$\dot{m} = \rho A V$$

Major loses (pressure drop due to friction) in a system are determined by the following equation.

$$\Delta P = f \frac{L}{D} \frac{\rho V^2}{2}$$

In the equation above the velocity term is squared while the density term is not. Meaning velocity plays a bigger role in pressure drop than density does. This causes a fluid that is flowing at a higher pressure to have less pressure drop than a fluid flowing at the same mass flowrate at a lower pressure. This is because the fluid at the lower pressure will have a lower density and thus must increase in velocity to meet the same flowrate. This higher velocity is then squared in the

pressure drop calculation meaning a fluid at a lower pressure will experience high pressure drop. Table 4.1 shows how the calculated pressure drop for the four most common sizes of tubing sold. It can be clearly seen how the pressure drop decreases as the diameter of the tubing increases.

Based on these initial calculations the tubing of outer diameter 1/4 [in] was not considered as the frictional pressure drop was simply too large to meet the pressure drop requirements. The 3/8 [in] outer diameter was also ruled out at this point as the pressure drop is greater than 10 [psi] and it will only go up once all the components are included in the calculations. Leaving only 1/2 [in] and 3/4 [in] outer diameter tubing as options for the higher flow rate O_2, CO_2, and CH_4 lines. Pressure drop calculations were also performed for the CH_4 line to the pilot flame but this line needs a much lower flowrate, a maximum of 10 [SLPM]. This flowrate is low enough that the pressure drop was negligible for all outer diameters considered. A 1/4 [in] outer diameter tubing will be more than sufficient for this line. Figure 4.7 and 4.8 show the tubing in the 1/2 [in] and 1/4 [in] diameters available from McMaster.

Figure 4.7 - 1/2 [in] Diameter Tubing

Figure 4.8 - 1/4 [in] Diameter Tubing

The straight metal tubing was chosen over the coil as the feed systems will consist mainly of straight lines. This will make the fabrication process easier.

4.4.2 Solenoid Valves

As mentioned in the previous section 1/4 [in] and 3/8 [in] diameter tubing had been ruled out leaving only 1/2 [in] and 3/4 [in]. Both sized were considered but after talking to several vendors it was apparent that finding a 3/4 [in] solenoid valve that met the system pressure requirement of 500 [psi] would be more difficult. As valve sizes increase pressure ratings decrease and price increases because a larger orifice is more difficult to close than a smaller one. For this reason the design was continued assuming a 1/2 [in] diameter size for the O2, CO2, and CH4 lines. After all the parts are selected pressure drop calculations can be carried out to see if the feed system meets the requirements.

For this system, a total of 8 solenoid valves are required. One for each gas source, two for the split methane line, two to be used for purging and one for the emergency purge line. Figures

4.9 and 4.10 show the 1/2 [in] solenoid valves chosen from Omega along with its detailed specifications.

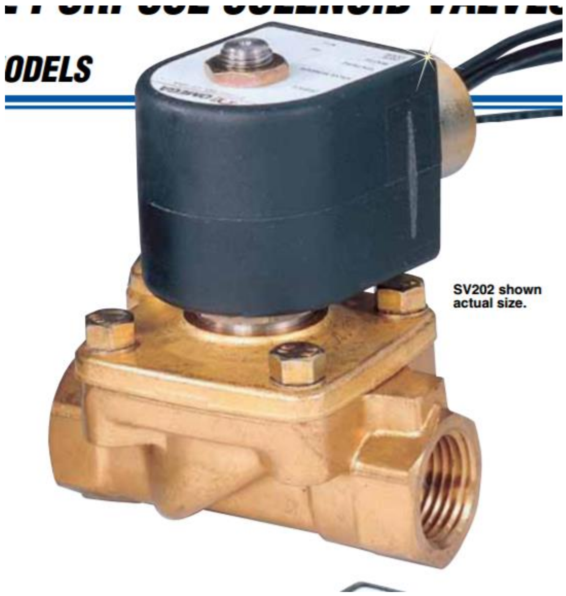


Figure 4.9 - 1/2 [in] Diameter Solenoid Valve

To Order *Visit omega.com/sv200_series for Pricing and Details*										
					DIFF PRES (psid)		TEMP		RESPONSE TIME	
MODEL NO.	NPT FITTING	ORIFICE	C_V	SEAL	MIN	MAX	°C	°F	OPEN	CLOSE
NORMALLY CLOSED MODELS										
SV201	⅜	19/32"	4.4	Buna-N	0	230	85	185	30 to 100 ms	350 to 900 ms*
SV202	½	19/32"	4.4	Buna-N	0	230	85	185	30 to 100 ms	350 to 900 ms*
SV203	¾	25/32"	9.6	Buna-N	5	230	85	185	50 to 80 ms	1.8 to 3 s
SV204	1	1"	12.5	Buna-N	5	230	85	185	50 to 80 ms	1.8 to 3 s
SV205	1¼	1⅛"	19.3	Buna-N	5	230	85	185	50 to 80 ms	1.8 to 3 s
SV206	1½	1 9/16"	29.0	Buna-N	5	230	85	185	50 to 80 ms	1.8 to 3 s
SV207	2	1 9/16"	38.6	Buna-N	5	230	85	185	50 to 80 ms	1.8 to 3 s
NORMALLY OPEN MODELS										
SV211	⅜	7/16"	3.5	Buna-N	5	600	85	185	120 ms	200 ms
SV212	½	9/16"	4.1	Buna-N	5	600	85	185	120 ms	200 ms
SV213	¾	¾"	9.6	Buna-N	5	230	85	185	50 to 80 ms	0.6 to 4.5 s
SV214	1	1"	12.5	Buna-N	5	230	85	185	50 to 80 ms	0.6 to 4.5 s
SV215	1¼	1⅛"	19.3	Buna-N	5	230	85	185	50 to 80 ms	0.8 to 5.8 s
SV216	1½	1 9/16"	29.0	Buna-N	5	170	85	185	50 to 80 ms	1.5 to 9.0 s
SV217	2	1 9/16"	38.6	Buna-N	5	170	85	185	50 to 80 ms	1.5 to 9.5 s

Figure 4.10 - 1/2 [in] Diameter Solenoid Valve Specification

Figure 4.11 and 4.12 shows the 1/4 [in] solenoid valve chosen along with its specifications

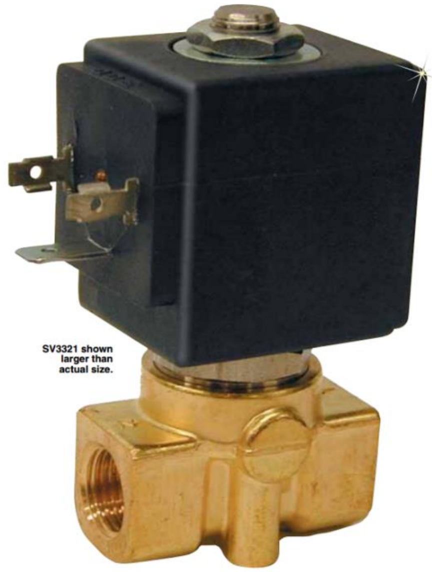


Figure 4.11 - 1/4 [in] Diameter Solenoid Valve

Model No.	Pipe Size	Orifice Size	Cv flow factor	Coil Watts	Minimum psi	Maximum Operating psi Differential	
						AC	DC
SV3321	¼"	³⁄₆₄"	0.07	8W	0	0	1300
SV3321*				12W	0	1450	1450

Figure 4.12 - 1/4 [in] Diameter Solenoid Valve Specification

4.4.3 Proportional Valves

For flow control a needle valve or a proportional valve is required to deliver the appropriate amount of gas for each line. As discussed earlier a proportional valve will be used to allow for remote operation from a safe location. However, finding a proportional valve that met the pressure requirements proved extremely difficult. The specialist company Kelly Pneumatics has proposed a solution by customizing a needle valve with a motor attached that could be controlled remotely. It would also be possible to choose the needle valve to be modified meaning it is possible to control the CV of the valve to allow for lower pressure drops.

Figure 4.13 shows a needle valve by Swagelok that has a CV of 1.8. This CV is high enough that it would not cause too large of a pressure drop and could potentially be used as the valve that would be modified by Kelly Pneumatics to work remotely.

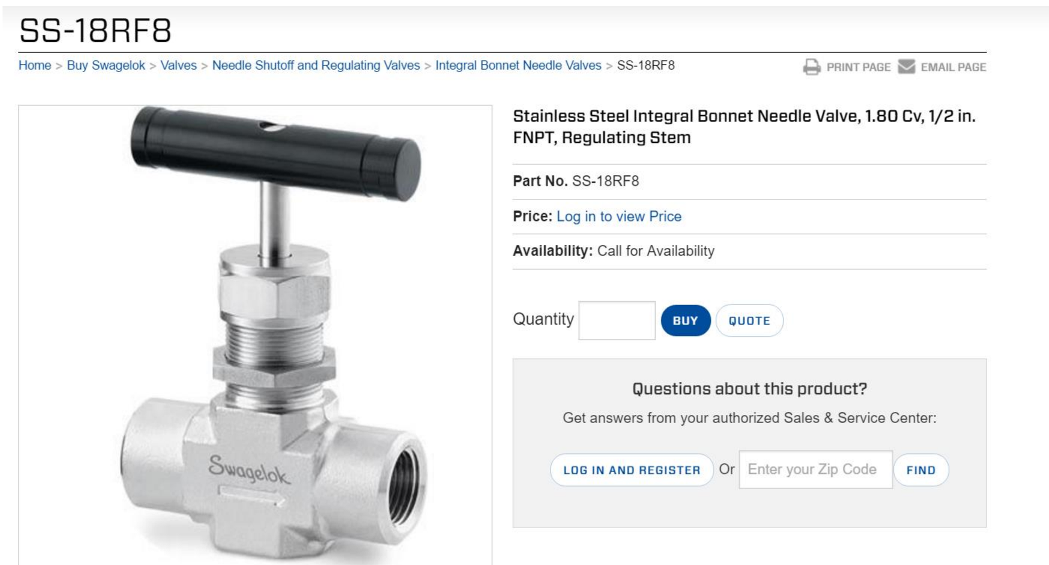


Figure 4.13 - Needle Valve

4.4.4 Flowmeters

For the flowmeters, several vendors were contacted searching for mass flowmeters that met the flow requirements. As mentioned earlier that flow requirements for CH_4, O_2, and CO_2 are 837, 1474, and 4267 [SLPM] respectively, while most commercially available mass flowmeters have a max capacity of only 1000 [SLPM]. One mass flowmeter was found that had a capacity of 2000 [SLPM] but unfortunately it had a max pressure rating of 145 [psi] and thus could not be used. Since the mass flowrate for the methane line is only 837 [SLPM] a 1000[SLPM] flowmeter can be used for this line. For the O_2 line the decision of using two mass flowmeters and

splitting the flow between the two was made after a pressure drop calculation estimated the pressure drop at 0.5 [psi] after considering all tube bends and fittings that would be required to install the component.

The CH4 and CO2 lines were slightly more difficult as they require much higher flowrates. Table 4.2 shows the flowrates of CO2 at different percent dilutions.

Table 4.2 - CO2 Percent Dilution

% Dilution	Flowrate [SLPM]
0.4	1532
0.45	1880
0.5	2298
0.55	2807
0.6	3446
0.65	4267

In table 4.2 it can be seen that flowrates needed to achieve close to 60% dilution are very high and grow by thousands of [SLPM] even with small increases in percent dilution. For practical reasons it was decided not to use 65% dilution for the experiment and instead use 45% which requires a much more manageable 1880 [SLPM]. This decreases the flowrate required by over 2000 [SLPM] while still maintaining a relatively high CO2 percent dilution. A much smaller 10 [SLPM] flowmeter will also be used for the pilot flame line. Adding these two flowmeters changes the layout of the system. Figure 4.14 shows the new schematic incorporating the flowmeters. A total of six flowmeters will now be used.

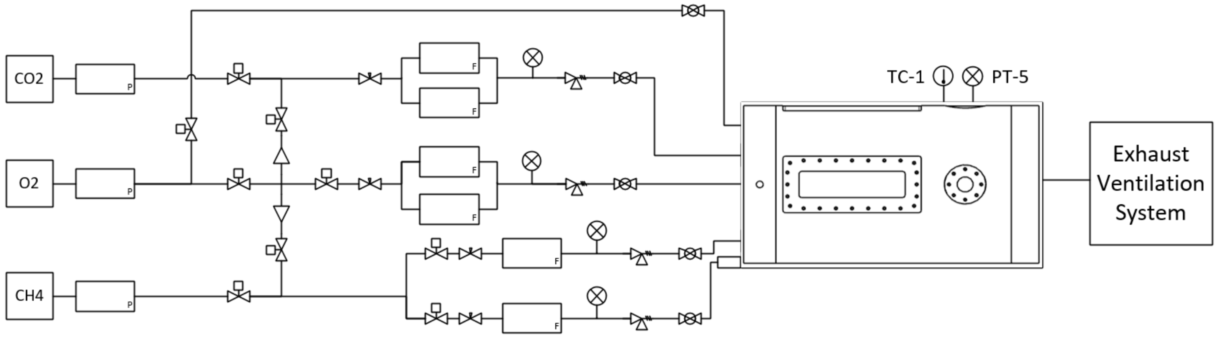


Figure 4.14 - Updated Schematic

Figures 4.15 shows specifications for the flowmeters chosen for the all four feed lines. No image was found on the Omega website for the 1000 [SLPM] or the 10 [SLPM] so a CAD drawing was made using the dimension from the official website as shown in Figure 4.15.

Dimensions: cm (inch)

Unit Maximum Flow Rate	Lay Length with Fittings	Maximum Height	Maximum Width	Connection-Compression Fitting
10 SCCM to 10 SLM	12.8 (5.02)	14.2 (5.60)	2.5 (1.00)	¼"
15 to 50 SLM	15.6 (6.15)	15.2 (5.98)	3.2 (1.25)	¼"
60 to 100 SLM	15.9 (6.27)	15.2 (5.98)	3.2 (1.25)	⅜"
200 SLM	22.4 (8.83)	16.8 (6.60)	4.4 (1.75)	⅜"
500 SLM	24.6 (9.67)	19.3 (7.60)	7.6 (3.00)	½"
1000 SLM	18.5 (7.30)	21.8 (8.60)	10.2 (4.00)	¾ FNPT

Figure 4.15 - Flowmeter Dimensions

4.4.5 Ball Valves

Ball valves are widely available at both the 1/2 [in] and 1/4 [in] diameters. The same is also true for check valves. Three ball valves were chosen at the 1/2 [in] diameter and two at the 1/4 [in] diameter. Figure 4.16 and 4.17 shows the ball valves selected.

Brass On/Off Valve
with Lever Handle, 1/2 NPT Female

Each | ADD TO ORDER

In stock
$9.47 Each
47865K23

Valve Function	On/Off
For Use With	Air, Inert Gas, Oil, Steam, Water
Activation	Manual
Connection Type	Pipe × Pipe
Connection	Threaded NPT Female × Threaded NPT Female
Pipe Size	1/2 × 1/2
Shape	Straight
End-to-End Length	2 5/16"
Maximum Pressure	600 psi @ 100° F
Maximum Steam Pressure	150 psi @ 366° F
Temperature Range	-50° to 400° F

Figure 4.16 - 1/2 [in] Ball Valve

Brass On/Off Valve
with Lever Handle, 1/4 NPT Female

Each | ADD TO ORDER

In stock
$8.27 Each
47865K21

Valve Function	On/Off
For Use With	Air, Inert Gas, Oil, Steam, Water
Activation	Manual
Connection Type	Pipe × Pipe
Connection	Threaded NPT Female × Threaded NPT Female
Pipe Size	1/4 × 1/4
Shape	Straight
End-to-End Length	1 3/4"
Maximum Pressure	600 psi @ 100° F
Maximum Steam Pressure	150 psi @ 366° F
Temperature Range	-50° to 400° F

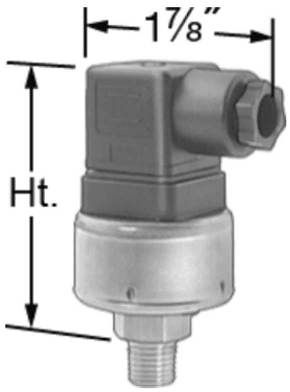
Figure 4.17 - 1/4 [in] Ball Valve

4.4.6 Pressure Transducers

Pressure transducers are not in-line components so they don’t need to be installed in the line itself. A simple tee connection can be used at the desired diameter. Four 1/4 [in] pressure transducers were chosen.

Figure 4.18 shows the pressure transducers chosen for all four feed lines.

Pressure Transmitter
Standard, 0-10 V, 1/4 NPT



Pressure Range, psi
✓ 0-500

[ ] Each

ADD TO ORDER

In stock
$147.71 Each
3196K2

Output Signal	0-10V DC
DC Voltage	14-30
Pipe Size	1/4
Height	2 3/8"
Pressure Range	0-500 psi
RoHS	Compliant

Figure 4.18 - Pressure Transducer

4.4.7 Pressure Relief Valves

Pressure relief valves are also widely available at both the 1/2 [in] and 1/4 [in] diameters. Five pressure relief valves were chosen all at the 1/4 [in] diameter as these are also not in-line components. Each relief valve will have a set pressure of 500 [psi] which is the max pressure the system will be designed to operate at. Figure 4.19 shows the pressure relief valves that were chosen for all four feed lines.

ASME-Code Fast-Acting Pressure-Relief Valve
for Air, 1/4 NPT Male, 3-3/16" High

Set Pressure, psi
✓ 500

Each

ADD TO ORDER

In stock
$111.08 Each
5825T21

Valve Function	Pressure Relief
For Use With	Air, Inert Gas
Activation	Pressure Driven
Inlet	
Pipe Size	1/4
Connection Type	Pipe
Pipe Connection Type	Threaded
Connection	NPT Male
Location	Bottom

Figure 4.19 - Pressure Relief Valve

4.4.8 Check Valves

For the check valves, only two are needed to go on the lines between the main feed lines. These are 1/4 [in] lines and thus two 1/4 [in] check valves were picked. Figure 4.20 shows the check valves chosen to go along with the solenoid valves in the 1/4 [in] line.

Compact Backflow-Prevention Valve
for Water & Inert Gas, 1/4 NPT Male x 1/4 NPT Male

Each

ADD TO ORDER

In stock
$10.42 Each
7768K16

Valve Function	Backflow Prevention
For Use With	Air, Inert Gas, Water
Activation	Pressure Driven
Connection Type	Pipe × Pipe
Connection	Threaded NPT Male Inlet × Threaded NPT Male Outlet
Pipe Size	1/4 × 1/4
Maximum Pressure	500 psi @ 70° F
Minimum Opening Pressure	1 psi
Temperature Range	-20° to 180° F

Figure 4.20 - Check Valve

4.5 Parts List

Table 4.3 shows a list with all the 34 components currently in the system design.

Table 4.3 - Component List

Item	Quantity
Tubing	42 [ft]
Solenoid Valve	8
Proportional Valve	4
Flowmeter	6
Pressure Transducer	4
Pressure Relief Valve	4
Ball Valve	5
Check Valve	2

Table 4.4 shows this list broken down into specifications.

Table 4.4 - Component Specification List

Item	Specification	Quantity
Tubing	1/2 [in]	18 ft
Tubing	1/4 [in]	24 ft
Solenoid Valve	1/2 [in]	4
Solenoid Valve	1/4 [in]	4
Proportional Valve	1/2 [in]	3
Proportional Valve	1/4 [in]	1
Flowmeter	1000 [SLPM]	5
Flowmeter	10 [SLPM]	1
Ball Valve	1/2 [in]	3
Ball Valve	1/4 [in]	2
Pressure Transducer	1/4 [in]	4
Pressure Relief Valve	1/2 [in]	3
Pressure Relief Valve	1/4 [in]	1
Check Valve	1/4 [in]	2

4.6 Pressure Drop Calculations

The pressure drop in the system was calculated by using the following equation.

$$\Delta P_{total} = \Delta P_{major} + \Delta P_{minor}$$

Where major losses are the losses relating to the friction inside the pipe and minor losses are the loses relating to obstruction in the flow such as fittings. The major losses in the system were calculated by the following equations.

$$\Delta P_L = f\frac{L}{D}\frac{\rho V^2}{2}$$

$$\frac{1}{\sqrt{f}} = -2log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right)$$

$$Re = \frac{\rho VD}{\mu}$$

Table 4.5 shows a legend for all variables and constants used in above equations.

Table 4.5 - Equation Legend

Symbol	Definition	Variable/Constant	Value
ΔP_L	Pressure drop	Variable	---
f	Friction factor	Variable	---
L	Length	Variable	----
D	Hydraulic diameter	Variable	---
ρ	Density	Variable	----
V	Velocity	Variable	----
ε	Absolute roughness	Constant	1.5E-05 [17]
Re	Reynolds number	Variable	----
μ	Dynamic Viscosity	Constant	1.45E-05 [18]

The minor losses were calculated by identifying all the K factors caused by various obstructions in each individual segment and then combining them to make a total K factor which

would then be applied to the pressure drop calculation. Figure 4.21 shows a chart where all the K factors used in the calculations were obtained.

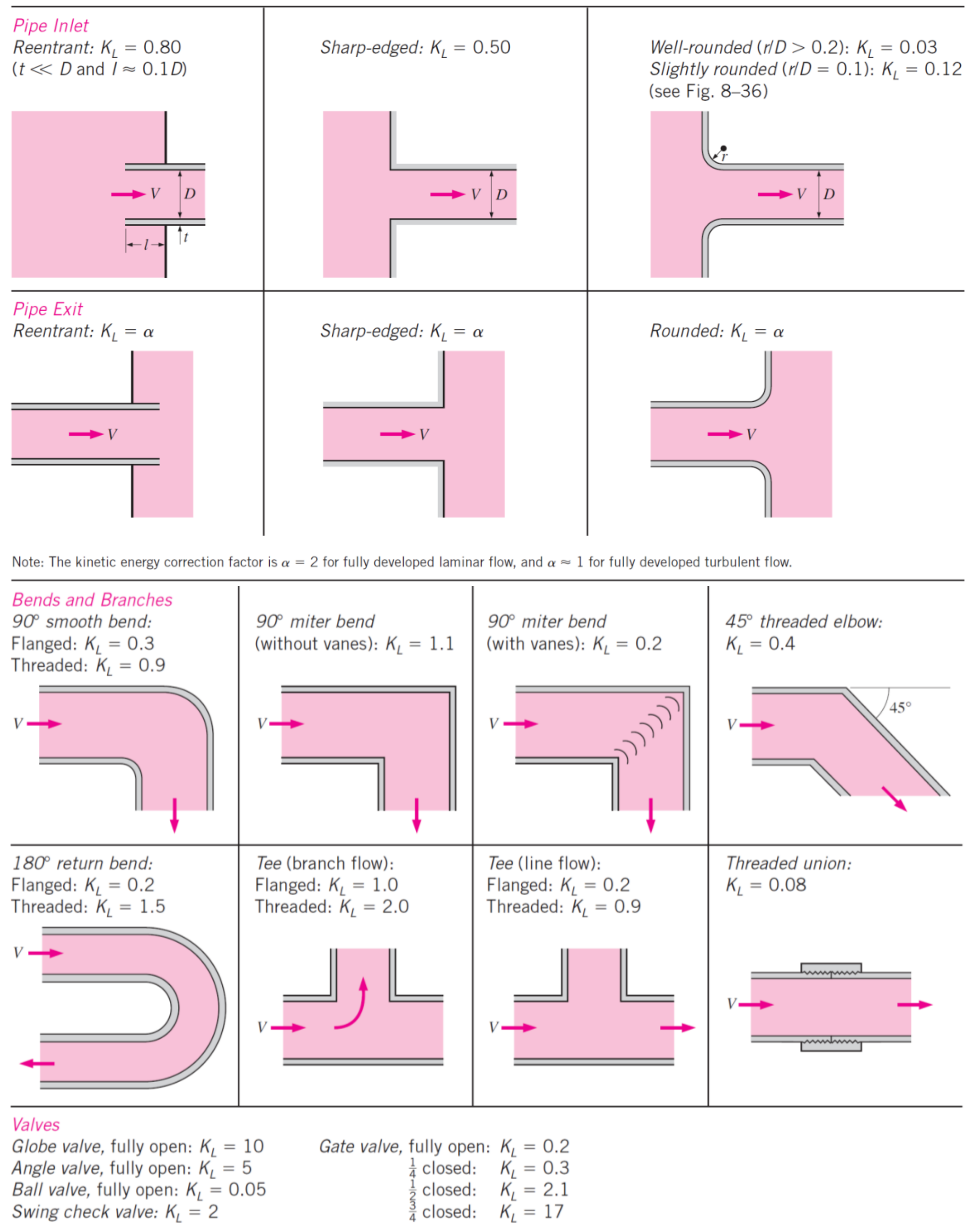


Figure 4.21 - K Factors Chart

To illustrate this, the pressure drop calculations for the methane line are shown below. The calculations start at the end of the system at the combustion chamber assuming a pressure of 290 [psi] and will work backwards until reaching the tank. This will determine the pressure at the tank required to achieve the required chamber pressure. Immediately before the combustion chamber is the injector which was assumed to have a pressure drop of 20% meaning the pressure before reaching the combustion chamber would be 348.1 [psi]. Before the injector is a small piece of tubing 6 [in] long. To calculate the pressure drop across this piece of tubing the density of methane needs to be taken into account using the new pressure that was just calculated. For methane the density is 16.527 kg/m^3 at 348.1 [psi] [16]. Next the major losses formulas are used to determine the pressure drop across this small piece of tubing which in this case are almost unmeasurable due to the small length of the tubing. Before this piece of tubing is a solenoid valve in which case the following equation was used to determine the change in pressure.

$$Q = 16.05 * C_v \sqrt{\frac{{p_1}^2 - {p_2}^2}{T * S_g}}$$

Where Q is the flowrate in SCFM, C_v is the flow rate of water in GPM at 60 [° F] needed to cause a pressure drop of 1 [psi] across the piece of equipment, P_1 and P_2 at the start and end pressure respectively, T is the temperature in Rankine, and S_g is the specific gravity of the fluid.

The solenoid valve has a C_v of 4.1 and after plugging in all the values an estimated pressure difference of approximately 1 [psi] was calculated. This same process is repeated for all sections of the system until reaching the methane gas tank as is shown in Table 4.6 and Table 4.7.

	T	SV	TB	SV	TB	NV	TB	FM	TB	PT	TB	RV	TB	SV	TB	INJ	HPC
CH4	358	358	358	357.8	357.7	357.7	357.3	357.3	348.2	348.2	348.2	348.2	348.2	348.2	348.1	348.1	290

Table 4.6 - Pressure Drop Calculations for CH4 in [psi]

Table 4.7 Pressure Drop Calculations Legend

Abbreviation	Component
T	Tank
SV	Solenoid Valve
TB	Tubing
PV	Proportional Valve
FM	Flowmeter
PT	Pressure Transducer
RV	Relief Valve
INJ	Injector
HPC	High pressure Combustor

Table 4.6 shows that the pressure required by the methane gas tank to achieve a pressure of 290 [psi] at the combustion chamber is 358 [psi]. The process was repeated for the O2 and CO2 lines as shown in Table 4.8 which show that the pressure required would be 362 [psi] and 367.8 [psi] respectively. With this information it is possible to size the tanks as we know that a minimum of approximately 370 [psi] is needed to achieve the desired pressure.

Table 4.8 - Pressure Drop Calculations for O2 and CO2 in [psi]

	T	SV	TB	NV	TB	FM	TB	PT	TB	RV	TB	SV	TB	INJ	HPC
O2	362	361.9	361.4	361.1	358.6	358.5	348.8	348.2	348.8	348.7	348.7	348.6	348.2	348.1	290
CO2	367.8	367.6	366.5	365.6	360	359.8	349.7	349.6	349.6	349.5	349.5	349.3	348.2	348.1	290

Table 4.9 shows the total pressure drop for all three gases as well as pressure at the tank required for all three gases to be able to achieve a pressure of 290 [psi]. Lastly, this chart shows the pressure drop not including the large pressure drop from the injector meaning this would be the pressure drop from only the feed system itself.

Table 4.9 - Total Pressure Drop

	Total Pressure Drop [psi]	Tank Pressure Required [psi]	Pressure Drop without Injector
O2	72	362	14
CO2	78	368	20
CH4	68	358	10

4.7 CONCLUSION

This section will return to the design requirements stated in Section 3.2 and compare the proposed feed system design to shows that all design requirements were indeed met. This feed system design is capable of controlling the flow of gases remotely from a safe location and has accounted for the purge procedure that will be conducted before testing. The final length of the design is 94 [in] which falls below the 120 [in] threshold. All component are for temperatures higher than 88 [°F] and temperatures below 44 [°F]. The system's main challenge were the pressure requirements as this system is operating are high pressures and must all have a low pressure drop. All components are rated above the systems design pressure of 400 [psi] and most notably the system has an estimated total pressure drop of 78 [psi]. Taking into account that 58 [psi] are automatically lost at the injector that means the feed system itself only has 20 [psi] of pressure drop. This project was also able to determine the required tank pressure needed to achieve the goal pressure of 20 [bar] at the combustion chamber. Given that the system is expected to lose close to 80 [psi], a minimum tank pressure of 370 [psi] is needed to achieve the desired chamber pressure.

References

[1] Natural Gas Prices. Retrieved February 24, 2017, from http://www.tradingeconomics.com/commodity/natural-gas

[2] How much carbon dioxide is produced when different fuels are burned? - FAQ - U.S. Energy formation administration (EIA). (2016, June 14). Retrieved February 24, 2017, from https://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11

[3] How much natural gas does the United States have, and how long will it last? - FAQ - U.S. Energy information administration (EIA). (2016, December 7). Retrieved February 24, 2017, from EIA, https://www.eia.gov/tools/faqs/faq.php?id=58&t=8

[4] What is U.S. Electricity generation by energy source? - FAQ - U.S. Energy information administration (EIA). (2016, April 1). Retrieved February 24, 2017, from https://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3

[5] EIA projects 48% increase in world energy consumption by 2040 - today in energy - U.S. Energy information administration (EIA). (2016, May 12). Retrieved February 24, 2017, from http://www.eia.gov/todayinenergy/detail.php?id=26212

[6] Bellman, D. (2007). ELECTRIC GENERATION EFFICIENCY. *Working Document of the NPC Global Oil & Gas Study*

[7] Intergovernmental Panel on Climate. "Climate Change 2014 Synthesis Report Summary for Policymakers. Print"

[8] Turns, Stephen R. *An Introduction to Combustion: Concepts and Applications*. 3 ed. McGraw-Hill, 2011. Print.

[9] Maldonado, Sergio E. "Experimental Investigation of Syngas Flame Stability Using a Multi-tube FUEL Injector in a High Pressure Ccombustor." (2014).

[10] Huijgen, W.J.J., & Comans, R.N.J. (2003). *Carbon dioxide sequestration by mineral carbonation Literature Review* (ECN-C--03-016). Netherlands

[11] Hilshorn, Steven R., Linda D. Voss, and Linda K. Bromley. "NASA System Engineering Handbook." (2017)(17 Feb. 2017). Web.

[12] "Fuels - High Caloric Values." *Engineeringtoolbox*. Retrieved May 9, 2017, from http://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html.

[13] Law, C.K., and A Makimo. "On the Off-stoichiometric Peaking of Adiabatic Flame Temperature." (2006).

[14] Huzel, Dieter K., and David H. Huang. *Modern Engineering for Design of Liquid-Propellant Rocket Engines*. American Institute of Aeronautics and Astronautics, 1992. Print.

[15] Janes, Agnes, and Jacques Chaineaux. "Experimental Study of CH4/O2/CO2 Mixtures Ammability." (2014). Print.

[16] "Peacesoftware." Retrieved May 9, 2017, from http://www.peacesoftware.de/einigewerte/methan_e.html.

[17] "Ventilation Ducts - Roughness and Surface Coefficients." *Engineeringtoolbox*. Retrieved February 27, 2017, from http://www.engineeringtoolbox.com/surface-roughness-ventilation-ducts-d_209.html.

[18] "Gases - Dynamic Viscosity." *Engineeringtoolbox.* Retrieved February 27, 2017, from http://www.engineeringtoolbox.com/gases-absolute-dynamic-viscosity-d_1888.html.

Appendix

Design Requirements Document

1.	The combustor shall operate at a pressure of 20 [bar]
2.	The combustor shall use a power input of 500 [MW]
3.	The combustor shall use a fuel mixture of oxygen and methane
4.	The combustor shall demonstrate continuous safe combustion for a period of 2 hours
5.	The combustor shall demonstrate the above by August 2017
6.	The feed system shall have a method to control and measure flowrates
7.	The system shall be able to provide reliable test results
8.	The system shall have a data acquisition system
9.	Each line shall have a seal for leak testing
10.	The feed system shall have a way to purge each line individually
11.	The high pressure combustor shall be located in the Fabens TX testing facility
12.	The high pressure combustor shall be positioned in the center of the room
13.	The high pressure combustor exhaust shall face the garage door
14.	The max length of the feed system shall be 120 [in]
15.	The mass flowrate of methane shall be 0.01 [kg/s]
16.	The equivalence ratio of the mixture shall be 1.14
17.	The mass flowrate of methane shall be 0.03508 [kg/s]
18.	The mass flowrate of carbon dioxide shall be 0.14 [kg/s]
19.	The feed system shall have a maximum operating pressure of 500 [psi]
20.	The feed systems shall have no more than 30 [psi] of pressure drop
21.	The feed system shall operate within a temperature range of 48 [°F] to 88 [°F]
22.	The materials for all components of the feed system shall be compatible with inert gases
23.	The systems shall be able to be controlled remotely from a safe location

24.	The system must not allow the mixture of the fuel and oxidizer before the combustion chamber
25.	Each feed line must have a pressure relief valve

Vita

Jorge A. Rosero is a graduate student at the University of Texas at El Paso (UTEP) where he also received his Bachelor of Science in Mechanical Engineering in December of 2015. At UTEP he has had many roles including teaching assistant, officer for the Society of Women Engineers (SWE) where he helped encourage young women to pursue an education in STEM fields, and research assistant for the Center for Space Exploration Technology Research which he joined in the summer of 2014 as part of the COURI Undergraduate Research Program under Dr. Norman Love. He presented his research at the COURI 2014 Summer Symposium where he was awarded 1st Place for Best Poster Presentation for his work on developing a stability map for syngas using a high pressure combustor. He has also received several scholarships including the Lyon Family Foundation Scholarship and the ExxonMobil LOFT Fellowship, and was invited to be a part of the planning committee for the university's new interdisciplinary research building which started construction in April of 2017. Outside of UTEP Jorge studied at the Kyushu Institute of Technology in Japan where he worked on a reusable rocket intended to reach low earth orbit and also conducted testing on the Horyu-4 Satellite that successfully launched into orbit in February 2017. He conducted two internships, his first with the U.S. Army: Brigade Modernization Command where he helped test new equipment to be used in military. His final internship with continued Jorge's focus in the energy sector with ExxonMobil, where he was involved in a major safety project where he analyzed the safety of chemical pipelines.

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