ABSTRACT

NONAVINAKERE VINOD, KAUSHIK. Design and Analysis of a Constant Volume Combustion Chamber to Test Premixed Combustion. (Under the direction of Dr. Tiegang Fang).

In recent years, environmental effects and changes are threatening the future of fossil fuel burning engines, advancements in developmental technologies are being limited by new problems that have not been studied extensively to forge a solution. This increases the need to experiment with engines to provide data for future analysis.

In this work a Constant Volume combustion chamber was designed that can run experiments with premixed combustion to generate data for analysis and to try and identify a path way to successfully generate super-knocking combustion with good repeatability. We believe that a CVCC with optical access can provide invaluable data when we study pre-ignition or super-knocking and help in understanding the causes and effects.

First a preliminary design was made for the constant volume combustion chamber based on current research and tested with structural simulations to verify structural integrity and create a base to be improved on. The sub systems necessary for the operation were also designed to accommodate the requirements of premixed combustion and also provide enough flexibility to make alteration to the operation of the system and study different types of combustion as needed.

Finally, the results of the simulations were used to optimize the design and make the system more efficient and improve the ease of operation and manufacturing. The second iteration was again tested and run through the full array of structural analysis to confirm the safe operation of the system when deployed.
Design and Analysis of a Constant Volume Combustion Chamber to Test Premixed Combustion

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Mechanical Engineering

Raleigh, North Carolina
2018

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DEDICATION

To my parents, for their love and trust.
Kaushik Nonavinakere Vinod is from Chennai, a city in the south eastern coast of India. He was born in 1995 to a Mrs. Rekha and Mr. Vinod. From a young age, he was inspired by engines and the magical way they moved vehicles just drinking some liquid. This laid the foundation for his interest in becoming a Mechanical engineer and work with engines. During his baccalaureate studies, he studied and researched on many topics related to engines and energy conversion systems. For his bachelors thesis he worked on designing and building prototype pyrolyzers that can pyrolyze waste plastics into vapors which can produce syngas that can be used to run engines. To continue his thirst for knowledge in engines he enrolled in North Carolina State University in the spring of 2017 to pursue his masters’ degree in mechanical engineering and joined Dr. Tiegang Fang’s research group in the summer of 2017. Wherein he learnt a lot on Super-knocking combustion, pre-ignition and the like before starting to work on designing a Constant Volume Combustion Chamber for the purpose of experimenting with premixed combustion.
ACKNOWLEDGMENTS

First and foremost, I would like to express my gratitude to my advisor Dr. Tiegang Fang for giving me the opportunity and the support to complete my work at North Carolina State University. His knowledge, motivation and trust allowed me to overcome all the difficulties and arrive at this destination.

I would also like to share my appreciation towards my committee members Dr. Alexei V. Saveliev and Dr. Tarek Echekki for their efforts to help me complete my thesis. I would also like to thank Dr. Jeffrey Eischen for helping me complete me design by sharing his knowledge and experience in his field.

I also like to sincerely thank my fellow students in Dr. Fang’s research group, Fujun Wang, Libing Wang, Abijit Padhiary, Akash Jerome and Yifan Song for helping me find a solution whenever I got stuck and teaching me new things and giving me a good time in the labs.

Finally I would like to thank my parents who have always encouraged me and helped me in all aspects of life. Without their help and care I would not even be here.
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CHAPTER 1

INTRODUCTION

1.1 Motivation

Over the last few years the growing environmental concerns and the fear of reduction in the supply of fossil fuels has pushed the development of engines to produce more power while using less fuel. On an average the power of engines in passenger cars has increased from 110 HP in 1980 to over 250 in 2013 and has been increasing ever since. However, at the same time the average miles per gallon rating for the same has increased from just under 18 mpg to over 32 mpg in the same period. For such an improvement to be achieved a lot of research and development had to be done on engines. A lot of problems had to be overcome. For example, knocking in engines were a huge limiting factor for downsizing and supercharging engines in the past decades. Similarly we predict that in the near future when we use alternative fuels with a higher energy density than normal fossil fuels in smaller engines to generate more power while consuming less fuel we will encounter problems like pre-ignition and super-knock that can threaten our research and development. We will need to study and understand these phenomenon to develop new technologies or improve existing ones to perform better in the future.

One way to study the workings of an engine is to study the combustion cycle and experiment on them. To get a better understanding of a combustion cycle it can beneficial if we capture visual data to supplement all other data we gathered from the process, there are two ways by which we can achieve this, using an engine with modifications to allow optical access or a combustion bomb. There are other types of systems that can satisfy the above conditions but their disadvantages outweigh the benefits and are eliminated from consideration. If we use a modified engine with optical access we will have a problem when we want to alter the conditions we want
to experiment with, we will be limited to the minor changes that can be performed on the engine to change experimental parameters. Therefore, to facilitate easy modification to parameters we chose to use a constant volume combustion chamber.

1.2 Objectives

- Design a Constant Volume Combustion Chamber that can handle the loads generated by Super-Knocking and pre-ignition with optical access.
- Design the supporting systems for the CVCC to handle premixed combustion and be modular enough to support configuration modifications down the line.
- Load test and verify the system and get the design approved by the EHS and ready for building.
- Create a rudimentary model to simulate pre-ignition in a combustion chamber induced by hot spots in the chamber.

1.3 Literature Review

Combustion research has come a long way when we look at the past decades, from just measuring and recording data out of experimental engines and theoretically working out the combustion cycle to visualizing the flame as it occurs inside the combustion chamber with optical engines and static combustion chambers. This is possible only because of the improvements in the method of experimenting with combustion. Advances in optical diagnostics of flames, sprays and combustion behavior helps us understand the physical and chemical behavior of combustion better. In this section we will look at some work done in combustion analysis setups.
Three common experimental apparatuses used to study combustion of fuel and their behavior are:

- Shock tubes.
- Rapid compression machines.
- Constant volume combustion chambers.

A shock tube is a simple device that is used to compress a test sample gas to ignite the gasses in an isothermal environment as shown by Gaydon, et al [2] the shock tube setup has a tube setup with a diaphragm separating two sections, one filled with the test gas and the other filled with a high pressure driver gas. When the diaphragm is opened the high pressure gasses from the driver side creates compression waves that coalesce to create a uniform wave called a shock front, which ignites the test sample [2]. A shock tube apparatus is usually only suitable for experimenting with fuels at very high temperatures and very short ignition delay.

A rapid compression machine is a similar device in operation, but it uses a piston to compress and rapidly heat and pressurize the gas inside the test chamber [3]. An RCM usually has the following parts: a driver piston, reactor piston, hydraulic motion control chamber, and a reaction chamber. [4] To study the combustion as it occurs optical access is usually provided to the reaction chamber part of the RCM. An RCM can be used to study pressures and temperatures at ignition of fuels that have an ignition delay of greater than 10 milliseconds thanks to the sustained high temperature and pressure environment created by the RCM. [5] However an RCM has its disadvantages, it is shown that an RCM outfitted with optical access to the combustion chamber is difficult to control and can introduce errors in measurement of data.

The figure shows a Rapid compression machine as adapted from the work of Mittal, et al:
Figure 1.1: Basic Illustration of a rapid compression machine by Mittal, et al. [6]

The drawbacks of an RCM include difficulty in repeatability of experiments and data as explained by Mittal, et al in their work. Other studies have also shown that during the motion of the piston to compress, creates a roll-up vortex that mixes relatively cold gasses from the boundary layer region into the hot gasses in the core region Griffiths et al., 1993a. This introduces uncertainty in the characterization of the mixture in the chamber. One other major drawback is that an RCM cannot be used with liquid fuels easily unless major modifications are done to the machine. Thus leading us to the third option a constant volume combustion chamber.

A constant volume combustion chamber or a CVCC is an experimental apparatus that is used to conduct experiments in combustion that can provide data close to what can be obtained from a real engine but with the benefit of having no moving parts and providing very good optical access if needed. Also unlike RCM and shock tube which are usually limited to gasses for experimentation, CVCCs can be used with liquid fuels also, they are the main experiments that are used for validation of computational studies performed on heterogeneous combustion. [7] A CVCC offers a good balance between Experimental ease and good data replication with actual engines. Rik, et al in their work show some of the differences in optical testing rigs used to study combustion. [8]
CVCC are mainly used to simulate conditions and combustion events when the piston is right near TDC on an engine. Numerous efforts to visualize the pre-ignition combustion process in IC engines have been made in the past but since super-knock or pre-ignition usually occurs at very high loads it is hard to replicate results in an engine or and other device, This difficulty, however, can be circumvented by using a simulated Constant volume combustion chamber to create conditions similar to those within IC engines, while providing excellent optical accessibility and ease of data collection.

Research groups like Engine combustion network at sandia national labs have created constant volume combustion chambers with multiple windows that can be used to study combustion and sprays with different optical tools like chemiluminescence, Schlieren photography and more. [9] The experimental procedure requires the heating up of the combustion chamber with a premixed gas mixture of acetylene and air to bring the atmosphere inside the temperature to a
controlled environment that closely resembles an engine's combustion chamber right at the end of the compression stroke. After the chamber is allowed to cool down to the required temperature and pressure the fuel sample can be introduced into the chamber and the combustion can be recorded. [10] The following image shows the CVCC installation at Sandia labs:

Figure 1.3: Figures showing the CVCC (left) and its optical data recording installation (right) at Sandia labs. [9]

One major advantage of using a CVCC is we can perform a myriad of different experiments in them. Parameters like air-fuel ratio, residual gasses, initial pressure and temperatures, fuel mix types and ignition systems can be easily altered to simulate different conditions and gather data. [11] The most common types of CVCC are classified as cubic, cylindrical and spherical. Usually, cylindrical chambers are preferred as they have benefits like ease of assembly and maintenance. The cylindrical CVCCs can be in one of two configurations, first one has the injection axis same as the cylinder axis called the vertical CVCC and the other one has the injection axis perpendicular to the cylinder axis called the horizontal CVCC. The horizontal CVCCs have an advantage of
being easy to construct and maintain with easy optical access, while the vertical CVCCs have geometry close to the actual engine.

Parisinejad, et al show the design of a horizontal CVCC and show the design verification with the finite element method. The chamber was used for observations of premixed combustion flames. [12] Chan et al and Xiao-Fei also shows work on using finite element analysis to verify the strength and design a vertical CVCC [13, 14] Xiao-Fei’s setup is a cubic CVCC for the benefit of having less weight.

Zhi Wang et al conducted several experiments on super knock with a Rapid compression machine. In the experiments carried out Pre-ignition and super-knock processes were captured by synchronous high speed direct photography and pressure acquisition, with the results indicating that detonation wave occurs in the unburned mixture. The mechanism of super-knock is constituted by floated hot spots induced deflagration to detonation followed by high pressure oscillation. Pre-ignition and super-knock were not observed in every RCM experiment. [15] This is similar to the sporadic characteristics of super-knock in IC engines.

Yunliang Qia et al also used an RCM setup to investigate knock and super knock, [16], to test conditions similar to real engines they used >99% pure iso-octane as fuel with ultra-high purity nitrogen and oxygen as the test mixture in the RCM. The mixture condition was stoichiometric at room temperature. The compression ratio in engines varies from 9 to 11 for naturally aspirated engines so 3 compression ratios were studied in the RCM (9.8, 12.2 and 15.5) which were able to cover the majority of the engines currently being used. The super-knock in engine was confirmed to be the result of detonation by comparing the pressure oscillation, thermodynamic state, and pressure rise relative to isochoric combustion with those of detonation observed in the RCM. The experimental results also indicate that the possibility of detonation
occurrence increases with increasing initial pressure under the same compression ratio. However, comparing to the pressure, temperature has less effect on detonation formation. It was found that the end gas combustion mode is closely related to the mixture energy density. Detonation in the RCM exhibits similar characteristics to super-knock in engines, including the peak pressure, the auto-ignition temperature, and the ratio of experimental pressure rise after super-knock to the theoretical pressure rise based on isochoric combustion. Generally, as the mixture energy density increases, the end gas combustion mode gradually transits from a no-auto-ignition mode to sequential auto ignition, and then to detonation. For the authors on their experimental setup auto-ignition did not occur if the energy density at the spark timing was lower than 17.53 MJ/m3. When energy density was below 19.99 MJ/m3, only the end gas sequential auto-ignition occurred and It was possible to cause either end gas sequential auto-ignition or detonation if the energy density was between 19.99 and 23.88 MJ/m3. Detonation always occurred if the mixture energy density exceeds 23.88 MJ/m3. The first auto-ignition spots commonly appear in the mixture near the cylinder wall. The detonation was initiated by near wall auto ignition. The authors also state that it is generally accepted that super-knock originates from pre-ignition.

Hao Yu et al, studied end gas auto ignition and detonation development in a closed chamber using a mixture of hydrogen and air in a CVCC.
In their 1D simulations they found that end gas combustion had 3 modes: normal flame propagation without auto ignition, auto ignition without detonation and detonation development. During the detonation development they observed high amplitude pressure oscillation which was similar to super knock. They further found that detonation development can be promoted by increasing initial pressure, temperature or chamber size. Also the reactivity of the end gas determines whether end gas auto ignition or detonation occurs. [17].

Experiments done by Simon et al with an optical engine show that they were successfully able to induce pre-ignited deflagration by deliberately introducing oil droplets into the combustion chamber. They found that the formation of enflamed zones via oil droplets is in accordance with recently proposed theories of super knock. When they further tested with a lower octane blend fuel the engine operated in pre-ignited knocking combustion, which is similar to super knock.
They also found that majority of auto ignition events occurred near the intake port, they came to a conclusion that it was because of a larger number of visible oil droplets and presence of oxygen near the intake port that caused this phenomenon. [18].

Qi, et al, conducted an investigation of super knock combustion mode with a one dimensional constant volume bomb [19]. They used a mixture of H2 and O2 to combust in the bomb, the idea of the experiment was that the pre ignition and subsequent super knock occurs within +/- 20 Crank angle degrees, so to simulate that condition a one-dimensional constant volume bomb was constructed and used. In the study they found that reducing the inlet temperature, while able to control the onset on knock was unable to suppress super knock.
In another series of experiments conducted by Hubert Kuszewski et al a constant volume combustion chamber was used. The effect of injection pressure in the range of 80 MPa–140 MPa on the period of ignition delay and the period of combustion delay was determined in the study. A long ignition delay period is disadvantageous because during this period, before igniting, a large amount of fuel accumulates in the combustion chamber, which causes an increase in peak combustion pressures because of this the operation of the engine becomes noisy, the load of elements of the piston-crank system increases which accelerates engine wear, and increases nitrogen oxide emissions and also cause engine knocking. Therefore, the ignition delay period should be shortened. For the duration of ignition delay period, factors such as: the auto ignition ability of the fuel, the micro-structure and macro-structure parameters of the fuel spray and the air temperature at the time of the start of fuel injection have the greatest impact. [20].

With super knock, its sporadic occurrence is one of the major obstacles in developing advanced highly boosted gasoline engines. Although pre-ignition is required for occurrence of super knock, it does not always lead to super knock [21]. In research done with RCM the authors were able to conclude that the mechanism of pre-ignition to super knock was due to hot-spot induced deflagration transitioning to hotspot induced detonation. Possible methods to induce pre-ignition and super knock in test engines and CVCC are to introduce oil droplets or carbon particles into the combustion chamber while controlling the pressures the engine is set to operate. The effect of varying pressure and other parameters like oil additives to fuel can also be tested to identify the effect on tendency to super knock. Combustion and pre-ignition tests involving research engines and combustion chambers will help in understanding the phenomenon better and will help to mitigate super knock in engines and provide the way for developing high powered compact engines.
CHAPTER 2

CHAMBER DESIGN

2.1 Overview of operation

This section gives an overview on the operation of the CVCC and later about its supporting subsystems. The following figure shows a basic schematic of all the subsystems and the chamber as they are to be connected:

Figure 2.1: Overall schematic of the CVCC with all the subsystems.
For a typical experimental run, the combustion chamber is first heated by cartridge heaters to the temperature required by the experimental case and then a vacuum is pulled inside the chamber through the exhaust system. This is done to control the environment in the chamber and to clear all the contents in the chamber that might skew the results of the experiment. After the required vacuum levels are achieved the next step is initiated. Now there are two methods to proceed with the experiment. If the experiment requires premixed fuel air combustion then the test fuel and the controlled air mixture as required by the experimental case are let into the chamber at controlled quantities and mixed before being ignited by the spark-plug to initiate combustion. The other method for experimenting with normal fuel injected combustion would be to create the environment inside the combustion chamber at the end of compression stroke by first combusting a controlled mixture of acetylene, oxygen and nitrogen inside the chamber. After the required environment is achieved, the fuel is injected into the chamber and the spark-plug ignites the mixture again to initiate combustion. Once combustion is completed and all data recorded the exhaust, valves are opened and the gasses in the chamber is vacuumed out to prepare for the next experimental run. The pressure and temperature data are collected by the transducers and the thermocouples and recorded to the controlling computer.
2.2 The constant volume combustion chamber

The base design of the combustion chamber was made with the help of data from several other existing combustion chambers and was customized to accommodate for our specific needs. The base structure of the combustion chamber was created by Dr. James Lowrie based on a preliminary literature review on constant volume combustion chambers. The physical shape and structural properties like materials and supports were then changed to suit specific operating conditions and to the load bearing requirements. The base structure for the combustion chamber consisted of just a rough shape of the combustion chamber body, two viewing glasses and 2 glass holders with gaskets to cushion the glass contacts. The design was improved and modified based on several iterations of load testing. The subsystems were designed based on the requirements of premixing fuel and gas outside the chamber. The following sections talk about the design of the chamber and all the subsystems.

2.3 CVCC design iteration 1

This iteration of the design was a no-compromise approach focused in achieving the maximum structural strength all throughout the chamber. This design calls for a larger chamber window and copper gaskets for sealing the chamber. Ultimately this design was altered to accommodate simpler window design and use a holder to provide structural support to the window. Let us go through the details of designing this iteration part by part.

The following image shows the Combustion chamber assembly with different cross sections showing different ports:
Figure 2.2: Image showing the 3D model of the assembled combustion chamber with all its parts.
Figure 2.3: Image showing an exploded view of the combustion chamber assembly.
2.3.1 Combustion chamber

As discussed above the base size and shape was carried over from Dr. James Lowrie's design. The figure shows the original base model. Requirements to be met for the chamber are to provide a large aperture viewing port to view and record combustion events for analysis, provide enough ports to accommodate all the required accessories and be strong enough to handle the loads of pre-ignition and super-knocking combustion. The final design of the chamber has six ports that provide access to the combustion volume for the various devices. The six ports are used for the following:

- Air inlet.
- Fuel injector.
- Exhaust valve.
- Spark plug.
- Temperature and pressure sensors.
- Mixing fan / Auxiliary devices.

All ports have a universal design and are interchangeable to facilitate variations in configuration. Plugs can be made conforming to the shape of the devices to be used in the ports to ensure perfect sealing. There are 6 more holes drilled onto the chamber walls to accommodate cartridge heaters that are used to control the temperature of the chamber. The combustion volume was finalized to be a cylinder with a diameter of 4 inches and height of one inch to provide a volume of 12.57 cu.in or 206 cc. The chamber was ultimately designed to handle a working pressure of 40 MPa inside the combustion volume with a factor of safety of 4. The final Combustion chamber design is an irregular dodecagon with a circumcircle diameter of 12.8 inches and a depth of 4.72 inches. Six of the twelve faces are used for the ports and the other six are used for the
cartridge heaters to be plugged in. The chamber has two large ports on the top and bottom faces. These are for the viewing windows and lead directly into the combustion volume. The walls of these ports will be threaded to accept the glands that will secure the viewing glass and its holder. The design uses standard 14 threads per inch and was chosen after calculating loads and stress testing the material. The six ports for use with instruments and valves have a hole diameter of 0.8 inches leading into the combustion volume. Slots for the cartridge heaters have a diameter of 0.4 inches and extend 3.15 inches into the chamber body. The design asks for at least one of the cartridge heaters to have a thermocouple inbuilt for use with the temperature control of the chamber. Sealing of the chamber volume was handled by gaskets between each part installed in the chamber. To aid in the sealing efficiency and to have a low leakage rate the angles on the glass faces that come in contact was chosen to be 54º from the horizontal this was chosen after simulating the load distribution and estimating what the sealing force will be for that specific angle. When a tightening load is applied on to the window by the gland the window pushes into the copper gasket which conforms to the shape of the chamber body sealing the combustion volume. The material used to make this part is AISI 4140. This material was chosen for its relatively low coefficient of thermal expansion and strength. Structural and thermal simulations were performed on the part with varying loads and materials before the material to make the chamber was chosen.

The following image shows the profile of the combustion chamber with the ports:
Figure 2.4: Image showing a cross section of the combustion chamber body with the ports for the various instruments.

Figure 2.5: Another cross section showing the heater ports and the instrument ports.
2.3.2 Viewing windows

The window is one of the most important part in the combustion chamber assembly. It provides access to view the combustion volume and record data as it happens. The main goal when designing the windows were to get an optimal compromise between aperture size and structural integrity. In a high-pressure combustion chamber the windows are among the weakest parts, structurally speaking. As most materials suitable to use as windows tend to fail by shattering unlike a metal which will have some elasticity before catastrophically failing, special care was taken when designing the windows and choosing the materials for it. in the original design suggestion made by Dr. James lowrie, he had suggested the use of Borosilicate as the material for the windows. Borosilicate has benefits like having very low thermal coefficient of expansion, being relatively cheap to manufacture and easy to machine into complex structures. the problem with borosilicate is it tends to fracture quite easily in a tensile loading condition. moreover, his design was for a much lower pressure rating when performing load and stress simulations on the design we were seeing failure at the glass. So, for the first iteration of the design we started testing and modifying the design to attain a factor of safety 4 and a maximum pressure safe pressure rating of 160 MPa. The window Materials tested include Fused silica (Quartz) and synthetic sapphire. To better understand the failure pattern and method of these crystals, fracture analysis was performed. The results were used to design the shape and the thickness of the crystals. Data from the fracture analysis was also used to design the sealing system and the holding system. The fracture analysis was performed by solving for critical stress intensity factor for mode one crack propagation; this gives us a way to calculate the maximum allowable stress on the glass surface before it fails for any crack depth or flaw size. The equation used to calculate the Critical stress intensity factor is as follows:
\[ \sigma = \frac{K_{ic}}{\sqrt{\pi c}} \]

Where \(K_{ic}\) is Critical stress intensity factor, \(\sigma\) is the Failure strength of the material and \(c\) is the flaw size or the crack depth. Solving the equation for various flaw sizes, we can obtain results that can be plotted to show variation of critical stress with flaw size on the surfaces. This calculation was done for both Quartz and Sapphire as shown below:

![Failure stress vs Flaw size](image)

Figure 2.6: Plot showing the difference in Failure stress vs flaw size for quartz and sapphire.

Looking at the plot we can see that sapphire has the most strength for any given flaw size. And for satisfying a Factor of safety of four we can have a surface flaw of up to 5 \(\mu m\) on the faces of the window which is easily maintainable when using sapphire if using 40/20 LASER quality.
sapphire from a reputable supplier. When we look at quartz, we can see that for the same stress the maximum surface defect cannot be bigger than 0.6 µm.

To finalize the shape of the windows a series of structural simulations were carried out on the window separately and as a part of the system to check the loads applied on the window and calculate stress concentrations and the areas most affected. The simulation setup consisted of a pressure loading condition inside the combustion volume and clamping loads applied on the top surface of the glass to simulate the tightening load applied by the glands on the glass. The effects of temperature were also considered in the simulation. The loads applied are as follows; pressure loading of 40 and 160 MPa inside the combustion volume to depict combustion events, a clamping load as calculated by the tightening torque required (calculations shown below in the results and discussion of chapter 4).

The following image shows the edge profile of the window:

![Filleted edges to reduce stress.](image)

Figure 2.7: Image showing a cross section of the sapphire widow.
The final window has dimensions as follows; diameter of 5.12 inches, thickness of 0.98 inches. The edge of the window is divided into 2 with a flat face and a conical face that sits on the chamber body with a copper gasket to cushion and seal the volume. The flat face measures 0.11 inches and the conical face measures 0.96 inches along the face with an angle of 126 Deg. All the edges are filleted to reduce stress concentration in the edges and causing chips, which could lead to fractures.

2.3.3 Gland and Gaskets.

The CVCC has cutouts through which the windows fall freely until they come in contact with the chamber body along their conical surface. This was done to avoid any misalignment of the window whenever it is installed as the conical surfaces tend to center the windows in the hole, but this introduces a problem of securing the windows tightly against the pressure from the combustion volume pushing it out of its place. Therefore, to hold the window in place and to provide a clamping load forcing the window against the body to create a seal the Gland/Holder is used.
The gland is designed to be machined out of the same material as the body as it is designed also to absorb some of the stresses in the system and not react differently to variations in temperature, as the system will have a lot of fluctuation thermally.

This part has threads cut into it that mate with threads on the body to seal the combustion chamber and hold the window in place during operation. The stresses involved in the threads were a major consideration when designing the shape and choosing the material for the gland. Another major design consideration was to make the cutout in the center to allow for a bigger viewing aperture, as this part will cover the window it governs how big the viewing aperture can be.

The gland has 2 sections one of which has the threads cut into it and the other which is cut into a hexagonal structure to facilitate easy tightening with a tool. The cylindrical part has 5.13 inches outer diameter and 3.94 inches inner diameter and is 1.07 inches long. The edges are either filleted or chamfered to prevent stress concentration. The image shows the structure and the cross section of the gland:

![Threaded portion](image)

Figure 2.9: Image showing the cross section of the gland.
Figure 2.10: Image showing the 3D view of the gland.

To add some cushion between the window and the gland a gasket is used. The gasket is designed to be made of copper sheet with a thickness of 1 mm. This gasket is intentionally designed to deform from the loads generated by the tightening of the gland and to accommodate small movements of glass caused by pressure or thermal expansion. Copper sheets were chosen to make the gaskets. There are two types of gaskets in the system, one goes between the window and the gland and the other one between the window and the body along the conical surface of the window. The gasket between the window and the body also helps to ensure a good seal of the combustion volume. Again copper was used as it can be replaced easily as it is relatively inexpensive to buy copper sheets and cut them in a waterjet to make the gaskets. They are also good in absorbing any sudden shocks that might occur on the window as it sits between the window and the other metal parts like the body and the gland.

Following images show both the gaskets and their cross section:
Figure 2.11: Cross section of gasket that goes between the Window and the body aka body ring.

Figure 2.12: 3D model of the body ring.

Figure 2.13: Image showing the gasket that goes between the gland and the window aka gland ring.
Structural simulations were performed on the gland and the gaskets as part of the whole system to ensure the choice of material to be correct and to verify the stress distribution in the parts. The simulation results as shown below confirm that the material can withstand the stresses that occur on the parts and will be safe under the loads considered for operation with a Factor of safety of four.

![Diagram showing positions of the gaskets as assembled into the combustion chamber.](image)

Figure 2.14: Image showing positions of the gaskets as assembles into the combustion chamber.

### 2.4 Design Iteration 2

For the second design iteration the structure and design for the window was modified to use a holder to further protect the window from the stresses. The body was also modified to accept a different method of sealing to control the leaking rate of the system under high pressure. Minor change to the combustion volume were also made to improve the structural integrity and to add more material on critical stress areas identified in the previous iteration. This helps to improve the load bearing capacity of the chamber. The supporting systems for the chamber remain unchanged so they will be discussed after at the next chapter.

The following image shows a cut section view of the assembled combustion chamber:
2.4.1 Combustion chamber

There is not a lot of changes done to the external structure of the body as the previous design. Major changes to the chamber were done on the combustion volume of the chamber and to the window seat to incorporate a seal and allow the use of a holder.

We finalized to use a ‘C’-ring seal as its recommended use case scenario is best suited for use in the combustion chamber. For the ring seal to work it had to be placed in a cavity made in the chamber body and the window or the holder must cover the cavity, so the window was redesigned to accommodate this. The ‘C’-ring chosen was based on the maximum pressure the ring can contain for its size. The ‘C’-ring can be seated into the chamber in one of two ways, with the slit facing outwards or inwards. For holding external pressure, the ring has to be placed with slit facing outwards and for holding internal pressure the slit has to be facing inwards, basically
the ring works to seal by expanding with by the pressure and pushing against the top slot surfaces and creating a tight seal around the opening. This method of sealing is more efficient even though it takes some of the pressure to expand the seal ring.

The following image shows the combustion chamber body with the cutouts for the ‘C’-ring seals:

![Cross section showing the ports and the slots for the new ‘C’-ring seal.](image)

Figure 2.16: Cross section showing the ports and the slots for the new ‘C’-ring.

One other change done to the combustion chamber body was to increase the structural strength at points where the simulations showed stress concentration for the first design. This was done to improve the strength and prevent any failing due to fatigue or over stressing. The major change was at the place in near the combustion volume that leaves the combustion volume and leads into the window seat, this place showed some stress concentration around the 6 ports drilled into the body as there is very little material at near the port holes. Now material is added to the
location in this design iteration and the simulations performed show a much-reduced stress concentration at the location. Lot of care was not to increase the combustion volume too much as adding material to the chamber walls to strengthen meant increasing the combustion volume.

Other changes to the body include modification to the window seating method. The design was updated to have a window with a holder this will help the window to distribute the force more evenly and have less stress on the edges as the whole edge is in contact with a holder to transfer all the forces. The new holder meant changing the seating method on the chamber.

2.4.2 Viewing windows

For the updated design the window shape was changed to allow the use of a holder, this holder allows for a better stress distribution of the window and improves rigidity. One more benefit is that now the gland doesn’t directly contact the window and sits on the holder. The window is held on the holder with the help of RTV applied on the contact surfaces. This also helps with the difference in coefficients of thermal expansion between the window material and the metal holder, even if the holder expands or contracts faster than the window the RTV will absorb some of the effects of change in size.

The following image shows the new design for the viewing window:

![3D image of one of the Quartz windows.](image)

Figure 2.17: 3D image of one of the Quartz windows.
The new window design is smaller than in diameter than the previous design this also allows us to use quartz instead of sapphire as the smaller window will fit into the holder and has enough support to relieve stress from the window and prevent any accumulations. This also allows for faster window changes when required for cleaning or any other operations. Having the holder ensures that the window can be protected from accidental scratches or cracks when installing or removing from the chamber.

### 2.4.3 Window holder

This is new part in the design iteration two and replaces the need for one of the gaskets found in the design iteration one. The windows holder’s purpose as the name suggests is to hold the window in place and provide support to it during operation.

The window holder is a simple conical ring with a step that will be made out of AISI 4140 same as all other parts. This is done in order to reduce stresses between the objects in contact caused by the difference in thermal expansion for different materials. AISI 4140 when hardened has a coefficient of thermal expansion of 0.08 to 0.15 µm/ ºC between 100 – 200 ºC. Whereas quartz has a coefficient of thermal expansion of 0.05 to 0.09 µm/ ºC between 100 – 200 ºC. This allows us to use this material with the window without any major stress concentration due to the difference in the properties.

The window holder also has another purpose in the combustion chamber, it works in conjunction with the ‘C’-ring seal to create a tight seal around the combustion volume and prevent any major leaks along the windows. The step provided in the holder mates with the slot cut out for the ‘C’-ring in chamber body. When the seal is placed in the cavity and the system is pressurized the seal will expand and open up to come in contact with the window holder closing up any small
crevices that may be there and provide a tight seal for the combustion volume. The following image shows a cut section of the window holder as modelled in Solidworks:

![3D cross section of the Window holder.](image)

**Figure 2.18: 3D cross section of the Window holder.**

### 2.4.4 Gland and gaskets

With the second iteration the design and structure of the gland remains the same. There is no changes made to the mounting method of the gland and the change is loads resulting from the modification of the window is lower than the previous design for which the gland was designed to handle.

The following image shows the Gland and the gasket used between the gland and the window holder to add some cushioning:
Looking at the gaskets, since the window now has a holder to conform to the shape of the combustion chamber the requirement of cushioning is not necessary as the holder absorbs most of the fluctuations in the size of the windows and the compensates for the expansion of the combustion chamber. The new iteration has only one gasket to help cushion the glass holder from
the gland when tightening the gland. This gasket is same as the one shown in the design iteration one and is made of the same material.

One new addition to help sealing the combustion volume in this design iteration is the addition of a ‘C’-ring seal. A 1/8\textsuperscript{th} inch seal ring is will be used considering the pressures to be held in and based on simulation results. [22]
CHAPTER 3
CVCC SUBSYSTEMS

3.1 Outline

For a Constant volume combustion chamber to function it requires several subsystems controlling other processes like gas handling, ignition, fuel supply, etc. This chapter talks about these systems in detail and explains the design considerations underlying each system.

The following are the different subsystems involved in the operation of the CVCC:

- Gas handling system.
- Fuel delivery system.
- Ignition system.
- Temperature control system.
- Data acquisition and control systems.

3.2 Gas handling system

The gas handling system comprises of the following three units that handle the different functions in and around the CVCC. They are as follows:

- Gas inlet systems.
- Vacuum system.
- Safety systems.

3.2.1 Gas inlet systems.

Gas inlet systems handle the process of controlling the gasses that enter the combustion chamber for experimental cases. They are responsible for attaining the perfect mixture of gases that enter the chamber and making sure the mixture is at the correct pressure and mixture ratio.
when it enters the combustion chamber. This system includes all the Gas valves, high-pressure gas lines, mixing system, inlet valves and pressure accumulators.

The gases proposed to be used in the system are Nitrogen, Air and Oxygen. If the experiment calls for non-premixed combustion, then Acetylene will also be used to pre-condition the combustion chamber. However, $N_2$, $O_2$ and Air are the main gases used for premixed combustion. Premix of fuel and air inside the chamber can be achieved by two methods:

1. Mix the gases and the fuel outside the combustion chamber and pressurize the chamber with the mixture.

2. Inlet gases into the chamber separately, inject the fuel into the chamber with the gases and mix the whole volume to achieve a homogeneous mixture inside the chamber with the use of a mixing fan.

The chamber and the subsystem is designed to handle both types of mixing as it makes the chamber versatile to try multiple conditions to accommodate different experimental cases. However, method two involving a mixing fan will be preferred as it ensures that the mixture ratios can be controlled with very fine granularity when mixing gases.

The following image shows the layout of the gas mixing and inlet systems, in the image M.F stands for Mixing fan, M.C stands for Mixing chamber, P.R.V stands for the safety pressure relief valve and F for a flame arrester;
The method for mixing the gases and making a premixed charge in the combustion chamber goes as follows: first the chamber and all the gas lines are vacuuumed out to remove any residual gases that might be lingering in the chamber. Then the regulators on the gas tanks are opened to let gases flow, since the gas regulators are not very accurate to control the mix based on partial pressures the pressure sensors in the combustion chamber will be used to determine how much gas to be filled in the chamber. Now, the solenoid valve controlling the nitrogen gas line is opened to allow nitrogen to flow into the chamber until the calculated partial pressure is reached.

Figure 3.1: Layout showing the gas mixing sub-system for the CVCC.
inside the chamber. After which the valve is closed. Now the next gas that is required by the current experimental condition is cycled in the same way until the required mix of gases are achieved inside the chamber. Once that is done, all the valves are closed and the fuel injection process will begin (discussed in the fuel injection section). Once the fuel is injected into the chamber the mixing fan in the chamber is activated to mix the gas and the fuel vapor to attain a homogenous mixture ready for combustion analysis.

If we want to mix the gases outside the combustion chamber and send a premixed charge into the chamber, the gases are first inlet into the mixing chamber to the required partial pressure. Then the fuel is injected into the mixing chamber where a homogenous mixture is attained and then the mixture is then sent into the combustion chamber by emptying the mixing chamber.

The High-pressure gas lines will be made with SWAELOK stainless steel tubes and fittings. With 1/8\textsuperscript{th} inch i.d. tubes making up all the lines. For the fittings, SWAGELOK 1/8\textsuperscript{th} NPT fittings were chosen after considering the maximum working pressures from the manufacturer’s specification. The following table shows details about 1/8\textsuperscript{th}, 1/2 and 1/16\textsuperscript{th} inch NPT fittings. [23]

Table 3.1: Manufacturer’s rating for different sizes.

<table>
<thead>
<tr>
<th>NPT size</th>
<th>Male Fittings (Mpa)</th>
<th>Female fittings (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>53</td>
<td>26.1</td>
</tr>
<tr>
<td>1/8</td>
<td>68.9</td>
<td>34.4</td>
</tr>
<tr>
<td>1/16</td>
<td>75.7</td>
<td>37.8</td>
</tr>
</tbody>
</table>

All the solenoid valves controlling the lines in the gas mixing system are from OMEGA SV 125 which is a Direct-acting solenoid with a 1/8\textsuperscript{th} inch orifice, an FKM seal and are normally closed. This valve was chosen for its IP ratings and the high-pressure operation with a maximum of 6.9 MPa. The valves will be connected to a controller interfacing with LABVIEW to automate.
processes. There will be three valves controlling the lines connecting the gas tanks to the mixing chamber and the combustion chamber, one valve leading from the mixing chamber to the combustion chamber and one valve for the vacuum system connecting to the mixing chamber and all the lines. A total of five solenoid valves will be used in the gas mixing system.

3.2.2 Vacuum system

The vacuum system comprises all the lines leading to the vacuum pump, the pump itself and the valves involved in the exhaust system. The vacuum pump planned to be used is an oil lubricated rotary vane pump that can provide a rough vacuum, which is suitable for vacuuming all the pressure lines and the combustion chamber.

The vacuum pump is crucial for the operation of the combustion chamber because any residual gases or particles from the previous combustion cycle has the potential to skew the results and alter the combustion characteristics. Therefore, before every combustion cycle a vacuum must be pulled inside the chamber to empty all the contents. The vacuum pump is also connected to the gas line leading into the combustion chamber, as even these lines must be vacuumed before shutting off the system or cleaning the lines.

The vacuum pump exhausts to the room’s gas evacuation system to vent all the vapors and gases outside the working environment.

3.2.3 Emergency system

The system is equipped with an emergency pressure relief valve, which is connected to the port in the chamber that has the inlet lines connected. This is there to ensure that there won’t be any dangerous pressure accumulation inside the chamber and also to be used a very fast and easy way to dump the pressure in the combustion chamber in case of any malfunction. The emergency pressure relief valve will be set to dump the chamber when the pressure inside the chamber reaches
and exceeds 50 Mpa. This is based on the working pressure of the chamber with 25% overprovisioning. A butterfly type emergency will be used in order to provide a quick action when the pressure is reached. The valve will also not be connected to any of the control systems of the system in order to isolate it from any malfunctions and will operate as a standalone system.

This pressure relief valve along with other emergency systems will be tested and ensured to operate reliably before the whole system is commissioned. The EHS department to ensure proper operation will overlook the testing.

### 3.3 Fuel delivery system

The fuel delivery subsystem consists of all the equipment used to pressurize the fuel and supply it to the destination for mixing it and making a premixed charge to be used in the combustion chamber.

The fuel delivery system has the following parts:

- Low-pressure pump.
- High-pressure pump.
- Pump driver.
- Fuel rail.
- Injector.
- Return lines and tank.

The following image shows a rough schematic of the fuel delivery system, here H.P denotes the high pressure pump and L.P denotes the low-pressure pump:
The operation of the fuel system is as follows: first, a low-pressure pump that feeds the fuel into the high-pressure pump draws out the fuel from the tank. The H.P pump then pressurizes the fuel and sends it into the rail where a pressure sensor monitors the fuel line pressure and reports it to the control system where it is compared to the set pressure required and based on the output the power to the pump is adjusted to raise or lower the pressure. Once the required pressure is achieved, the fuel can be then injected into the combustion chamber or the mixing chamber as per the requirements of the current experimental case. The fuel from the high-pressure fuel in the rail that is not injected is returned into the tank with the use of a pressure reducer attached to the line.

The Low-pressure pump used will be an off the shelf fuel pump that is designed for use in automobile fuel tanks. This has enough pumping head to draw out the fuel from the tank and feed it to the H.P pump at the pace the pump requires. The High-pressure pump will be a repurposed high-pressure pump from an engine and will be driven by a high power motor, which can be controlled with fine granularity to ensure a wide range of pressure outputs from the high-pressure
pump. The fuel rail will also be an off the shelf fuel rail as designing one would require a lot of safety concerns considering the pressures the system will be working with. The fuel injector can also be replaced to any injector with a common mounting system and a standardized connection to the fuel injector to try to facilitate a wide range of injectors to produce different types of sprays or to be used with different fuels.

The whole system will be linked to the control program running in a LABVIEW environment that controls all other aspects of the combustion chamber.

For safety concerns, the electric power to the fuel delivery system is isolated from the others and the high-pressure pump will be started only at the time when injection of fuel is required and is turned off all other times. In addition, a high-speed solenoid valve is connected to the fuel rail to dump all the pressurized fuel into the fuel tank in the event of an emergency shutdown.

3.4 Ignition system.

The ignition system is responsible for creating the spark inside the chamber to ignite the contents and start combustion. The ignition system has the following parts:

- Ignition coil.
- Power supply.
- High-tension wires and control system.
- Spark plug.

The ignition system was designed to use mostly standard parts similar to the fuel delivery system to aid in safe equipment and easy interchangeability. The schematic is as follows: the ignition system will be a simple breaker controlled system with a solid-state relay controlling the release of the high voltage from the high voltage coils. The ignition coil is powered by a power supply like a car battery and sends the high voltage to a standard spark plug that is fixed to one of
the ports of the combustion chamber to generate the spark. Using a standard spark plug means, the system can be used with any type of available standard spark plugs with just a simple modification to the plug that houses the spark plug into the combustion chamber.

3.5 Temperature control system

For the combustion chamber to simulate the conditions of an internal combustion engine’s combustion chamber, the environmental conditions also have to be simulated. For the CVCC this means heating up the combustion chamber as a whole to match the current experimental requirements. Heating the chamber can also help prevent condensation on windows when running experiments.

The chamber temperature is increased with the use of cartridge heaters placed all around the combustion chamber. The cartridge heaters used are from WATLOW heaters and they are from the Fire rod line up of heaters. Each heater is 10 mm in diameter and has a total length of 3.25 inches. There is a non-active region of 0.1 inch on both ends of the heaters. This is also accounted for in designing the holes in the combustion chamber to accept the cartridge heaters. There are 6 heaters in total with a working power of 3000 watts. The heaters are rated to 1019 watts each based on the surface area. The heaters will be connected to a closed loop control system which can be used to regulate the temperature of the chamber and hold it at a certain temperature for the entirety of the experimental run. The controller will also be linked to the system control program to automate the process and record data.

The following image shows a cartridge heater that will be used in the combustion chamber:
Figure 3.3: Image of a WATLOW fire rod cartridge heater.

The cartridge heaters will be held in the holes with the use of OMEGABOND 400 high temperature set cement which is rated for use up 1425 Celsius or 2600 Fahrenheit.

3.6 Data acquisition and control systems

The data acquisition system includes the pressure sensor, thermos couples and data collectors reporting operation of all the systems. The data collected is used to generate experimental data and run the system. All sensors and controls will be connected to NI DAQ boards and interfaced with LABVIEW. LABVIEW will be used as the main control software as it is versatile in operation. The timings of various functions like injection, imaging and valve openings will be automated and synchronized in LABVIEW.

The pressure transducer used inside the combustion chamber will be a Piezo electric pressure transducer from KISTLER type 603CA with a maximum pressure range of 0-1000 bar with an overload of 1100 bar and a sensitivity of -5 pC/bar. [24] Continuous operation temperature range is -196 to 200 Celsius. The sensor will be connected to a charge amplifier which in turn will be connected to the DAQ for data collection.
Other pressure sensors connected to the gas lines and the mixing chamber are OMEGA general purpose transducers that relay the data to the DAQ and to LABVIEW for control and recording.
4.1 Overview

This chapter discusses about the results of a series of structural simulations done on the CVCC assembly using ANSYS to verify the capability to withstand the loads during operation. The normal working pressure of the combustion chamber will be between 30 and 40 Mpa peak when performing combustion experiments. We needed to achieve a factor of safety of four and the chamber had to be safe for up to a minimum of 160 Mpa so loading simulations were performed with loads of 160 Mpa and 40 Mpa to analyze the stresses and material capabilities.

The following chapter talks about the simulation procedure and results for both the Design iterations.

4.2 Simulation setup

For the first iteration the simulations involved loading the CVCC from inside the combustion chamber with the pressure being tested. A no-displacement constraint was applied to the outer bounds of the combustion chamber to prevent free body motion in the simulation. The image shows the location on the combustion chamber where the pressure condition was applied. The pressure load was applied in all directions inside the combustion chamber. Contacts were created between all the parts with refined mesh. The following image shows the loading condition applied on the combustion chamber body:
The mesh was refined after each run until there was no change in the resulting stresses in the simulation. The following table shows the materials chosen for fabricating the various parts:

Table 4.1: Materials used to make the combustion chamber and all its parts.

<table>
<thead>
<tr>
<th>Part</th>
<th># required</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Body</td>
<td>1</td>
<td>AISI 4140 steel</td>
</tr>
<tr>
<td>Viewing Glass</td>
<td>2</td>
<td>Sapphire</td>
</tr>
<tr>
<td>Gland</td>
<td>2</td>
<td>AISI 4140 steel</td>
</tr>
<tr>
<td>Gland Ring</td>
<td>2</td>
<td>Copper</td>
</tr>
<tr>
<td>Body Ring</td>
<td>2</td>
<td>Copper</td>
</tr>
</tbody>
</table>
The material properties used for the simulation are as follows:

Table 4.2: Properties of materials used for simulations.

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AISI 4140</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[25]</td>
</tr>
<tr>
<td>Density</td>
<td>kg m^-3</td>
<td>7850</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>GPa</td>
<td>208</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td></td>
<td>0.29</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>675</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>MPa</td>
<td></td>
</tr>
</tbody>
</table>
4.2 Results and discussion

4.2.1 Design Iteration 1

The following table shows the corrected converged results for a very fine mesh on each part:

Table 4.3: Converged stress values after the pressure loading simulation.

<table>
<thead>
<tr>
<th>Pressure (Mpa)</th>
<th>Glass</th>
<th>Gland</th>
<th>Body</th>
<th>Gl-Ring</th>
<th>BD-Ring</th>
<th>Threads</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>163.7</td>
<td>74.622</td>
<td>160.2</td>
<td>255.77</td>
<td>440.17</td>
<td>92</td>
</tr>
<tr>
<td>160</td>
<td>654.740</td>
<td>298.46</td>
<td>640.8</td>
<td>1023.48</td>
<td>1760.5</td>
<td>374</td>
</tr>
</tbody>
</table>

The following images show the Stresses and the deformation occurring in the various parts in the CVCC, when loaded with a pressure of 160 MPa:

Figure 4.2: Stress distribution in the chamber body
Figure 4.3: Total deformation seen in the combustion chamber with both structural and thermal loads applied.

The maximum deformation in the chamber body occurs around the holes drilled for attaching all components like injectors and the valves. This area around the port holes are the weakest areas around the chamber as there is not much material to support the loads but once the ports are occupied and filled with plugs and spacers the deformation and stress concentration around the holes should be reduced to a much lesser value.
Figure 4.4: Stress distribution in the window.

Figure 4.5: Total deformation of the window.
Figure 4.6: Stress distribution in the gland.

Figure 4.7: Stress distribution in the gland ring.
Looking at the stresses in different parts, we can see that the material chosen can withstand the pressures and operate with a safety factor more than 4. The AISI 4140 steel chosen for fabricating the body and gland that holds the glass can be heat-treated to have a yield strength of more than 800 MPa, which is comfortably above the stresses generated in the loading simulations. The copper rings, although they incur a huge stress when loaded are still safe to be used in the chamber as its main purpose is to cushion the glass from the clamping forces of the gland and to act as a seal between the Glass and the Chamber body. It can be replaced easily. For the crystal window to be safe, we need to ensure that we get a piece of glass cut in the C-plane of the crystal as it is proven to have the highest flexural strength as suggested in the reference [6].
4.2.2 Design Iteration 2

For the second design iteration the major changes made were the change in design of the window and the addition of a holder to the window assembly. The following images show the equivalent stress distribution in the different parts of the Combustion chamber:

Figure 4.9: Stress distribution in the chamber body with the second design iteration.

Figure 4.10: Stress distribution in the window for second iteration.
Figure 4.11: Stress distribution on the gland with the second iteration.

Figure 4.12: Stress distribution in the window holder.
Figure 4.13: Stress distribution in the gland ring with the second design iteration.

The following table shows the corrected converged maximum stress values calculated on the various parts of the body:

Table 4.4: Converged maximum stresses in the second iteration of the combustion chamber.

<table>
<thead>
<tr>
<th>Pressure (Mpa)</th>
<th>Glass</th>
<th>Gland</th>
<th>Body</th>
<th>Gl-Ring</th>
<th>Window Holder</th>
<th>Threads</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>587.19</td>
<td>327.69</td>
<td>594.73</td>
<td>1108.43</td>
<td>860.14</td>
<td>374</td>
</tr>
</tbody>
</table>

Looking at the images we can identify that the stress accumulations shown on the parts are lower than the ultimate strength of the material. We can also infer from the images that the overall stress distribution in the window has reduced considerably with the new design and makes it much safer to use.
To verify if the threads can withstand the loads, tensile stress area of the threads were calculated with the following equation [28]:

\[ A_t = \pi \left( \frac{E_{s\text{ min}}}{2} - \frac{0.16238}{n} \right)^2 \]

Where \( A_t \) is the tensile stress area, \( E_{s\text{ min}} \) is the minimum pitch diameter of the thread and \( n \) is the number of threads per inch. The minimum pitch diameter was taken to be 5.13 inch with 14 threads per inch.

We get an effective tensile stress area of 20.5 in\(^2\). At a FOS of 4, the forces acting on the threads are calculated from the pressure acting on the glass pushing the gland out. At 160 Mpa over an inside face of the glass whose surface area is 47.78 in\(^2\), we get a total force of 1108783 lbf acting on the area. So for the threads the total load acting on it will be 1108783 lbf. To calculate the clamping force on the threads we can use the following relation [29];

\[ T = c \cdot D \cdot F \]

Where \( T \) is the applied torque, \( c \) is the coefficient of friction of the threads, \( D \) is the nominal diameter of the thread, and \( F \) is the bolt tension.

To get a minimum nominal bolt tension of a 2100 lbs. (estimated based on current setup) with a major diameter of 5.19 inches and a coefficient of friction of 0.2 for steel we will need to apply a torque of at least 182 foot pound on the gland.

The final load on the thread material is 54189 psi, which is 374 MPa. AISI 4140 has a tensile yield strength of 673 MPa and is safe enough to handle almost 2 times this load. Just 6 threads can hold the whole load at FOS 4. At 40 MPa pressure loads, all the loads are handled by just 2 threads of the gland. Based on the results shown above we can say that the design is safe to a minimum safety factor of 4.
CHAPTER 5

CONCLUSION

A Constant volume combustion chamber that can experiment with premixed fuels was designed and analyzed using Structural simulations. The results of the simulations suggest that the second iteration of the combustion chamber is safe to withstand the loads.

Manufacturing of the combustion chamber parts will begin soon after we procure all the raw material and will be commissioned as soon as possible so that experimentation can soon begin. Some sub systems like the fuel delivery system and the gas supply will be borrowed and modified from an existing Constant volume combustion chamber as it will keep costs down and accelerate completion of the process and allow us to start experimentation soon.

The design has also been verified and approved for deployment by the EHS of NCSU. The combustion chamber once built, will be tested extensively to verify against the numerical simulations done in Ansys. This will be done with the presence of EHS authority. To ensure conformance to safety codes.
REFERENCES


