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Design and Development of a Fuel Injector for a Liquid Rocket Engine

Interim Report

FYP-18-24

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October 26, 2022

Declaration

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Abstract

Previous rockets in the Nakuja project have been solid propellant rockets, which have a low burn time and a low apogee. With the aim of reaching an altitude of 100 kilometres, the rocket engines have to be switched from solid rocket motors to liquid propellant engines. Thus, there is a need to develop an injector that would introduce and atomize this liquid propellant in the combustion chamber so as to produce the necessary thrust required via their combustion.

This project looks into the design of the injector, specifically the pintle injector, using design procedures such as 3D modelling and simulation of various parameters affecting parts of the pintle injector with software such as Autodesk Inventor and Ansys, the electrical circuit design of the igniter with EasyEDA and Proteus Professional, and achieving control in the ignition of the propellants. The results would be a well-structured and assembled injector, a completely defined Printed Circuit Board for the electrical circuit and a sound control logic for prompt ignition. The design should be able to introduce the propellants at the required velocity and pressure for combustion.

Chapter 1

Introduction

This chapter gives a brief background on the injectors used in rockets, their functions and some of the developments concerning the injectors. Objectives are then given to come up with the required design and a justification as to why the proposal is important.

1.1 Background

The injector is designed within a liquid rocket engine to atomize and mix the fuel with the oxidizer that will provide the required thrust without endangering hardware durability. The injection system is an important part since it dictates the performance significantly. Proper mixing ensures that there is a smooth and stable combustion in the combustion chamber. As the injection system atomizes the fuel and the oxidizer, it also provides a pressure drop to prevent pressure pulses from moving up into the feed system. In addition to the functions stated above, the injector acts as a sensitive element that may generate and modify flow oscillations because of its intrinsic unsteadiness and interactions with the combustion-chamber and feed-system dynamics [1].
For an injector to have a high performance the combustion chamber should have the following characteristics: a high combustion efficiency, shorter combustion length and wall

temperature within metallurgical limits. The injection system consists of two components which include the distributor and the injector head. The main function of the distributor is to ensure a homogeneous supply of propellant to the individual injectors. To achieve this, a much lower velocity of liquid propellant in the distributor must be maintained. It acts as a settling chamber. A perfect sealing must be maintained between the fuel and the oxidizer distributors for a safe operation [2].

For the combustion of the liquid fuel to be accomplished, it must be converted into fine droplets so that evaporation and mixing of liquid fuel with oxidizer can be achieved easily in the least possible time. This process of converting bulk liquid fuel into an array of several smaller droplets is what is known as atomization. The bulk liquid is converted initially into a liquid jet. The liquid jet gets disrupted subsequently due to various forces such as internal and external forces. Surface tension tends to pull the liquid in the form of a sphere as it has minimum surface tension. Viscosity is an internal force that affects the atomization process since it opposes any change in the shape and geometry of the liquid. The aerodynamic force helps in disrupting the liquid ligaments into droplets. The sum of the disruptive forces exceeds the overall surface tension force. The liquid, therefore, is disintegrated into ligaments and subsequently gets converted into smaller droplets[3].

An igniter is to supply a sufficient amount of heat energy to initiate the chemical reactions in the main propellant. Igniters draw energy from the limited stored energy onboard with the rocket engine to initiate combustion. Proper selection of ignition system depends on the nature and phase of propellants, need for a restart, system safety, altitude relight capability, weight and space considerations. A rapid and reliable ignition of incoming propellants must be ensured before propellants are accumulated in the combustion chamber to prevent explosions. The starting propellant flow rate is kept lower than the full flow rate, which ensures a smooth ignition process and prevents an excessive accumulation of propellants in the combustion chamber. It is essential that once the propellants are ignited, they must remain in combustion mode to act as a pilot ignition source for fresh propellants entering the thrust chamber[4].

1.2 Problem statement

For the Nakuja project, the aim is to design a whole rocket that would reach an apogee of 100 km. This would revolutionize space exploration in our country, enabling the launch of satellites to outer space. Before this is undertaken, tests would have to be carried out to determine the parameters for the engine to be used in the rocket. These would be conducted on a rocket engine test stand.

The rockets that have been designed before, the N1 and N2 rockets, used solid propellants. These solid propellants limited them to low apogees, which would not be capable of outer space exploration. Also, with these current designs being solid propellants, the specific impulse of the rocket engines, which is a measure of the propellant efficiency, is low. The lower the specific impulse, the more the propellants.

Thus there is a need to develop a liquid engine rocket which guarantees higher specific impulses and a higher apogee than solid propellant rockets. An injector would have to be designed so as to introduce the liquid propellants to the combustion chamber. This injector would have to fulfil all the requirements of the engine during testing, as well as prove that it would sustain fuel supply to the combustion chamber during flight.

1.3 Objectives

1.3.1 Main Objective

To design and develop a fuel injector for a liquid rocket engine.

1.3.2 Specific Objective

1. To design and fabricate a mechanical structure that should atomize and mix the propellants to ensure that the desired combustion efficiency is achieved.

2. To design and fabricate an electrical circuit to power the sensors and the igniter to ensure that combustion takes place.

3. To develop the ignition control algorithm to ensure there is combustion in the combustion chamber.

4. To integrate and test the mechanical, electrical and control modules.

1.4 Justification of the study

The injector is an essential part of the liquid rocket engine. Designing and developing the injector is a crucial task. The type of injector chosen will help in minimizing fuel consumption while attaining maximum thrust and combustion efficiency in order to reach the apogee. Failure to choose the correct design, the rocket's reliability will be greatly affected which might result in a lack of success in the project. This will be achieved by ensuring the required flow rates are maintained in the combustion chamber. Therefore, it is important that the design will help in achieving the goal of this project by lowering the specific impulse which will reduce the amount of propellants to be used while still maintaining the combustion efficiency.

1.5 Scope

This research focuses on the design and development of an injector for a liquid rocket engine. The injector is meant to provide the required amount of thrust so as to help the rocket travel the required distance. Even though there are several types of injectors which include: shower head, self-impinging doublet, cross-impinging triplet, centripetal or swirling and pintle, this research will focus on swirl coaxial or the pintle injector which are more efficient in atomization of the propellants.

Chapter 2

Literature Review

2.1 Introduction

This section goes on to describe the injector and the igniter in full detail and looks at some of the past work and findings that have been documented by different authors and institutions.
The injector is a separate system in the engine of a rocket which introduces the propellant to the combustion chamber. The role of this injector is to ensure the atomizing and proper mixing of the propellants inside the combustion chamber [5]. There are different types of injectors used for various applications, each with its own advantages and drawbacks. The main integral part of the injector is the manifold, which routes the propellant from their respective feed lines of single orifices inside the injector. It also induces pressure loss inside the injector, and the overall design of the injector, whether simple or complex, determines the complexity of the manufacture of the injector.

2.2 Type of Injectors

2.2.1 Showerhead Injector

This is the most basic type of injector design. In this type of injector, the propellant streams do not impinge, and they emerge at 90° to the face of the injector. It can be used for both liquid and gaseous propellants. While being used in applications requiring low chamber pressure, this type of injector exhibits high-performance efficiencies but does not provide the recommended mixing and atomization, as it relies on turbulence and diffusion so as to achieve mixing of the propellant, thus it is mostly used for fuel film cooling of the chamber wall [6]. It is obsolete to modern trends, as it requires a large chamber volume for efficient combustion of the propellants, which would increase chamber weight and overall rocket weight [3].

2.2.2 Self-Impinging Injectors

These types of injectors have the propellants colliding (impinging upon themselves) so as to atomize them. It employs self-impinging pairs of fuel and oxidizer, and mixing is achieved in the combustion chamber by volatilization of the propellants and by turbulence. Being like on like impingement injectors, they greatly improve flash atomization as compared to showerhead injectors [7]. They provide good combustion stability for medium performance levels. Other advancements of this injector have a secondary impingement of the fuel and oxidizer right after the primary like on like impingement.

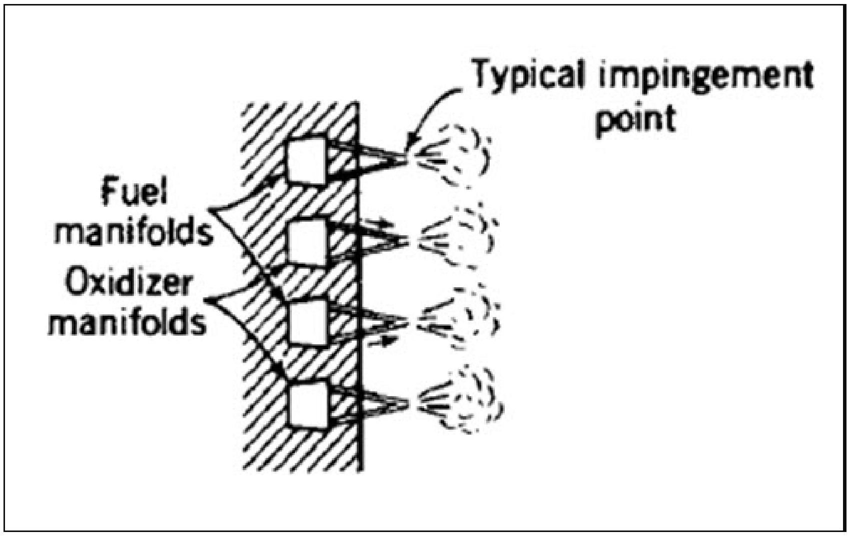

Figure 2.2.1: Self-impinging injector[5]

2.2.3 Cross-Impinging Injectors

These are similar in design to the self-impinging injectors, except that one of the propellants from one manifold impinges on another propellant from another manifold. They can be classified further into:

- **Doublet** – This design has the oxidizer and fuel impinging in pairs, leading to good liquid phase mixing and atomization. Drilling of accurate holes does not ensure high combustion performance in these injectors, as the resultant angle of the momentum vector varies with the mixture ratio. As discovered by W.H Lai, at lower jet speeds, the jets impinge on each other and merge into a single stream, and then break up into large droplets [8]. With an increase in velocity, a rim forms, to the point that an erratic rim is observed, leading to induced vibrations.

- **Triplet** – To eliminate the change in the resultant angle of the momentum vector, the unlike triplet was designed. This has one of the propellants coming out from two side orifices, while the other propellant comes out from a centre orifice. The choice of either two oxidizer jets or two propellant jets depends on the propellant combination. The elimination of variations in the momentum vector resultant angle significantly increases engine combustion performance [5].

- **Quintlet** – In this type, four jets of one propellant impinge on one stream of the other propellant [5].

2.2.4 Coaxial Injectors

The coaxial injector in itself is a non-impinging injector that is normally used for non-hypergolic propellants and is preferred when the propellants are hypergolic in nature [9]. It consists of two concentric tubes with a recessing length, where one of the propellants, preferably liquid oxygen, flows in the central tube at a low velocity, while the gaseous propellant flows in the co – concentric tube at a much higher velocity. The main purpose of this is so that the gas at higher velocity breaks up the liquid at the opening, leading to atomization. A variant of this is the coaxial swirl injector, whereby the liquid enters the injector chamber at an entry that is tangential to its axis. This liquid obtains a conical shape, and it disintegrates into ligaments and atomizes upon exit of the injector chamber [1].

Figure 2.2.2: Coaxial Swirl Injector[10]

2.2.5 Pintle Injector

This is an advancement to the coaxial injector that looks to eliminate the combustion instabilities associated with the other types of injectors and can deliver high combustion efficiencies of between 96% to 99% [11]. In a typical pintle engine, one of the propellants flows from the upper part of the injector, flows down inside the pintle and is ejected through sets of calibrated orifices at the pintle tip to the combustion chamber in a radial flow. The other propellant flows laterally inside the pintle and meets a multi-role orifice that distributes the propellant evenly across the lower chamber, before entering the combustion chamber as a cylindrical thin sheet. This axial and radial flow is what causes the mixing and atomization [12].

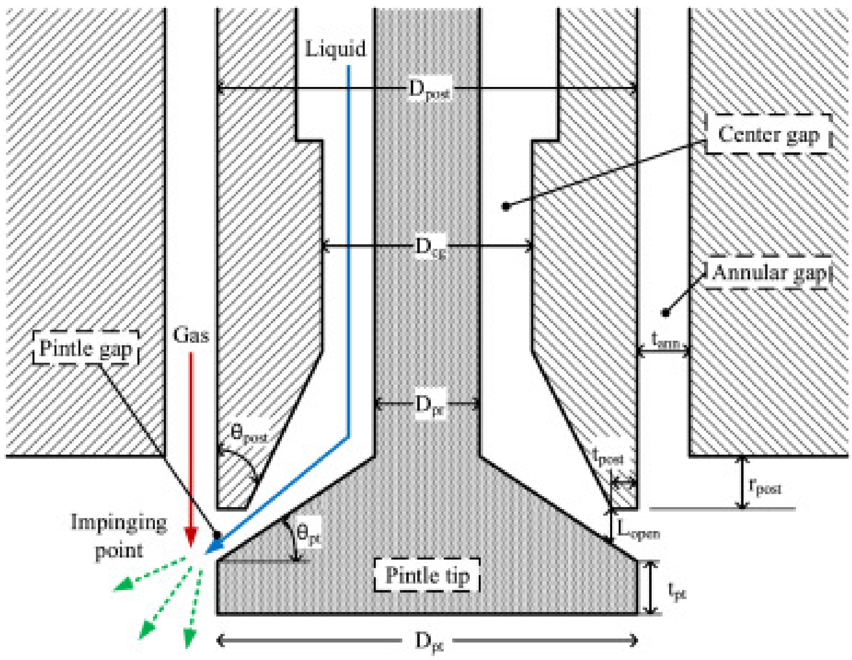

Figure 2.2.3: Pintle Injector[13]

2.3 Types of Ignitor Systems

2.3.1 Magneto systems

The engine spins a magnet inside a coil, or, in earlier versions, a coil inside a magnet, opening a contact breaker, thus interrupting the current flow and causing a high voltage to jump over a small gap. These systems were used in earlier versions of engines due to their simplicity and reliability, being of less weight than using a battery or a dynamo. The output of a magneto depends upon the speed of the engine, therefore, starting them could prove problematic.

In the earlier versions, so as to provide a high voltage spark from low battery voltage, a device, similar to an electric buzzer but larger in comparison, known as a ‘tickler’ was used. The direct current would pass through an electric coil and pull open a pair of contacts, causing an interruption in current, and hence the magnetic field collapse. This collapse would induce a high voltage, which would only drop by causing an arching across the contacts. This would go on continuously, leading to a train of sparks [14].

2.3.2 Electronic ignition

The mechanically time electrical ignition presented its own disadvantages, such as the mechanical wear of the contacts due to the make-and-break contact cycles, as well as oxidation of the contacts during sparking. The contact breaker points were replaced by angular sensors, whereby a vaned rotor breaks a light beam, or by a Hall effect sensor, which would respond to a rotating magnet mounted on the distributor shaft. The sensor output is shaped and processed by the suitable circuitry, then used to trigger a switching device, which causes a large current to flow in the coils [14].

2.4 Types of Igniters

2.4.1 Hypergolic Igniters

This is a bipropellant combination that ignites spontaneously when the liquids composing the bipropellant impinge on each other. An external igniter 'signal' is required to trigger the flow of the hypergolic fluid, which then collides with the oxidizer to cause a combustive reaction [5].

For modern hypergolic igniters, a cartridge with end caps is provided. Each of these end caps has a rupture disc assembly, which is about two. The first rupture disc provides a motive to drive the piston, while the second disc ruptures as the piston moves towards the discharge end so as to deliver the hypergolic fluid to the combustion chamber.

One of the disadvantages of the use of these types of igniters is their lack of feasibility, especially in testing conditions, as the types of fluids used as igniters are not economical to use for a test stand [15].

2.4.2 Pyrotechnic igniters

These are slow burning firecrackers that are modified for the ignition of rocket engines. They can be inserted from below at the end of a wooden plastic or stick or can be mounted on the injector's face. Although they are simple in nature, they are rarely in use, as to achieve the required heat release required by modern large engines, their size would be impractical and the ejection of the parts could cause damage to the inner parts of the chamber walls [5].

In operational designs, they often do not ignite the main propellant but ignite a pilot flame that is fed by a small portion of the main fuel. This then goes on to ignite the rest of the propellant. The composition of these types of igniters consists of mainly magnesium, which offers great efficiency and performance. It is usually combined with Teflon for propulsion, and the oxidation resulting from the combination releases high amounts of energy.

Another disadvantage that may arise from the use of these types of igniters is the vulnerability of auto-ignition from electrostatic discharge, as seen in the Pershing II missile [16].

2.4.3 Spark Igniters

These types of igniters have been developed over time to provide higher efficiencies, and are mainly applied in areas where repeated starts is required. A variant of these, called the Augmented Spark Igniters (ASI), counters the limitations or inefficiencies of the earlier spark plugs in direct combustion by firing into a small chamber the size of a gas generator, whereby a small amount of propellant is introduced and the flame resulting from this, in turn, ignites the main propellant, just as in the pyrotechnic igniters [5].

A typical spark plug consists of a dual gap spark plug, ceramic metal seals, a high-voltage transformer, a storage capacitor and an electronic circuit module. The sparkplug, ignition exciter and high voltage components can be packed in a high pressure sealed enclosure so as to retain their operability even when in space, but limited to small to medium sized rockets due to heat losses [1].

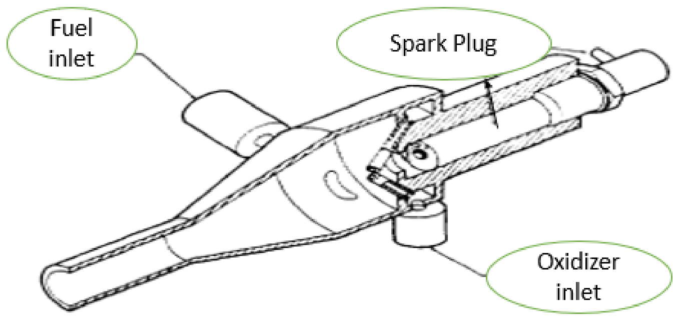

Figure 2.4.1: Spark igniter[5]

2.4.4 Torch Igniters

Also called an augmented spark impinging igniter, this type of igniter injects propellants into a pre chamber where they are activated and energized. The flame then stabilizes and exits into the main combustion chamber where it ignites the main flow directly or encounters a coaxial stream to produce a secondary flame. It is usually 10-35 mm in diameter; size varies with thrust [5].

The torch igniter has some advantages over the original spark igniter. First, it is able to provide a large number of ignitions as compared to a spark plug. It can also operate satisfactorily over various propellant flows and mixture ratios [1].

2.4.5 Resonance igniters

Resonance heating created from the flow of high-pressure gas is used to ignite the liquid propellant. It consists mainly of a propellant supply, sonic orifice, mixing chamber and resonator cavity. The high pressure gas (usual hydrogen) arrives at the sonic nozzle, whereby it is then expanded in the mixing chamber and subsequently directed to the resonator cavity, in which compression and expansion take place in cycles. Consequently, due to this expansion and compression, the gas reaches high temperatures and is exhausted at the outlet. The oxidiser is then introduced at the outlet, causing the ignition of the mixture. These types of igniters can also be used for a wide range of propellant combinations [1].

2.5 Previous Work Done Concerning Injectors and Igniters

1. `The School of Aeronautics and Astronautics, Purdue University`, designed a low cost hydrogen/oxygen augmented spark igniter for the ignition of kerosene and documented their work. Their main focus was on providing literature for the design of this type of injector. Their initial design experienced hard starts and extensive hardware damage of the nickel electrode used, due to the higher temperatures inside the torch chamber. They redesigned the torch tube and repurposed the torch chamber.

2. `The Portland State Aerospace University` designed a pintle injector for their 500 lbf thrust 3D printed liquid fuel rocket engine. They documented the various calculations that they used in the design. Their main focus was constructing an engine that would provide high performance and stable operation without affecting the durability of the thrust chamber. The ease of machinability was the main advantage that led to the choice of the pintle injector, among others such as thrust per element and throtteability.

3. `Copenhagen Suborbitals` developed a coaxial swirl injector for their BPM100 engine which would then be tested on the BPM5 engine, which previously used a showerhead injector. This was done for validation of the performance of the en-

gine with the new injectors. The injector consisted of 19 swirlers, each with three sections, with the outer and inner parts soldered together using nitrogen in a glass tube. The whole injector was made out of brass which would produce a good surface finish upon exposure to the soldering process. the use of a nitrogen glass tube was chosen to address the challenge that resulted from the use of a ceramic oven in soldering.

2.6 Summary of Gaps

From the literature review conducted, the project aims to address the following gaps:

- The design for coaxial swirl injectors requires high precision machinery for accurate manufacture of injector elements, which are not easily obtainable and may require outsourcing.
- The design of pintle injectors has mainly been oxidiser-centred due to its easier machinability but is not applied to small engines.
- The high temperatures in the combustion chamber, which are as high as 1000 $°C$ may extend to the faceplate of the injector. This may lead to the melting of the faceplate as brass has a low melting point, specifically, 930 $°C$.

The challenges addressed above were solved as follows:

- Designing a pintle injector rather than a coaxial injector, which would be easily manufactured in-house.
- Designing for a fuel-centred pintle injector, which would be adaptable to the small rocket engine that was intended to be developed.

- Using stainless steel in place of brass, which has high durability and a higher melting point, but employing a different design so as to reduce the overall weight of the injector and hence reduce overall cost.

Chapter 3

Methodology

This section will look into the mechanical design of the pintle injector, considerations for the dimensions of the injector elements and the selection of materials to be used. It will finally look into the design of a spark igniter that will use electric current to produce a spark. The ignition will be controlled by a microcontroller.

3.1 Mechanical Module

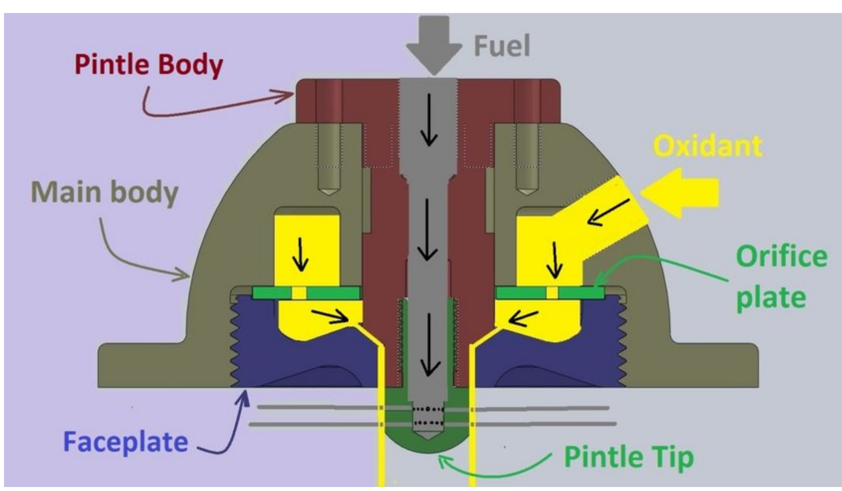

Figure 3.1.1: Elements of a typical pintle injector [12]

The pintle injector will consist of five elements which include: the pintle tip, pintle body, injector body, orifice plate and a faceplate. A reverse engineering approach was used to obtain our current mechanical design. Since mass flow rates determine the size of holes which are located on the pintle tip and the orifice plate. The equation used to determine the mass flow rates is given as[5];

$$T = \dot{m} I_{sp} g \tag{3.1.1}$$

Where,

- T =Thrust in the chamber
- $\dot{m}$ =Total mass flow rate
- I_{sp} =Specific impulse
- g =Gravitational acceleration

The specific impulse which indicates the efficiency of the engine used to determine the mass flow rates was 237.63179 s. The total force to be produced during combustion in the combustion chamber is 2.76622 kN. The mass flow rate obtained was 1.18703 kg/s. The O/F ratio is 1.5. This ratio was used to obtain the flow rates of the propellants from the total mass flow rate. The mass flow rate of ethanol will be 0.47481 kg/s and that of gas oxygen will be 0.71222 kg/s.
The pintle injector to be designed will be fuel-centred. Ethanol will be ejected through a set of calibrated orifices located at the pintle tip, which delivers metered propellant mass flow into the combustion chamber, in form of radial lines. Gas oxygen enters the injector laterally, passes through a multi-role orifice plate and reaches the combustion chamber, in form of an axial flow. The total area of the orifices used to meter propellants flow is given by:

$$A_{inj} = \frac{\dot{m}}{C_d \sqrt{2\rho\delta p}} \tag{3.1.2}$$

Where,

- A_{inj} =Total area of the orifices
- $\dot{m}$ =Total mass flow rate
- C_d =Discharge Coefficient
- ρ =Density of the propellant
- δp =Desired pressure drop across the injector

The value of the discharge coefficient used was 0.8. The value of the mass flow rates used was 0.47481 kg/s for ethanol and that of gas oxygen was 0.71222 kg/s. The density of ethanol used was 789 kg/m^3 and that of gas oxygen was 1.428 kg/m^3. The pressure drop used for both propellants was 5 bars.
Using these parameters, the parts are designed according to each of their own dimensional and material requirements.

Item	**Parameter**	**Value**
1	Thrust	2.76622 kN
2	Specific Impulse	237.63179 s
3	O/F Ratio	1.5
4	Total Mass Flow Rate	1.18703 kg/s
5	Discharge Coefficient	0.8
6	Mass Flow Rate (Ethanol)	0.47481 kg/s
7	Mass Flow Rate (Gas Oxygen)	0.71222 kg/s
8	Density (Ethanol)	789 kg/m^3
9	Density (Gas Oxygen)	1.428 kg/m^3

Table 3.1.1: Parameters Used in Design Work.

3.1.1 Pintle Tip

An important dimensionless variable that was used to determine the dimensions of the pintle tip was the ratio of chamber-to-pintle diameters. The value for this quantity should vary from 3 to 5 [17]. The diameter of the pintle tip was chosen to be 30 mm which was compared to the 143.07mm of the combustion chamber.

The skip distance is defined as the length that the annular flow must travel before impacting the radial holes divided by the pintle diameter. The value should be equal to one [17]. The length of this annular flow was thus determined to be 30 mm.

The total area of the orifices was 21.1296 mm^2. The number of holes on the pintle tip will be 27. The choice of the number of holes was determined by the availability of the machines around. Each hole will have a diameter of 1 mm.

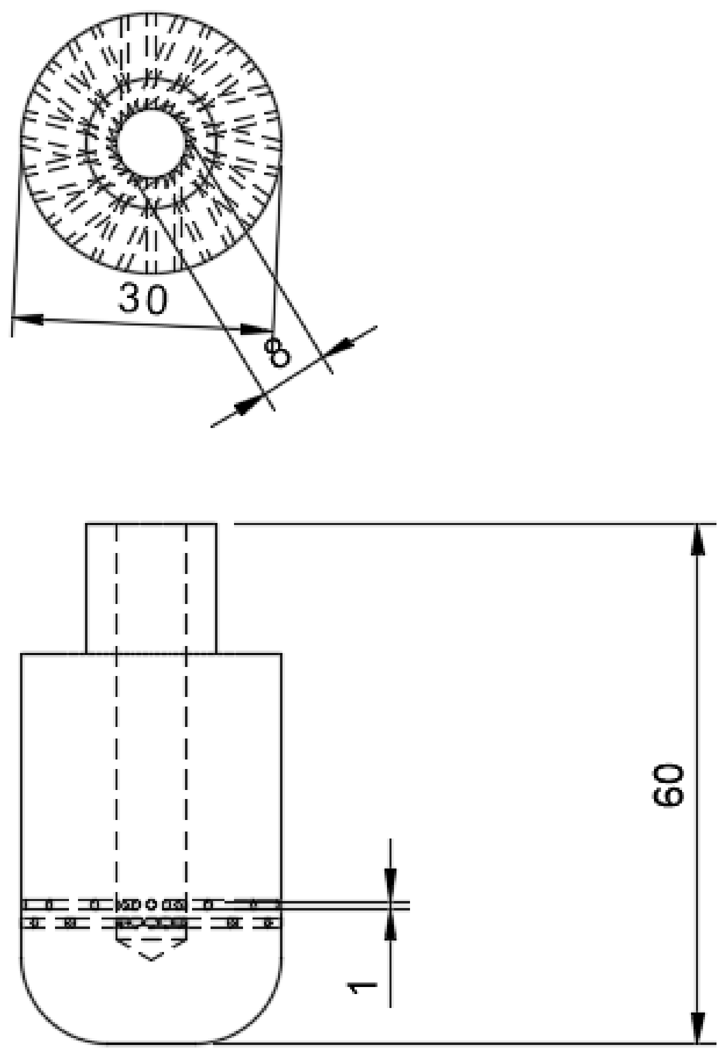

Figure 3.1.2: Pintle Tip

Material Selection

The pintle tip was designed to produce a mass flow rate of 0.47481 kg/s. For this to be achieved the accuracy of the diameter which is 1 mm of the holes must be achieved. The material to be used should be a good conductor of heat. Rounded tips tend to reduce the amount of heat that is to be subjected to the pintle tip. It should be machined easily without affecting the properties of the material. From the requirements mentioned above the following materials were selected for consideration which included aluminium and copper.

Copper has high thermal conductivity and it is soft. Copper has a high cost. The material is not readily available. Aluminium was selected as the material to be used to fabricate the pintle tip due to the cost and machinability. The low melting point can be handled by using a rounded tip. Since the pintle tip might be manufactured several times it will be easier to obtain the required parameters.

3.1.2 Pintle Body

The pintle body was designed to transfer fuel from the pipes into the injector which then finally flows through the pintle tip. This part will be exposed to the least amount of heat. The top of the pintle body has to be assembled to the injector body. Bolts will be used since they offer flexibility in the design. Assembling and disassembling the pintle body from the injector body is necessary as it allows modification of the part. The total height is dependent on the structure of the injector body and the faceplate. The total height is 60 mm. A through hole is to be drilled which will have a diameter of 8 mm. A hole of 15 mm will be drilled and threaded from the bottom and the depth will be 15mm. This diameter was used since the pintle tip has to be assembled within the pintle body.

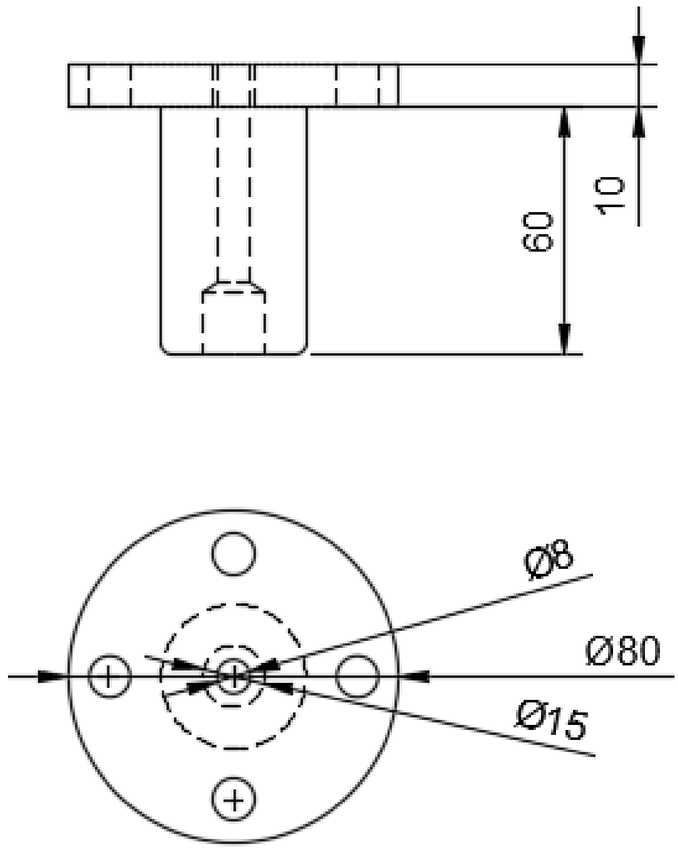

Figure 3.1.3: Pintle Body

Material Selection

The pintle body will not be subjected to heat as compared to the pintle tip. Considering that the dimensions of the element are small, a machinable material has to be chosen. Internal threading has to be performed for assembling to occur. The pintle body was mated with two parts by using threads. It was mounted on the injector body by using four bolts in the assembly. Due to the many operations that are to be performed on the pintle body, some materials were considered which included brass and aluminium.

Brass and aluminium were considered in the design of the pintle body. The main reason that brass was not chosen is that it has low corrosion resistance. This will affect the purity of the propellants. Aluminium was chosen due to its wide availability. It can also be easily machined. Comparing brass to aluminium, aluminium is better because it cannot be corroded by ethanol. Corrosion will affect the concentration of ethanol which will affect the combustion of the propellants.

3.1.3 Orifice Plate

The orifice plate is a part of the injector that is responsible for causing the pressure drop of the oxidant. It was designed in such a way that it had a total of 100 mm in diameter so that it can fit within the injector body. The total area of the orifices was 745.006521 mm^2. The number of holes selected to be on the orifice plate was 15. Each hole will have a diameter of 8 mm which is four times the size of the holes of the pintle tip. The thickness of the plate will be 10 mm. A small thickness was chosen to reduce the weight of the whole injector. A through hole was formed at the centre of the plate. The hole was meant to allow the pintle body to pass through it. It will have a diameter of 35 mm which is equal to the thickness of the pintle body. This is to ensure that there is sealing to prevent the gas from escaping.

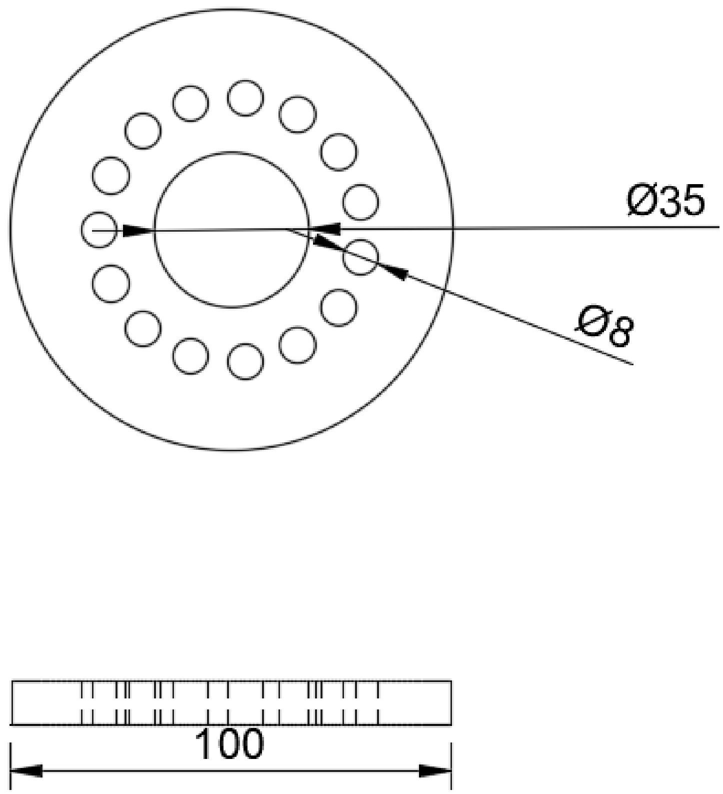

Figure 3.1.4: Orifice Plate

Material Selection

The orifice plate is to withstand the pressure from the oxidant. The material should not react with the gas oxygen. Most metals react with oxygen to form metal oxides. Rust is a form of iron oxide which can affect the physical properties of a material. Aluminium and stainless steel were considered in the design of the orifice plate.

Since the injector is to be light, aluminium was chosen in this case due to its low density. The cost of this injector is to be low and for this to occur the use of stainless steel was minimized.

3.1.4 Faceplate

The faceplate was to be located at the bottom of the injector body. The main purpose of this part was to provide an annular gap of 1 mm between the pintle body and the exit of the gas [17]. It will have a 35 mm hole at the bottom. This is what created the annular gap. It also ensured that the orifice plate was located within the injector. Threaded holes were formed at the outer diameter. Bolts and nuts were used to assemble the faceplate to the injector body to ensure that a tight connection was formed. This is to prevent the gas from escaping. A hole of diameter 80 mm was drilled at the centre to sandwich the orifice plate between the faceplate and the injector body.

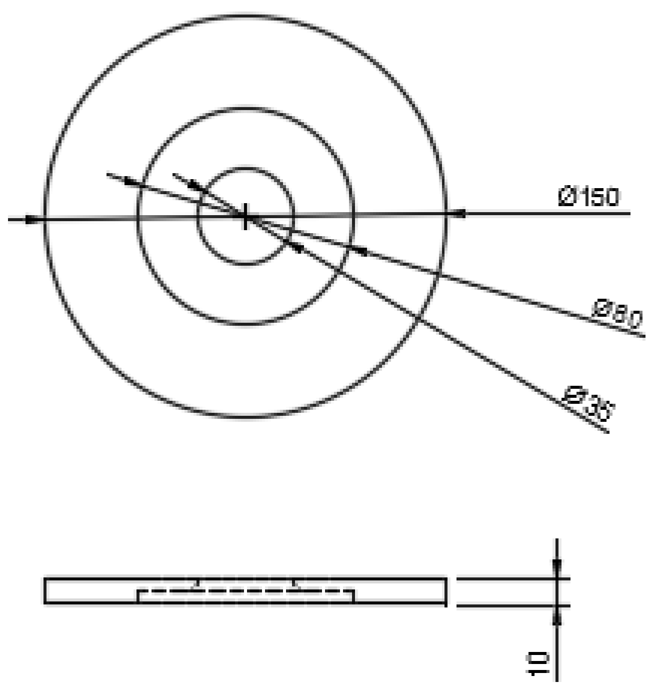

Figure 3.1.5: Faceplate

Material Selection

The faceplate will be exposed to the flame during combustion. Considering this, only materials with high melting points were considered. This will prevent the injector from melting. If melting occurs this means that the whole injector will fail. To prevent this from occurring some of the materials that were selected included: tungsten, aluminium and stainless steel. Tungsten was considered since it has a melting point of 3422 $°C$. To save on cost and to reduce the weight of the injector, tungsten was eliminated.
Aluminium was not a suitable material to machine this element since it will lead to failure due to melting. It has a low melting point. Stainless steel is preferred in this case. Stainless steel is available in the market and it has a high melting point of 1530 $°C$.

3.1.5 Injector Body

This is the housing of the whole injector. It has a diameter of 150 mm which will enable the whole injector to settle on top of the combustion chamber. The diameter of the combustion chamber should be equal to that of the injector to ensure that there was compatibility. It had a through hole at the centre which would house the pintle body. The surface of the body had a hole of diameter 10 mm which will allow the oxidant to get into the injector. At the bottom, the injector body had a hole of diameter of 100 mm and a depth of 10 mm which would accommodate the orifice plate. The total height of the injector body was selected to be 50 mm.

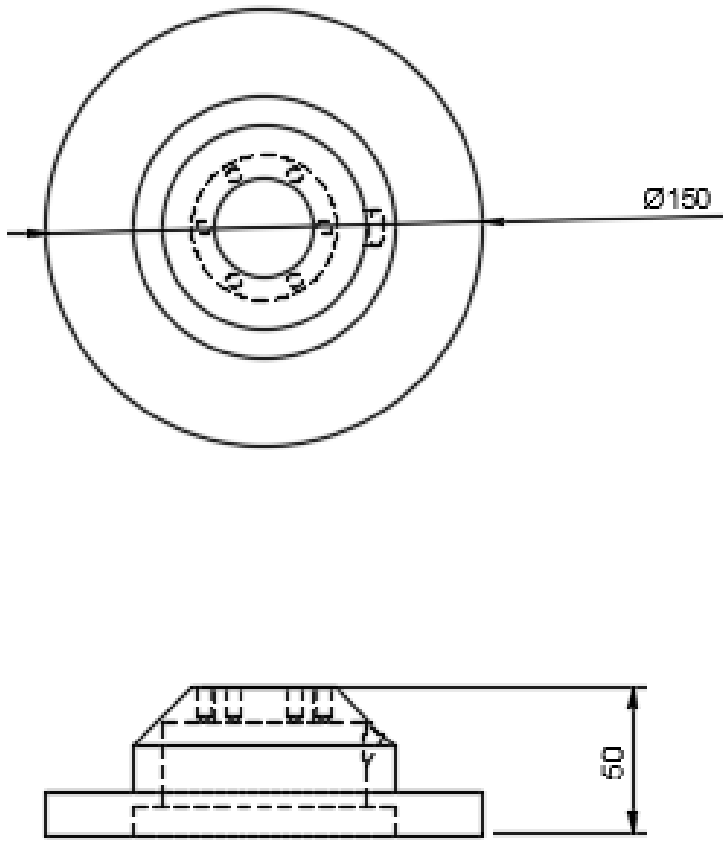

Figure 3.1.6: Injector Body

Material Selection

The injector body should be strong to house the two elements stated above. Since it was located at the top of the combustion chamber, a lot of heat will be induced into the material. A material with a high melting point was preferred in the design. The body has a complex architecture since it has a chamfered edge. A material that can be easily machined was to be selected in the design.

The materials that were considered in the design of the injector body were cast iron and stainless steel. Cast iron can easily be machined through casting to obtain the given geometry. On the other hand, cast iron has a lower melting point of 1204 °C as compared to stainless steel which has a melting point of 1530 °C. Stainless steel was chosen so as to withstand the amount of heat generated by the flame.

3.2 Electrical Module

3.2.1 Choice of Igniter

Considering the three types of igniters, the pyrotechnic igniter was the most favourable igniter for the combustion of propellants in this project. This is due to the following reasons:

1. The main propellants that are to be used are ethanol and gaseous oxygen. Ethanol is not a hypergolic fuel, and its collision with gaseous fuel would not provide enough force or energy that is required for ignition.
2. The current demand from the primary circuit to support the power demand of the primary side of the transformer to be used for the spark igniter would be too high. Since ignition was to occur with 15 kilovolts, drawing a current of 2A, the amount of current required for the primary side using a 12 V battery would be around 2500A, which would be practically impossible to draw out of a 12V battery.
3. Electrically ignited systems are easy to monitor, and they can be easily adapted to a control system depending on the parameters and state required in combustion.

3.2.2 Design for the Igniter

By choosing the pyrotechnic igniter as the type of igniter to be used for this project, two preliminary designs were chosen for the igniter. These included:

1. Design with pre-ignition in a prechamber inside the igniter

2. Design with ignition directly in the combustion chamber

The latter design was the better among the two that were considered. It involves the introduction of electrodes directly into the combustion chamber through the walls. The electrodes would then be used to provide the parking that is needed. In comparison to the former, the design was easy to implement on a rocket had simplicity in design and can be used for a wide range of propellants.
Looking at the time for flame stabilization for this design, it was not as much of a difference as much as that of the prechamber device, thus this also motivated the choice in the second design.

3.2.3 Choice of circuit Design

When it came down to the circuit design, two designs were considered depending on the nature of the task they were required to perform. The two types were:

1. Hardware-based circuit
2. Software-based circuit

The circuit design that was eventually chosen was the software-based circuit. This circuit that was designed employed the use of a programmable microcontroller which would then work using the same principles as the 555 timers, but using different parameters, to produce a signal that would switch on another high voltage circuit. This circuit used pressure as a parameter in the design, whereby the signal from a microcontroller would be triggered by a pressure sensor.

The pressure was the best parameter to choose from as it had already been used as a constant in the mechanical design. With a combustion chamber pressure of 2MPa, the software design and control were easy to design and implement.
This design was specifically chosen as it was easy to monitor the pressure values within the combustion chamber and as compared to the hardware-based circuit, in the case whereby certain parameters need to change, no destruction of circuits or replacement of circuit components would have to be carried out.
The components are discussed in detail below:

1. Power Source - Two 9 V batteries would be used as power sources were used, one for the logic circuit and the other for the igniter circuit.

2. Microcontroller - This served as the control unit for this circuit. The microcontroller chosen was an Arduino Nano, which is actually smaller than the other Arduino variants. The Arduino receives input from the pressure sensor, and produces a signal depending on the logic, to control the operation of the sparking circuit.

3. Darlington Pair Transistor - A transistor was used in this circuit so as to act as a switching element to the sparking circuit. Each pin of the microcontroller sources a logic HIGH voltage of 5V, and sinks or sources 40 mA current. So as to ignite the pyrotechnic, current of between 3A would need to flow within the igniter circuit. Thus a transistor that would be able to handle a maximum current of about 5A was required as a switching transistor. Thus the TIP120 Darlington pair transistor was chosen which had a maximum collector-emitter current of 5A.

4. Buck Converter - As the power source that was used was 19V, and the microcontroller requires a maximum of 5V, the voltage had to be stepped down. Thus the LM2596 buck converter was used, which has an adjustable output voltage from an unregulated voltage input, through a potentiometer.

5. Nichrome wire - This is a low resistance wire that is used to provide the heat required for combustion of the pyrotechnic. The amount of heat generated by the

coil is directly proportional to the square of the current through the circuit. The value of resistance of the nichrome wire used was 3 ohms. The amount of heat generated is governed by the equation:

$$H = I^2RT \tag{3.2.1}$$

Where **H** is the heat generated, **I** is the amount of current through the secondary circuit, **R** is the resistance of the nichrome wire and **T** is the time of current flow in seconds.

6. Pressure Sensor - The pressure sensor was used to provide the pressure readings to the microcontroller for switching the sparking circuit. The pressure sensor that was used was the PS8808-2000k3CBNG.

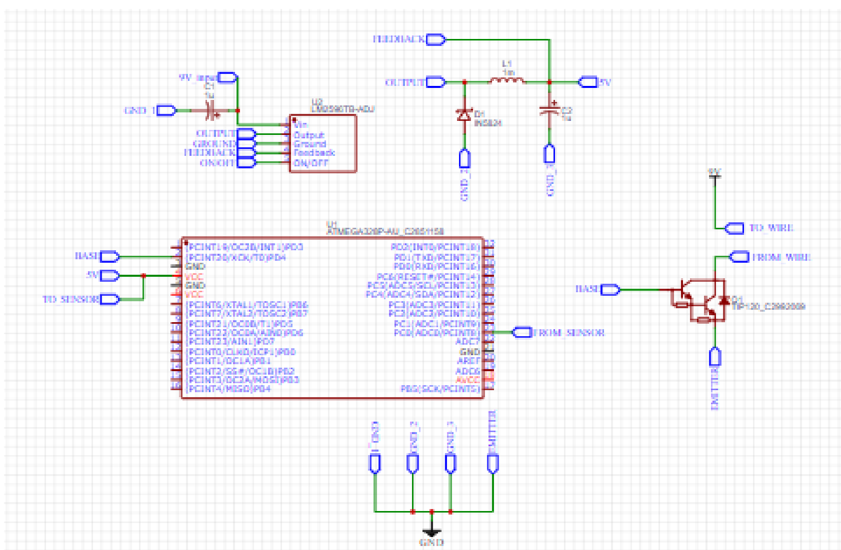

Figure 3.2.1: Designed Circuit

3.3 Control Module

The main role of the control module was to synchronize the ignition of the propellants inside the combustion chamber with the stabilization of pressure inside the combustion chamber.

- Once the desired pressure is achieved inside the chamber, the sensor sends a digital signal to the microcontroller.
- The microcontroller then writes a HIGH value to a pin connected to the base of the transistor.
- This causes the transistor to act as a switch, causing the current to flow through the secondary circuit
- The flow of current causes heating in the coil, which then ignites the pyrotechnic.

The flow chart for the process is represented below:

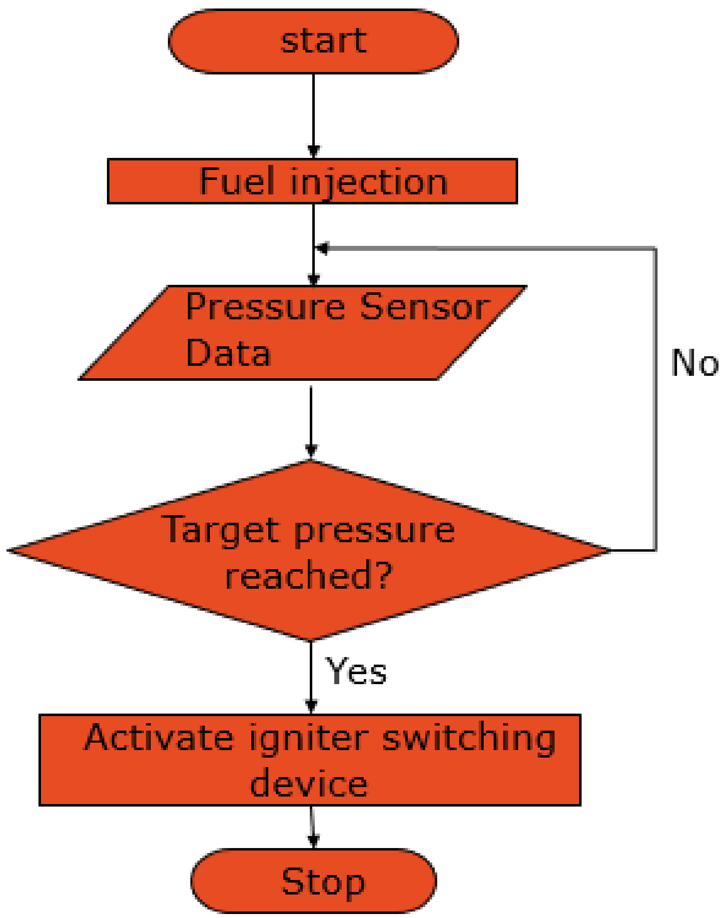

Figure 3.3.1: Flow Chart

Chapter 4

Results and Discussion

4.1 Pintle Injector

For the dimensions obtained above, a pintle injector was designed and assembled as shown in figure 4.1.1. The pintle injector assembly will be used to atomize and mix the propellants to be used. The design should also give the required pressure, the pressure of the feed line must be greater than the pressure in the combustion chamber.

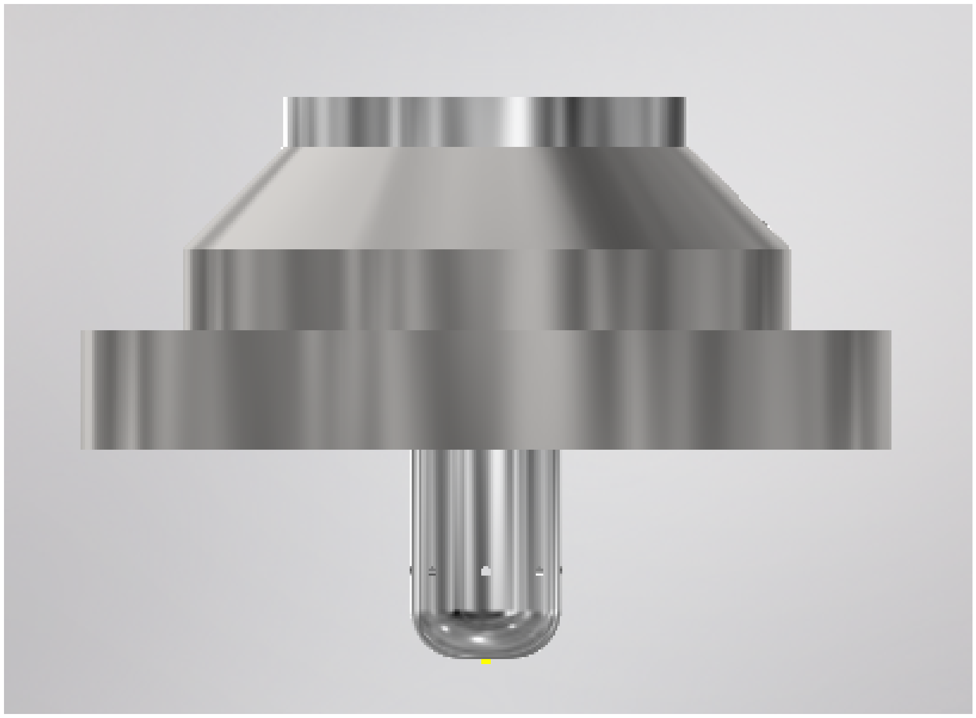

Figure 4.1.1: Assembly of the Pintle Injector

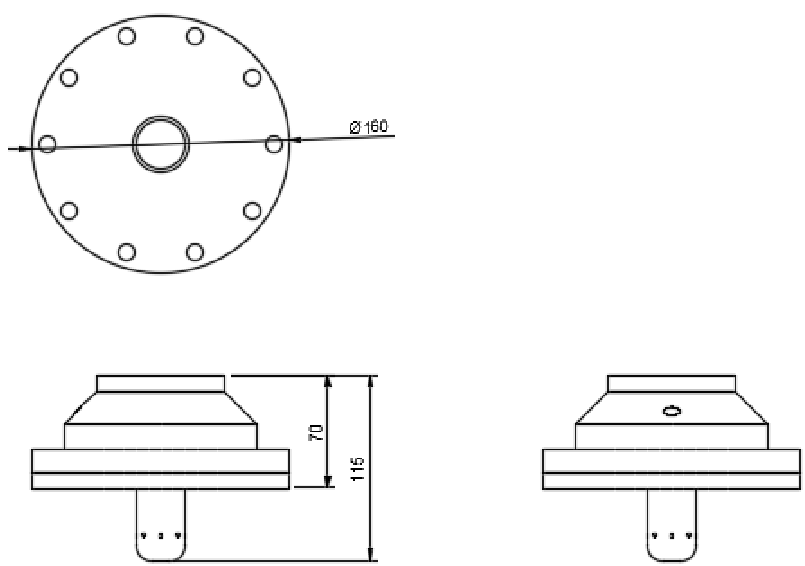

Figure 4.1.2: Drawing of the Pintle Injector

4.1.1 Fluid Flow Analysis for Ethanol

The pintle tip simulation was done on ANSYS using the available parameters such as the pressure inlet which is 25 bars and the mass flow rate at the exit is 0.47481 kg/s. The pressure at the exit was obtained as 21 bars. The design seems accurate since the pressure at the inlet was greater compared to the pressure at the outlet. The same was observed for velocity. The velocity was increasing as the fuel was flowing towards the exit. Velocity is inversely proportional to pressure. The parameters used to obtain the results are shown in the table below.

Item	**Parameter**	**Value**
1	Density	789 Kg/m^3
2	Viscosity	8.34×10^{-4} Pa/s
3	Inlet pressure	25 bars

Table 4.1.1: Ethanol Parameters.

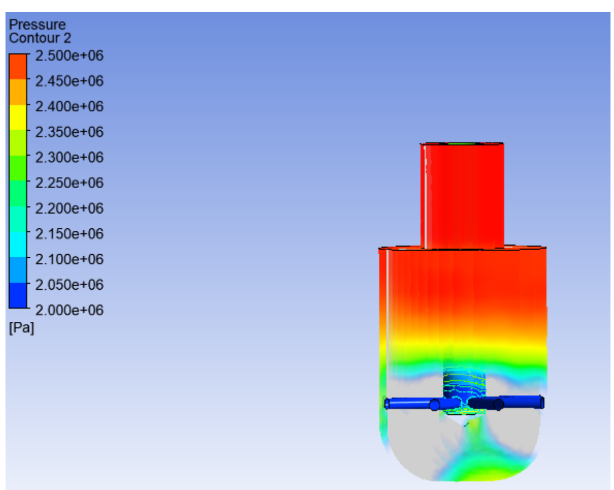

Figure 4.1.3: Pressure Analysis on the Pintle Tip

4.1.2 Gas Oxygen Fluid Flow Analysis

The pintle tip simulation was done on ANSYS using the available parameters such as the pressure inlet which is 25 bars and the mass flow rate at the exit is 0.71222 kg/s. The pressure at the exit was obtained as 21 bars. The design seems accurate since the pressure at the inlet is greater compared to the pressure at the outlet. The same was observed for velocity. The velocity was increasing as the oxidant was flowing towards the exit. Velocity is inversely proportional to pressure. The parameters used to obtain the results are shown in the table below.

Item	Parameter	Value
1	Density	1.428 Kg/m^3
2	Viscosity	2.04×10^{-5} Pa/s
3	Inlet pressure	25 bars

Table 4.1.2: Gas Oxygen Parameters.

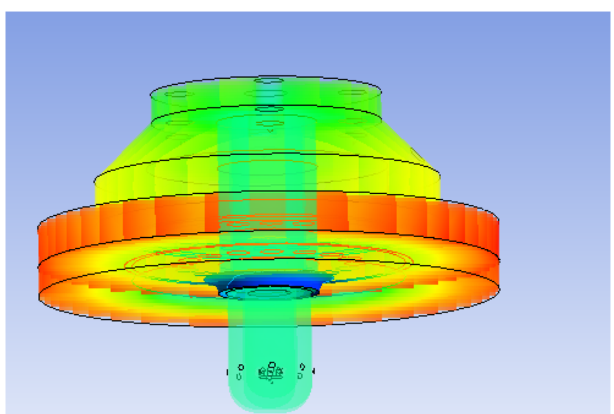

Figure 4.1.4: Fluid Flow Analysis for Oxygen

4.2 Spark ignition experimental results

A practical was carried out at the High Voltage lab so as to investigate the relationship between the ignition gap distance and the amount of voltage required for ignition. The data was obtained as follows:
With air as the material medium:

Gap(mm)	**Voltage(kV)**	**Current(A)**	**Time(s)**
2.5	4	13.6	2.6
5	7	6.6	3.19

Table 4.2.1: Lab Results.

Information gathered from this experiment was that as the voltage increases, the current reduces. Also, increasing the voltage for the same ignition gap results in an increase in the time required for sparking.
This experiment was especially useful in determining the amount of power that was required in the secondary circuit.

4.3 PCB Layout

The PCB layout for the electrical module was developed as follows:

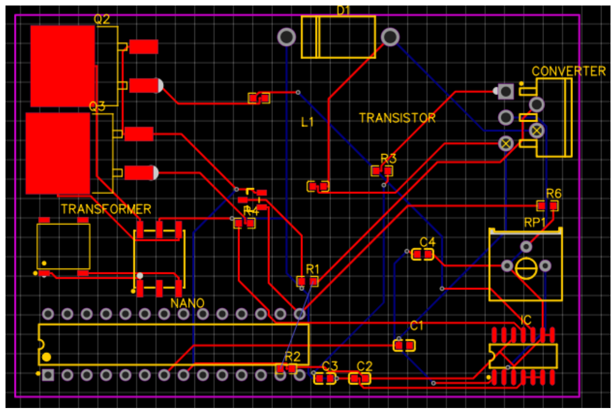

Figure 4.3.1: PCB Layout

The 3D view of the PCB is as follows:

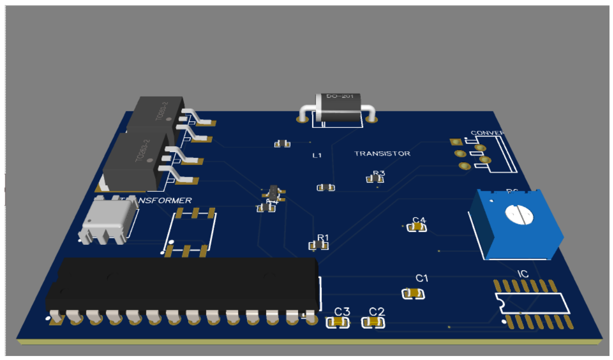

Figure 4.3.2: 3D VIEW

Chapter 5

Conclusion

1. A pintle injector has been designed. It can ensure that there is proper atomization and mixing of the propellants. The design has minimized the size of the injector so as to reduce its weight of the injector.

2. Simulations were carried out using ANSYS. These gave a visual representation of how ethanol and gas oxygen will flow through the elements of the pintle injector.

3. The type of igniter was chosen and an electrical circuit designed for it.

4. The control logic for the ignition of the propellants was developed and integrated with the electrical and electronic circuits.

Appendix A

Work Plan

In order to complete the tasks, work is scheduled to be done according to the following work plan;

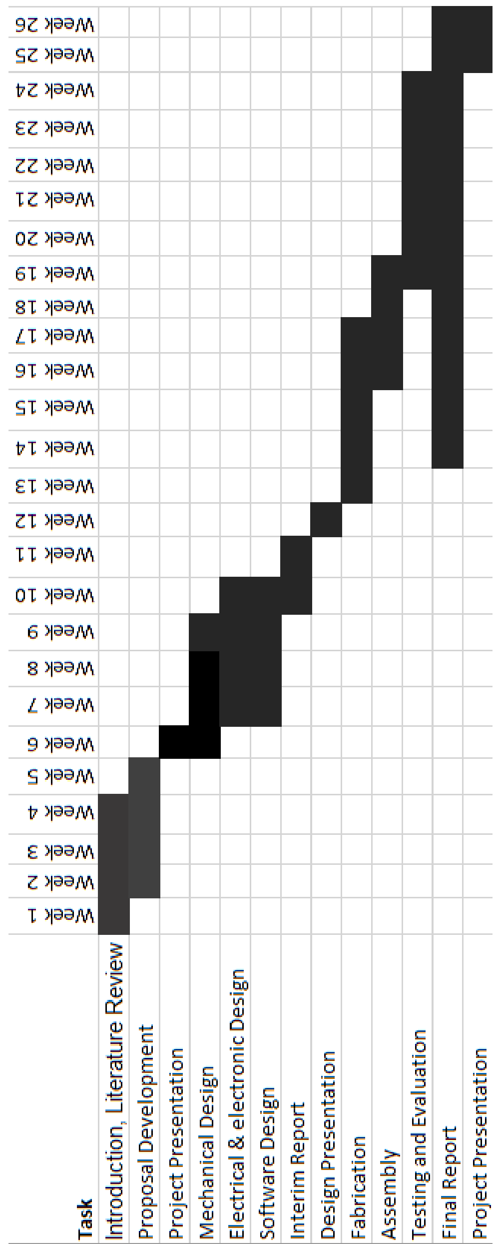

Table A.0.1: Work Plan

Appendix B

Budget

The project is expected to require the following resources in order to achieve the stipulated results.

Item	**Description**	**Cost**
Arduino Nano	Synchronizes the chamber pressure and ignition	1400 /=
Pressure Sensor	Detect change in propellant pressure	8768 /=
2 9V Power Supply	Power to primary and secondary circuits	300/=
LM2595 DC-DC Converter	To step down voltage	250 /=
Metal Rods	For overall mechanical structure	36500 /=
Resistors	Supplementary circuit components	30/=
TIP120 Darlington Pair	To act as a switch for the secondary circuit	50/=
Fabrication cost	Machining of the injector elements at NMC	24998/=
Total Cost		**72096** /=

Table B.0.1: Budget.

Bibliography

[1] D. Mishra, *Fundamentals of Rocket Propulsion*, C. Press, Ed. Taylor Francis Group, 2017.

[2] W. L. Ronald Humble, Gary N. Henry, *Space Propulsion Analysis and Design.* The McGraw Hill Companies, Inc., 1995.

[3] K. H. Dieter and H. H. David, *Modern Engineering for Design of Liquid-Propellant Rocket Engines*, A. R. Seebass, Ed., 1992.

[4] G. P. Sutton and O. Biblarz, *Rocket Propulsion Elements.* John Wiley Sons, Inc., 2017.

[5] K. H. Dieter and H. H. David, *Design of Liquid Propellant Rocket Engines*, 1967.

[6] M. Bouziane, A. E. de Morais Bertoldi, P. Milova, P. Hendrick, and M. Lefebvre, "Experimental investigation of showerhead injectors on performance of a 1-kn paraffin-fueled hybrid rocket motor," 2019.

[7] B. S. Waxman and B. J. Cantwell, "Effects of injector design and impingement techniques on the atomization of self-pressurizing oxidizers," 2012.

[8] W. Lai, W. Huang, and C. Chu, "Atomization and mixing characteristics of an unlike-doublet impinging-jet," 2004.

[9] D. A. Feikema, "Atomization characteristics of swirl injector sprays," 1995.

[10] I. Müller, M. Kuhn, I. Petkov, S. Bletsch, K. Huybrechts, and P. V. Cauwenbergh, "3d-printed coaxial injector for a lox/kerosene rocket engine space propulsion," 2018.

[11] G. A. Dressler and J. M. Bauer, "Trw pintle engine heritage and performance characteristic," 2000.

[12] A. P. Rene Nardi Rezende, "Experiments with pintle injector design and development," 2015.

[13] D. R. Rajendran, S. Prasad, S. S, T. S. Phutane, and V. S. Saoor, "DESIGN AND OPTIMIZATION OF PINTLE INJECTOR FOR LIQUID ROCKET ENGINE," *International Journal of Engineering Applied Sciences and Technology*, vol. 5, no. 1, pp. 151–159, may 2020.

[14] S. University, "Course notes on rocket systems."

[15] Taylor, "Hypergolic igniter," 2005.

[16] L. de Barros, A. P. M. Pinheiro, J. da Encarnação Câmara, and K. Iha, "Qualification of magnesium/teflon/viton pyrotechnic composition used in rocket motors ignition system," 2016.

[17] N. Ashgriz, *Handbook of Atomization and Sprays*, 2011.