DEVELOPMENT AND TESTING OF SOLID PROPELLANT – BASED IGNITION TORCH FOR LPRE

By

Irtza Fatima

Alveena Rizwan

Supervisor

Dr. Ihtzaz Qamar

Department of Aeronautics and Astronautics

Institute of Space Technology, Islamabad

2021

DEVELOPMENT AND TESTING OF SOLID PROPELLANT – BASED IGNITION TORCH FOR LPRE

A thesis submitted to the

Institute of Space Technology

in partial fulfillment of the requirements

for the degree of Bachelors of Science in

Aerospace Engineering

By

Irtza Fatima

Alveena Rizwan

Supervisor

Dr. Ihtzaz Qamar

Department of Aeronautics and Astronautics

Institute of Space Technology

July 30, 2021

Institute of Space Technology

Department of Aeronautics and Astronautics

DEVELOPMENT AND TESTING OF SOLID PROPELLANT – BASED IGNITION TORCH FOR LPRE

By

Irtza Fatima

Alveena Rizwan

APPROVAL BY BOARD OF EXAMINERS

____

Dr. Ihtzaz Qamar

CERTIFICATE

This is to certify that the research work described in this thesis is the original work of authors and has been carried out under my direct supervision. I have personally gone through all the data/results/materials reported in the manuscript and certify their correctness/authenticity. I further certify that the material included in this thesis is not plagiarized and has not been used in part or full in a manuscript already submitted or in the process of submission in partial/complete fulfillment of the award of any other degree from any institution. I also certify that the thesis has been prepared under my supervision according to the prescribed format and I endorse its evaluation for the award of Bachelor of Science in Aerospace Engineering degree through the official procedures of the Institute.

Dr. Ihtzaz Qamar

AUTHOR’S DECLARATION

We take full responsibility of the research and testing conducted during the Final Year Project titled **“Development and Testing of Solid Propellant – Based Ignition Torch for LPRE”**. We solemnly declare that the research and development work presented in this Thesis is done solely by us with no significant help from any other person; however, small help wherever taken is duly acknowledged. We have also written the complete thesis by ourselves. Moreover,weI have not presented this thesis (or substantially similar research and development work) or any part of the thesis to any other degree awarding institution within Pakistan or abroad.

We understand the management of IST has zero tolerance policy towards plagiarism. Therefore, we as an author of the above mentioned thesis, solemnly declare that no portion of our thesis has been plagiarized and any material used in the thesis from other sources is properly referenced. Moreover, the thesis does not contain any literal citing (verbatim) of more than 70 words (total) even by giving a reference unless we have obtained the written permission of the publisher to do so. Furthermore, the work presented in the thesis is our own original work and I have positively cited the related work of the other researchers by clearly differentiating our work from their relevant work.

We further understand that if we are found guilty of any form of plagiarism in our thesis work even after my graduation, the Institute reserves the right to revoke our BS degree.

Moreover, the Institute will also have the right to publish our name on its website that keeps a record of the student who plagiarized in their thesis work.

____

Irtza Fatima

170101064

____

Alveena Rizwan

170101086

I hereby acknowledge that submitted thesis/report paper is the final version and should be scrutinized for plagiarism as per IST policy.

____

Dr. Ihtzaz Qamar

Dated: _______________________

Dedicated to

Allah Almighty who gave us guidance, strength, intellect and protection.

Our beloved parents who are the source of inspiration and gave us strength when we thought of giving up and provide their moral, emotional, spiritual and financial support.

Our respected and beloved supervisor, Dr. Ihtzaz Qamar for his advice, guidance and support.

And lastly,

To Sir Ali Asghar who helped us out throughout our research with utmost sincerity.

ABSTRACT

This report contains the introduction of our project and the design and development of solid propellant based ignition torch for LPRE. The report also contains the selection of the solid propellants for the low temperature solid propellant – based ignition torch. Project plan, literature review, timeline, methodologies used, testing and the results obtained form the testing are discussed in this report. PROPEP and CPROP are used for the selection of solid propellants. CATIA is used for the design of combustion chamber and nozzles. Test bed is designed and fabricated for carrying out the testing of solid propellant – based ignition torch. Data Acquisition (DAS) is used for displaying the results calculated by the pressure and temperature sensors.

PROJECT OBJECTIVE

Our main objective is to design and develop a low temperature solid / composite propellant based ignition torch to start the ignition in the liquid propellant rocket engine. The temperature range should be between 700-1000K.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

1 CHAPTER 01

INTRODUCTION

The ignition of a liquid propellant rocket engine (LPRE) is a very critical. Hard start can cause a lot of instabilities in a LPRE. It is very important to avoid combustion instabilities in LPRE. In case of LPRE different methods are used for ignition including:

- Spark Ignition
- Liquid Torch Ignition
- Solid Propellant Torch

This project focusses on the design, development and application of the low temperature solid propellant based ignition torch to start the ignition in liquid propellant rocket engine (LPRE). The aim of this project is design, fabricate and analyze the efficient, safe and cost-effective low temperature solid/composite based ignition torch. In this project, chemical composition of solid propellant for ignition torch will be formulated. In next step grain design and fabrication will be carried out for ignition torch. Hot testing of the torch will be carried out and required parameters will be noted. In final stage, integrated testing of a LPRE chamber and solid propellant torch will be carried out. The main emphasis of this project is to determine the temperature, pressure and burn rates of the ignition torch.

1.1 Aims and Objectives

Our main objective is to design and develop a low temperature solid / composite propellant based ignition torch to start the ignition in the liquid propellant rocket engine. The aim of this project is to determine the temperature, pressure and burn rates of the ignition torch.

Our aim to design and develop the ignition torch consist of following steps:

- Finalize the chemical composition
- Making a propellant grain
- Designing and developing nozzle
- Fabrication of test Bed
- Hot Testing

Parameters that are needed to be measured at the end of our project are:

- Temperature measurement
- Pressure measurement
- Burn Rate measurement

1.2 Design Points

For LPRE ignition torch, we keep some parameters fixed as we cannot take all parameters e.g.;

1. **Temperature of ignition torch**

   As we are designing and developing low temperature solid propellant based ignition torch, that's why the temperature obtained after the testing should be less than the stoichiometric temperature of the selected propellant pair. The temperature range should be between 700-1000K.

2. **Pressure of the ignition torch**

   The pressure of ignition torch should be higher than the pressure of the LPRE. If the pressure of ignition torch is less than the pressure of the LPRE, there would be no start of the rocket engine. And if the pressure is too much high, then there would be hard start which can cause explosion or can bring severe damages to the engine.

3. **O/F Ratio**

As we are designing low temperature solid propellant based ignition torch, our propellant grain should be fuel rich and O/F should be less than 1.

4. **Mass flow rates**

Mass flow rates should be 5% less than that of LPRE. If mass flow rates are higher, it will create instabilities in LPRE that will eventually lead to the poor performance of LPRE.

5. **Burning time**

Burning time should be less as we are designing and fabricating the ignition torch. We only need 5-6 seconds of burning time in order to get a sustainable flame.

The design of the nozzle is dependent on all the above-mentioned things.

1.3 Methodology

In our project the first step was the selection of propellant. The software used for the selection of propellant pair are CPropep and Propep. After the selection of the propellant pairs, we did the testing of these propellants pairs and shortlisted the propellant pairs from the observation made after the testing. After selecting the suitable propellant for our torch, the designing and the fabrication of the grain would be carried out. Grain would be fabricated using different formulas and MATLAB codes. Next step would be the designing and development of the nozzle and the combustion chamber. Based upon different pressure values, nozzles with different throat diameters would be designed and fabricated. After that we would design and fabricate our test bed that would be used for the temperature and pressure measurement. And finally after the assembly, the final testing would be carried out. Following is the flow chart summarizing the procedure of our working.

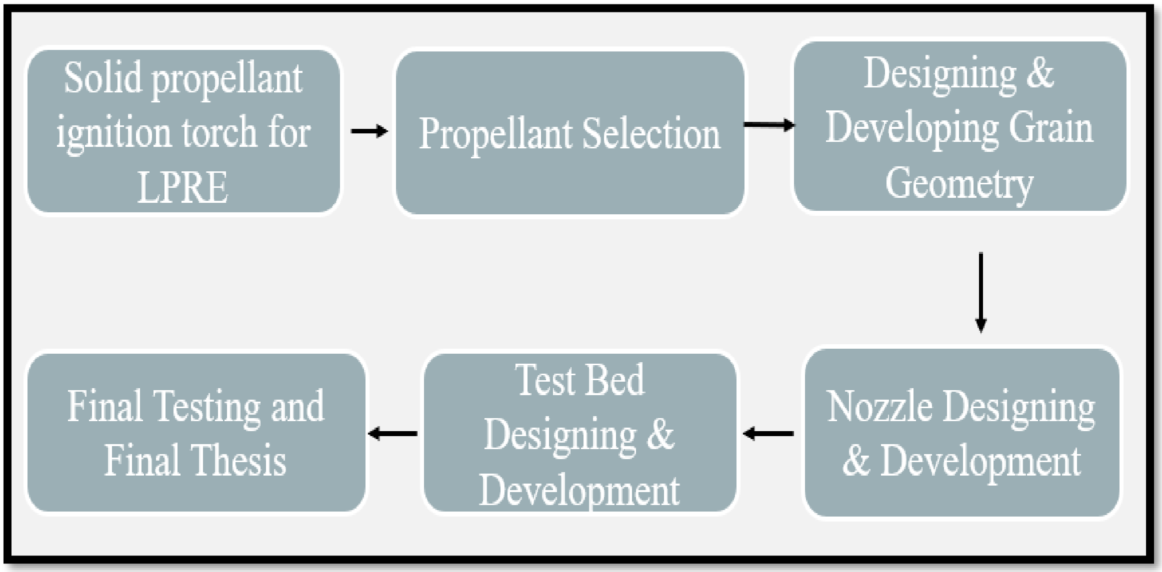

Figure 1.1 Methodology

1.4 Deliverables

The deliverables of our project are:

- Development of Propellant Grains
- Nozzle
- Test Bed
- Results
- Final report

The key deliverable of our project is low temperature solid propellant based propellant grain.

2 CHAPTER 02

LITERATURE REVIEW

2.1 Liquid propellant Rocket Engines

LPREs have great advantages in the Aerospace industry. They have been used in the Space Shuttles to take the humans in the orbits. Apart from that, they have been used in the missiles (unmanned) in order to make the satellites rotate in the orbits. In the World War 2, they were used in high research peed aircrafts. The LPREs consist of the fuel and oxidizer pumps that are kept separately from each other. They are pumped to the combustion chamber, where they are being ignited by some external means and then start burning after being mixed. As combustion process takes place, temperature and pressure keeps on increasing. At a very high temperature and pressure, the exhaust gases are generated. These exhaust gases then exit through the nozzle and the flow is accelerated. These exhaust gases result in the creation of the Thrust. Here the Newton's Third law can be observed. Thrust is dependent on the mass flow rates in the engine of the rocket. High mass flow rates produce higher amounts of thrust and vice versa. It also depends upon the velocity of the gases exiting through the nozzle as well as the pressure being created at the exit part of the nozzle. The mass flow rates, exit velocity and the exit pressure, all these parameters are directly linked with the nozzle and how it is designed. Variations in the nozzle design would result variations in these parameters and in return the Thrust would be affected. The nozzle's portion with the smallest area of cross sectional is called Nozzle Throat represented by At. At Mach number = 1, nozzle is supposed to be choked. The pressure generated at the exit is represented by the Pe and the velocity at exit is Ve. At a particular design condition, Pe can be equal to the free stream pressure. If we suppose that the free stream pressure is represented by Po then the thrust equation is mathematically shown as follows.

$$F = \dot{m} * Ve + (pe - p0) * Ae$$

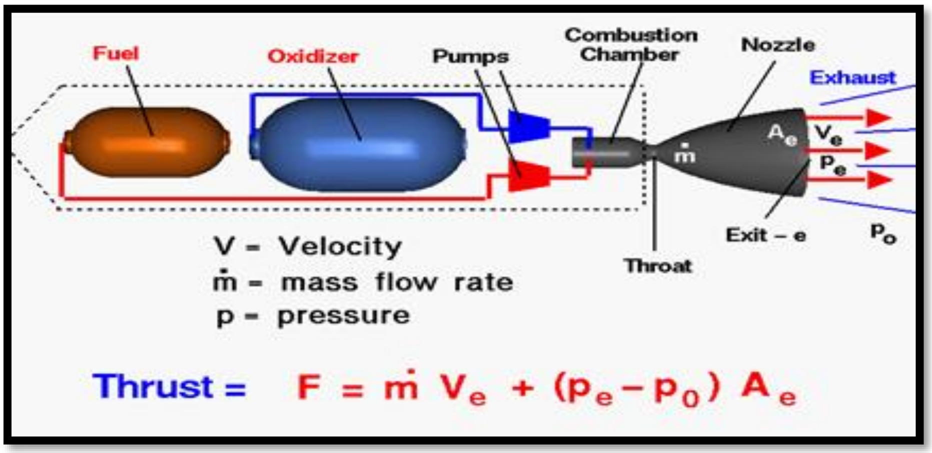

Figure 2.1 Thrust Equation

2.2 Liquid Rockets versus Solid Rockets

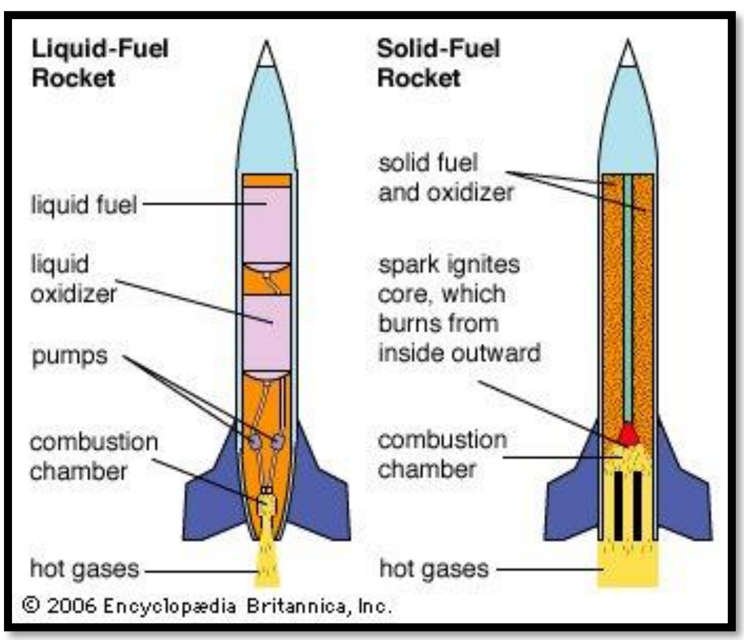

Figure 2.2 Solid v/s Liquid Rockets

Liquid rockets are considered to be more beneficial because their Specific Impulse (ISP) is high and as well as density. So the propellants used in the rockets would occupy the less space in the tanks thus decreasing the weight and making the rocket more efficient. Liquid Rockets can be classified as mono-propellant rockets, bi-propellant rockets and tri-propellant rockets. The tri-propellant rockets are very rare.

2.3 Ignition in LPREs

There are a lot of methods to initiate the ignition process. In the case of the Liquid rockets, it is compulsory that the ignition provided is consistent and stable. If there is inconsistency in the ignition process, it could create a problem in the startup. For instance, excess pressure would be built in the combustion chamber due to the excess amounts of propellant-pair. It would result in the hard-start of the engine and as a result, there could be a blast.

2.4 Igniters used for LPREs

There are many types of igniters that could be used for the ignition of LPREs. They could be

- Plasma Igniter
- Solid Propellant Ignition Torch
- Laser Igniter

Each of these are briefly discussed below

2.4.1 Plasma Igniter

This igniter has specially been made for Liquid Rockets ignition. In this device, a very dense and super-hot plasma jet is propelled which is composed of fluorine element and its compounds to the chamber. This process is carried out to burn the mixture of propellants which are in the cold state initially. The igniter is composed of:

- Co-axial and Cylindrical Electrodes
- Solid Teflon Plastic (Cylindrical bar shaped)

The bar is placed between these electrodes. The electrode on the outer side is tube shaped made of some metal mainly stainless steel. On the other hand, the electrode on the inner side is a pin (also metallic). The bar is fitted between the inner and outer electrode and acts as an insulator. Igniter is placed on the engine's Combustion Chamber in 2 ways

- It can be on the injector plate on engine's upstream side
- On the side-walls of the combustion chamber
- Behind valve opening prior to the ignition

The valve must be closed immediately so that the cylindrical bar between the electrodes (made up of Teflon) does not melt because of combustion chamber's heat.

2.4.2 Solid Propellant Ignition Torch

A solid propellant ignition Torch consists of a combustion chamber and a nozzle built in itself. The mixture of the propellant pair is placed inside the chamber, where it is ignited through some external means and then being burn. A pyrotechnic ring can be used to initiate the combustion process in the chamber. As the burning starts, increase in the temperature and the pressure take place. The exhaust gases start coming out through the nozzle generating the thrust and ultimately starting the engine of Liquid Rocket.

2.4.3 Laser Igniter

Such type of igniters is usually used for the bi-propellant Liquids Rockets. . This laser ignition approach is based on a novel dual pulse format capable of effectively increasing laser generated plasma life time up to 1000 % over conventional laser ignition methods. In the dual-pulse format tinder consideration here an initial laser pulse is used to generate a small plasma kernel. A second laser pulse that effectively irradiates the plasma kernel follows this pulse. Energy transfer into the kernel is much more efficient because of its absorption characteristics thereby allowing the kernel to develop into a much more effective ignition source for subsequent combustion processes.

2.5 Solid Propellants

Solid propellants are those which are composed of oxidizer and fuel both in the solid state. First of all, the appropriate fuel and oxidizers are selected. They are prepared separately and then mixed with each other properly. They are mixed with each other with some binders or linking agents. After that the mixture is kept for 7 to 8 days for curing under the specific temperature and pressure. Solid propellants have the advantage over the liquids that they are easy to handle and can be prepared instantly. However, high temperatures and high pressures may cause the solid grains to crack. So it must be kept in mind that they should be kept at the specific temperature and pressure.

2.5.1 Solid Propellant Types

Basically, there are 2 types of Solid Propellants

- Double Based Solid Propellants
- Composite propellants

These are briefly discussed below

2.5.1.1 Double Based Solid Propellants

These are composed of:

- Nitrocellulose
- Nitroglycerine
- Additives

The main difference between these two types is the separation of fuel and oxidizer.

In this type, the fuel and oxidizer are not separate from each other.

2.5.2 Composite Propellants

Here the oxidizer and fuel are separately used and then mixed with each other in order to compose a grain. The oxidizers that are usually used are listed below

- Ammonium Nitrate
- Potassium Chlorate
- Ammonium Chlorate

The fuels are listed below:

- Hydrocarbons
- Asphaltic-type compounds
- Plastics

3 CHAPTER 03

METHODOLOGY

In our project the first step was the selection of propellant based on the design points. The software used for the selection of propellant pair are CPropep and Propep. After the selection of the propellant pairs, we did the testing of these propellants pairs and shortlisted the propellant pairs from the observation made after the testing. After that we would select the suitable ignitor for our propellant pair because at stoichiometric O/F, there is maximum combustion efficiency but as our composition is low temperature fuel rich so we need some type of igniter for the best combustion performance. After selecting the suitable propellant and suitable ignitor for our torch, the designing and the fabrication of the grain would be carried out and the samples of the fabricated propellant grain would be tested along with the ignitor. Grain would be fabricated using different formulas and MATLAB codes. Next step would be the designing and development of the nozzle and the combustion chamber. Based upon different pressure values, nozzles with different throat diameters would be designed and fabricated. After that we would design and fabricate our test bed that would be used for the temperature and pressure measurement. For the fabrication of the test bed we would first select the sensors that would be used to measurement of temperature and pressure. After that we have to select the software that are used to display the display the readings of pressure and temperature obtained after testing of the ignition torch. And finally after the assembly, the final testing of the solid propellant based ignition would be carried out. Following is the flow chart summarizing the procedure of our working.

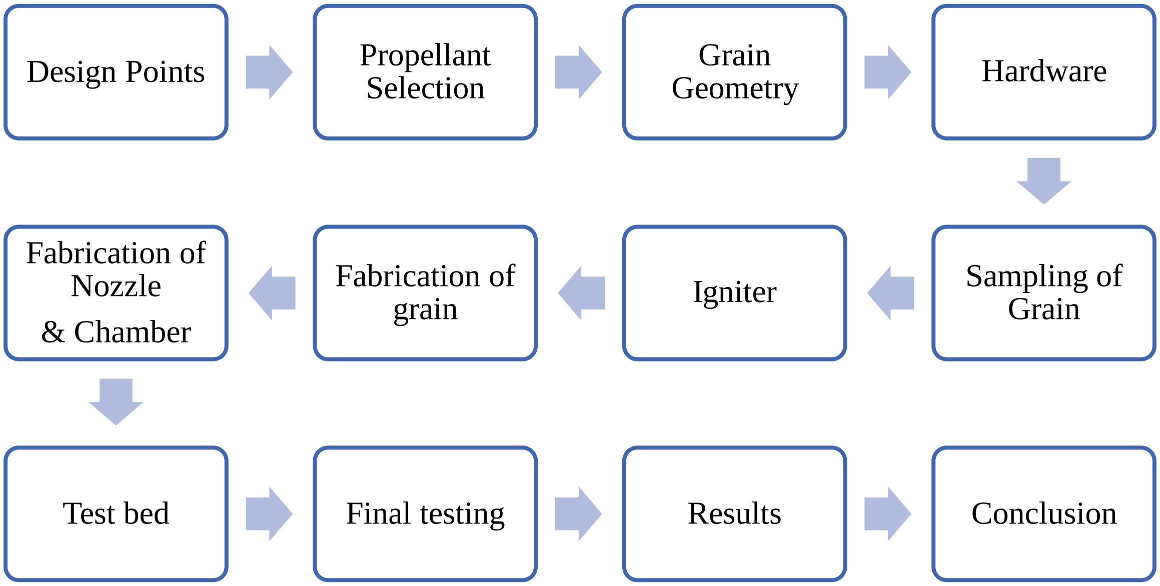

Figure 3.1 Methodology

3.1 Work Flow Diagram

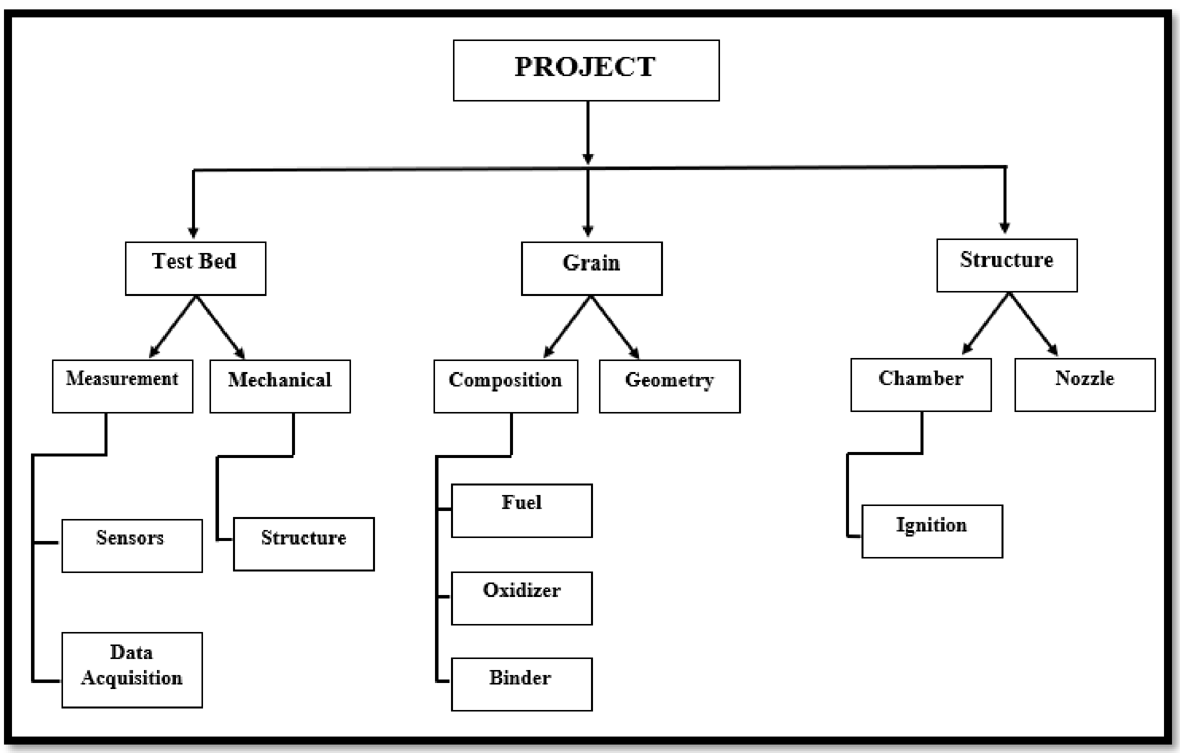

Figure 3.2 Work Flow Chart

4 CHAPTER 04

POPELLANT SELECTION

4.1 Propellant:

A propellant is a chemical material that is used for the production of energy or pressurized gas that is subsequently used to create movement of a fluid or to generate propulsion of a vehicle, projectile, or other object. Modern solid propellants have three basic components: an organic elastomeric binder, a solid oxidizer, and a metallic fuel additive.

4.1.1 Propellant Elements

Solid propellants comprises of three main ingredients:

i. Fuel
ii. Oxidizer
iii. Binder

Two, or even three, of these may be contained in the same material. Nitrocellulose is an example of all three, when colluded. The brief explanation of these elements is given below.

4.1.1.1 Fuel

A fuel is something that can burn in the presence of air. The source of oxygen for fuel is oxidizer. Normally used propellant for composite solid propellants is Powdered Aluminum. Other used fuels are boron, sucrose, mixture of carbon and sulfur and HTPB.

4.1.1.2 Oxidizer

An oxidizer is a chemical that is used to oxidizes another chemical or substance. Oxidizers normally used for composite solid propellants are Ammonium Perchlorate (AP), Potassium Nitrate (KNO_3) and ammonium nitrate.

4.1.1.3 Binder

The binder a chemical that binds the fuel and oxidizer together to form a cohesive whole by the process known as cohesion.

4.2 Selection of Propellant

4.2.1 Aluminum/Ammonium Perchlorate

Table 4.1 Al / AP

AP (Oxi)	Al (Fuel)	O/F	Temp
20	25	0.8	2362.253
18	27	0.666667	2296.12
16	29	0.551724	2287.851
13	32	0.40625	2264.244
10	35	0.285714	2217.206
8	37	0.216216	2145.901
6	39	0.153846	2004.164
5	40	0.125	1797.922

4.2.1.1 Graph of Al/AP

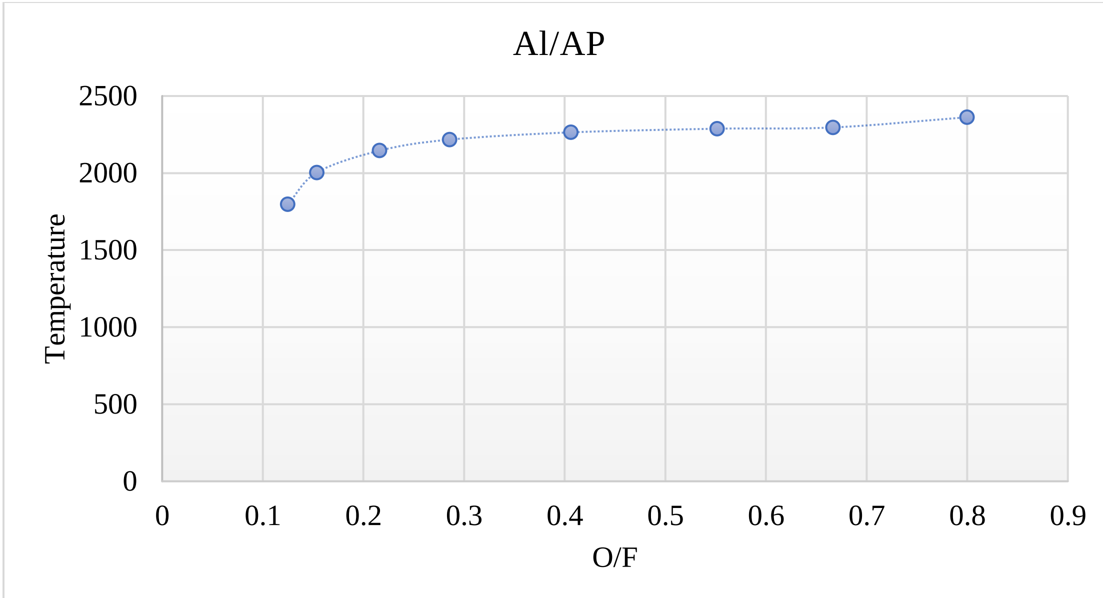

Figure 4.1 Al/AP

4.2.2 Aluminum / Potassium Nitrate

Table 4.2 KNO_3/Al

KNO_3	**Al**	**O/F**	**Temp. (°C)**
18g	27g	0.667	2671.68
16g	29g	0.551	2653.61
13g	32g	0.406	2589.32
10g	35g	0.285	2302.67
8g	37g	0.216	2012.04
6g	39g	0.153	1451.36
4g	41g	0.097	974

4.2.2.1 Graph of KNO_3/Al

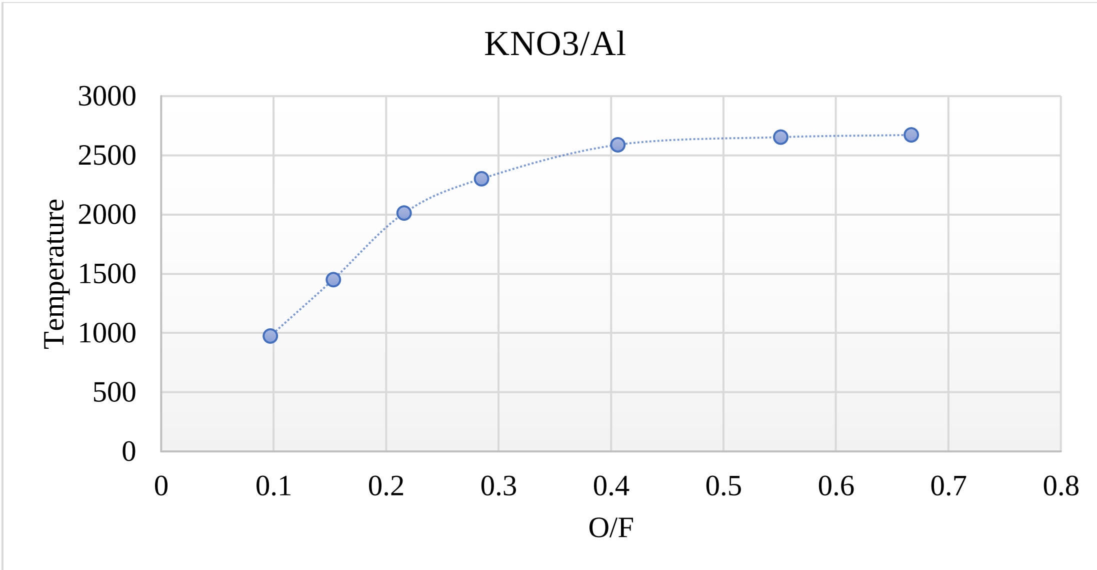

Figure 4.2 KNO_3/Al

4.2.3 Boron / Ammonium Perchlorate / HTPB

Table 4.3 Boron / AP

AP (Oxi)	Boron (Fuel)	O/F	Temp
21	25	0.84	2068.396
18	28	0.642857	2024.474
16	30	0.533333	1975.829
12	34	0.352941	1763.322
10	36	0.277778	1565.749
8	38	0.210526	1331.316
6	40	0.15	1084.779
5	41	0.121951	959.318
4	42	0.095238	832.125

4.2.3.1 Graph of Boron/AP

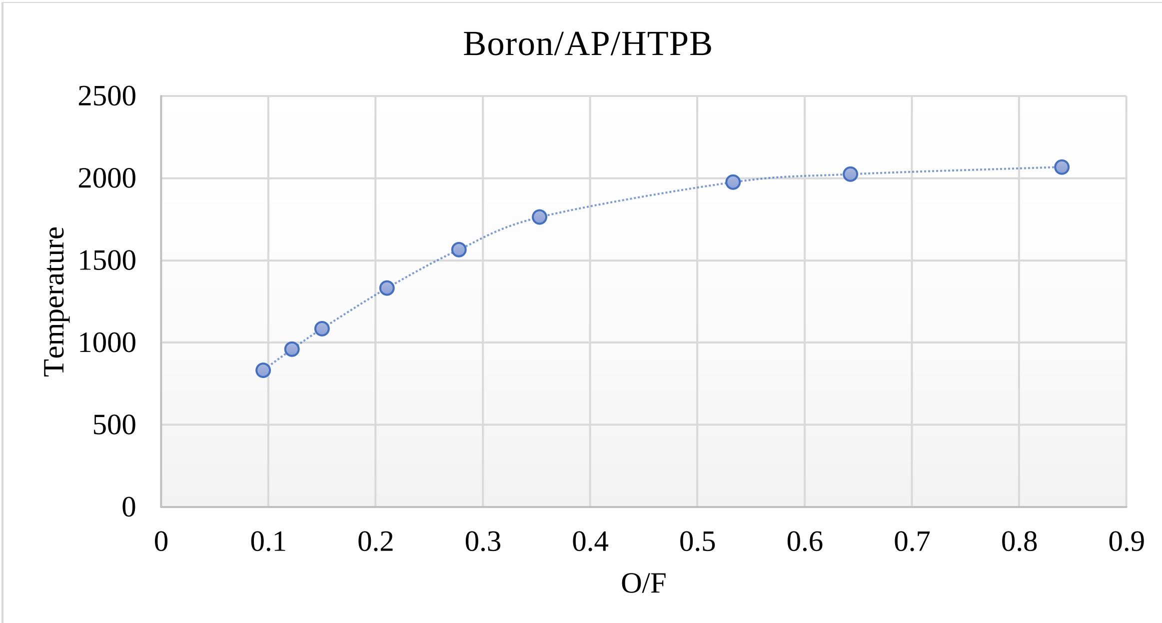

Figure 4.3 Boron / AP

4.2.4 Sucrose / Potassium Nitrate

Table 4.4 Sugar / KNO3

KNO3	Sucrose	O/F	Temp
21	24	0.875	798.329
19	26	0.730769	778.319
16	29	0.551724	748.329
13	32	0.40625	717.7072
11	34	0.323529	696.5713
8	37	0.216216	663.2519
6	39	0.153846	639.6225

4.2.4.1 Graph of Sugar/KNO_3

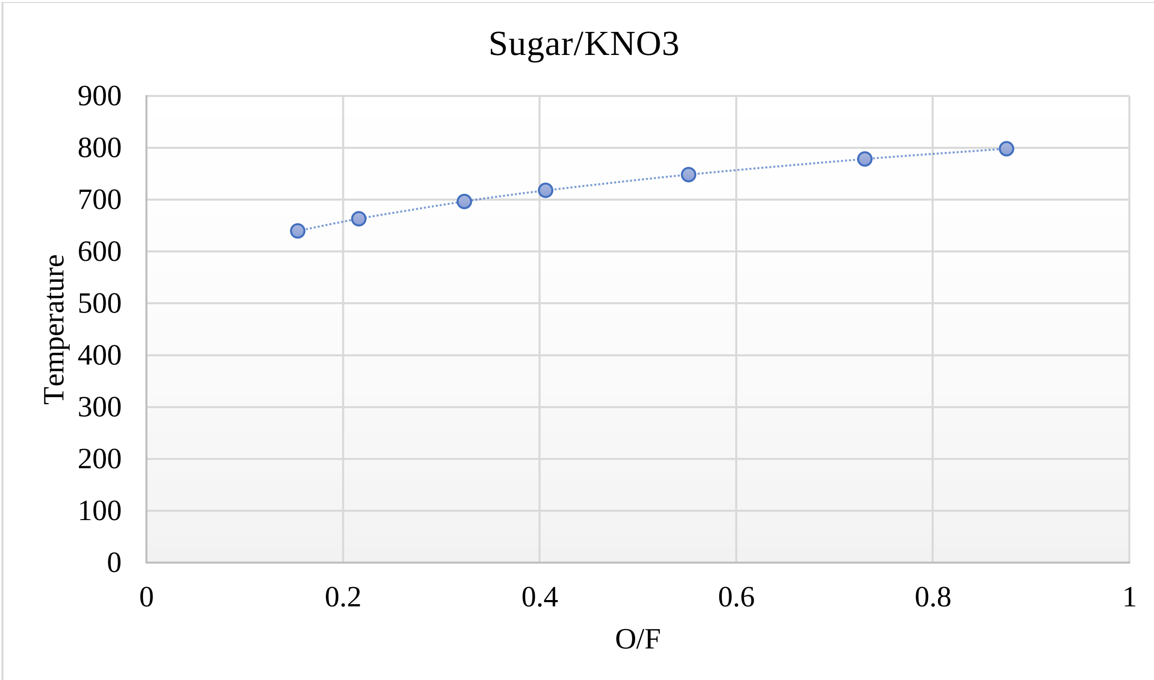

Figure 4.4 Sugar / KNO_3

4.2.5 Sucrose / Ammonium Perchlorate

Table 4.5 Sucrose / AP

AP	Sugar	O/F	Temp. (°C)
21g	24g	0.875	965.34
19g	26g	0.73	867.75
16g	29g	0.551	812.7
13g	32g	0.406	781.18
11g	34g	0.323	758.62
8g	37g	0.216	721.18
6g	39g	0.153	692.72

4.2.5.1 Graph of Sucrose / AP

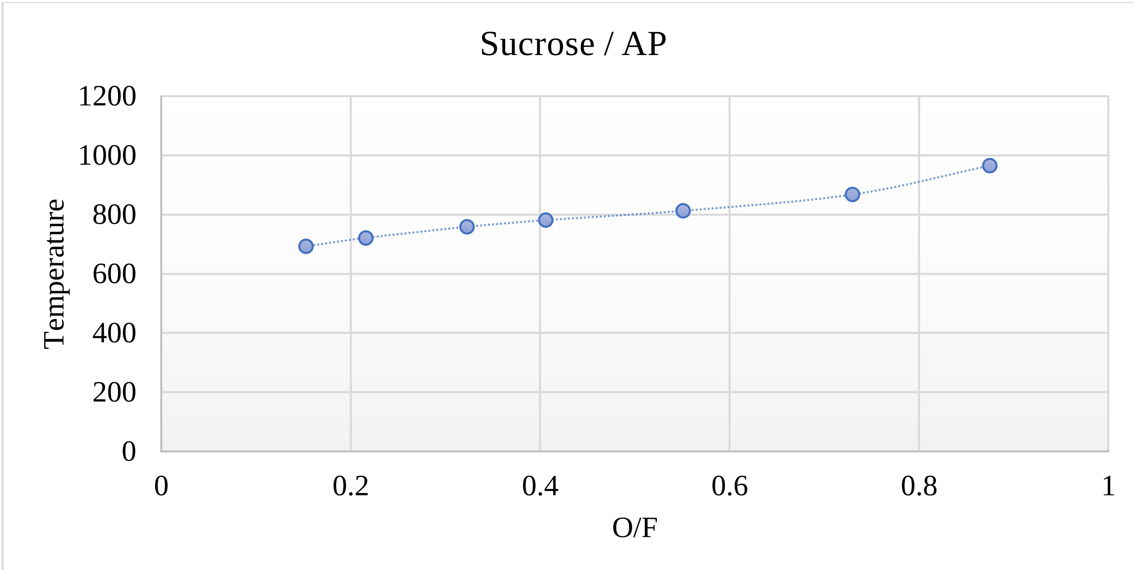

Figure 4.5 Sucrose / AP

4.2.6 Gun Powder

Table 4.6 Gun Powder

KNO3 (Oxi)	C+S (Fuel)	O/F	Temp
41.66	(5.56+2.78)	4.9952	2042.99
38.66	(7.56+3.78)	3.409	1714.489
34	(11+5)	2.125	932.626
31	(13+6)	1.631578	909.466
26	(16+8)	1.08333	887.588
23	(18+9)	0.85185	867.399
17	(22+11)	0.515152	817.502
11	(26+13)	0.28205	714.8698
8	(28+14)	0.19047	581.2423

4.2.6.1 Graph of C/S/KNO_3

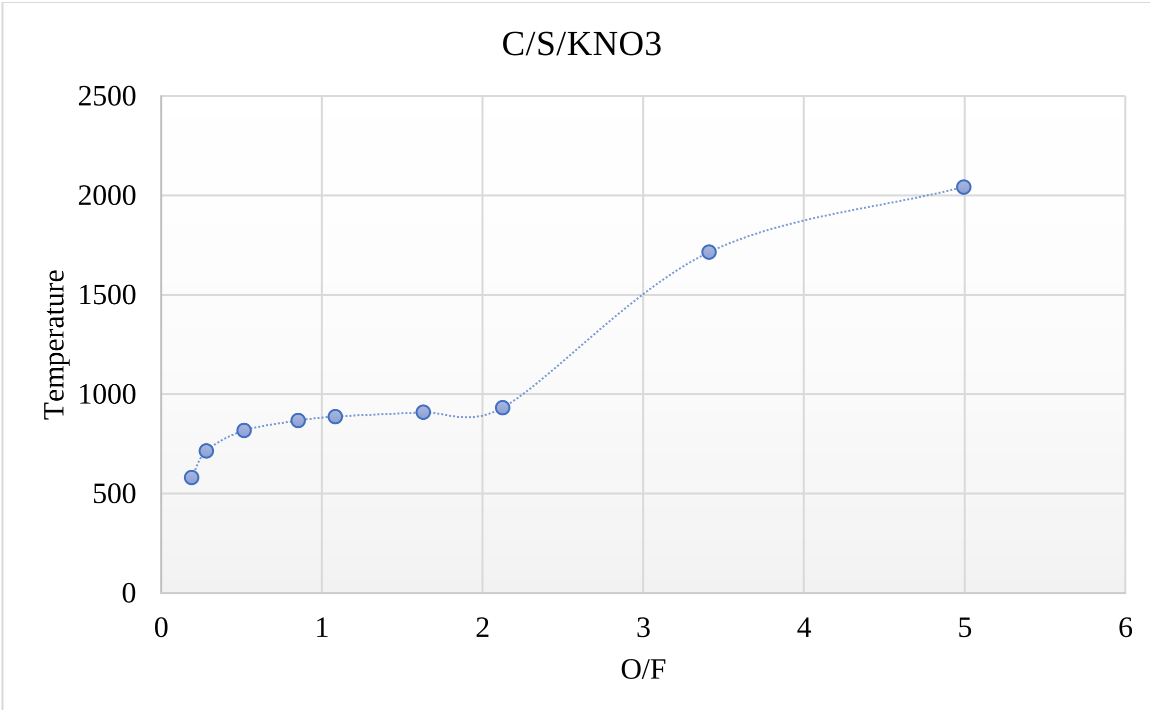

Figure 4.6 Gun Powder

4.2.7 Ammonium Perchlorate / HTPB

Table 4.7 AP/HTPB

HTPB	AP	O/F	Temp. (°C)
5g	5g	1	925.85
6g	4g	0.67	880.21
7g	3g	0.428	838.35
8g	2g	0.25	793.41

4.2.7.1 Graph of AP/HTPB

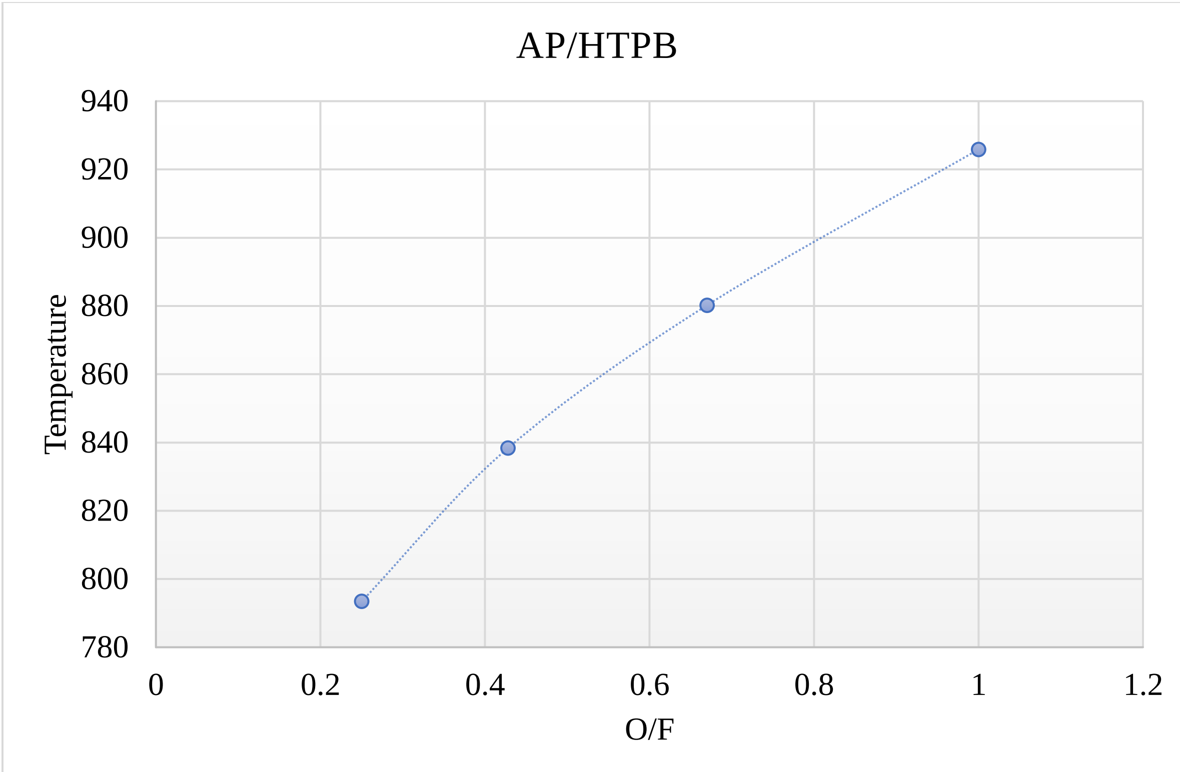

Figure 4.7 AP / HTPB

4.3 Testing of Propellant Pairs

After the selection of different propellant pairs, we tested these propellant pairs so that we can select propellant pair for our ignition torch. We observed the testing and residues of different propellant pairs and on the basis of these observations we selected our final propellant pairs.

The testing of different propellant pairs are shown below along with the observation made after the testing.

4.3.1 Aluminum / Ammonium Perchlorate

Figure 4.8 Testing of Al/AP

4.3.1.1 Comment

A reaction similar to firecracker was observed but the temperature obtained in this case was very high.

4.3.2 Aluminum / Potassium Chlorate

Figure 4.9 Testing of Al / KNO_3

4.3.2.1 Comment

Again in this case, a reaction similar to firecracker was observed but the temperature obtained in this case was also very high compared to our temperature limit.

4.3.3 Boron / Ammonium Perchlorate / HTPB

Figure 4.10 Testing of Boron / AP / HTPB

4.3.3.1 Comment

Stable flame was observed in this case and the temperature was also within the range.

4.3.4 Sucrose / Potassium Nitrate

Figure 4.11 Sucrose / KNO_3

4.3.4.1 Comment

This propellant pair led to burning and the temperature calculated in this case was 798°C. This ultimately caused sugar to melt as its melting temperature is 186°C.

4.3.5 Sucrose / Ammonium Perchlorate

Figure 4.12 Sugar / AP

4.3.5.1 Comment

Also in this propellant pair, the sugar got melted.

4.3.6 Gun Powder

Figure 4.13 Gun Powder

4.3.6.1 Comment

It was observed that the burning was stable but the visible residue was left behind.

4.3.7 Ammonium Perchlorate / HTPB

Figure 4.14 AP / HTPB

4.3.7.1 Comment

Again a reaction similar to firecracker was observed but for this propellant pair the temperature was also in our given range.

4.4 Selected Propellant Pair

The selected propellant pair after selection from software and observation obtained from testing are given below:

Table 4.8 Selected Propellant Pair

Propellant Pair	O/F
AP + HTPB	0.428
Boron + AP + HTPB	0.721

5 CHAPTER 05

SELECTION OF GRAIN GEOMETRY

5.1 Grain Geometry

The composition of composite solid propellants is very complex compared to other solid propellants. Composite solid propellants are the mixture of separate fuel and oxidizer along with small quantities of other chemicals such as curing agent, plasticizer and binding agent. All these chemicals are then mixed and processed in order to give them specific geometric form. These specific geometric shapes in which the propellants are processed is called grain geometry.

There are different types of grain geometries that greatly influence the thrust-time profile curve. Different grain geometries are given below:

5.1.1 End burn grain

End burn grain is the grain which is in the form of cylinder. It is also called cylindrical grain. In end burn grain the pressure is constant through out the length of the grain. Normally, solid propellant grains are cylindrical in shape because of 3 reasons:

- Fit perfectly in the rocket
- Easy to fabricate
- Have maximum volumetric efficiency

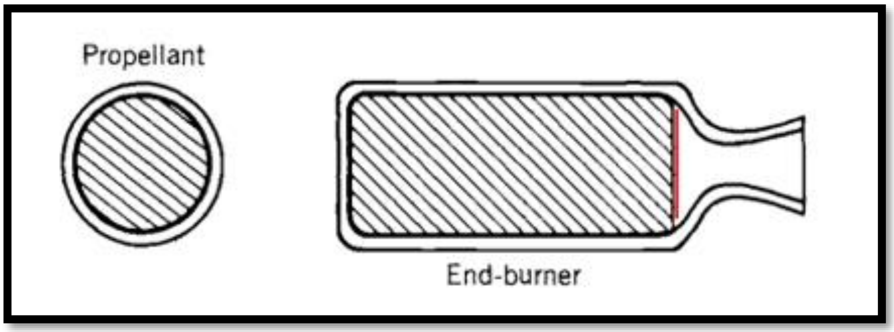

Figure 5.1 End burn grain

5.1.2 Tubular grain

Hollow cylindrical grain is called tubular grain. Tubular grain provides progressive burn which means that with time thrust increases. In tubular grain, the burning is from inner surfaces towards the outer surfaces.

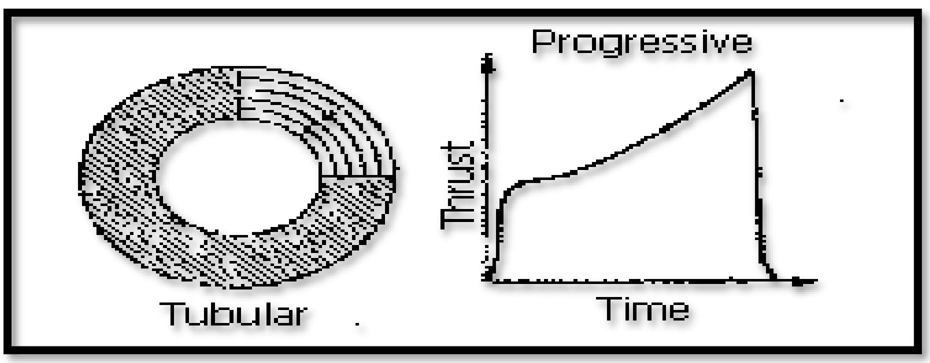

Figure 5.2 Tubular grain

5.1.3 Rod and tube grain

In this type of grain the core is in the form of rod and tube. Rod and tube grain gives a perfectly neutral burn which means that thrust is constant through out the burning of the propellant grain.

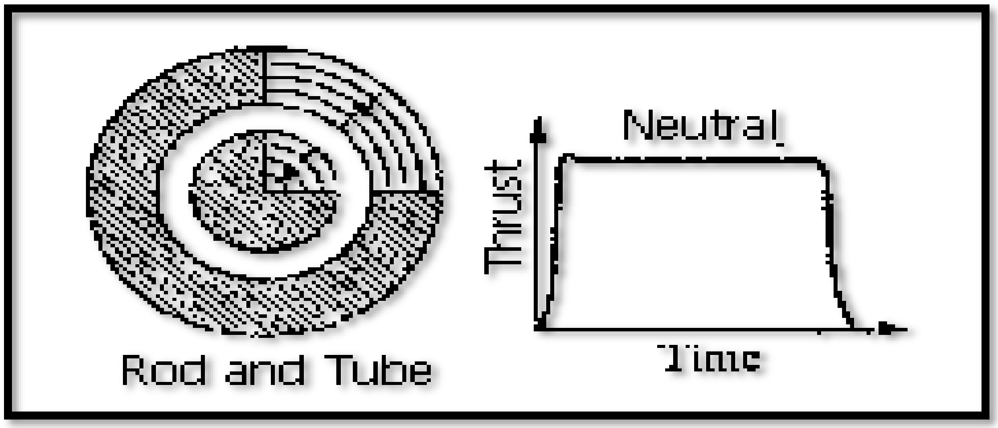

Figure 5.3 Rod and tube grain

5.1.4 Star grain

The core of star grain is in the form of star and the burning is almost neutral but not perfectly neutral which means that thrust is almost constant with time.

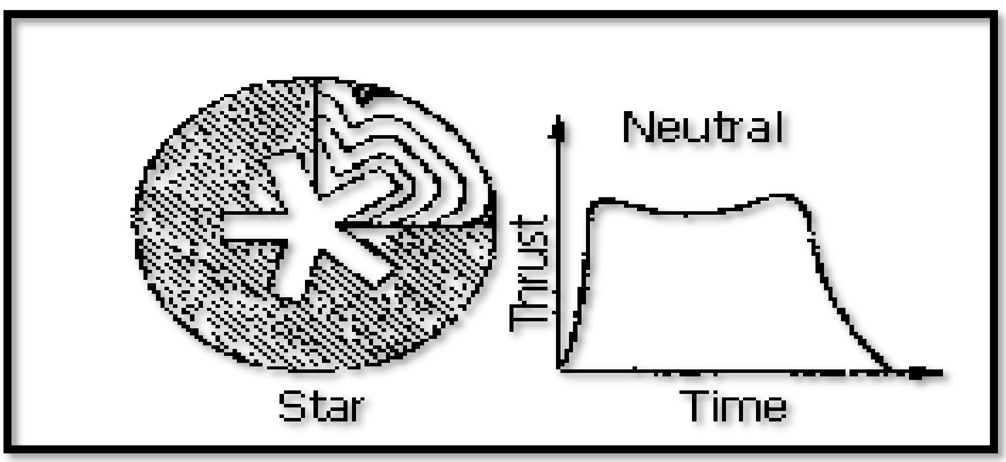

Figure 5.4 Star grain

5.1.5 Double Anchor grain

The double anchor grain provides regressive burn which means that thrust decreases with time.

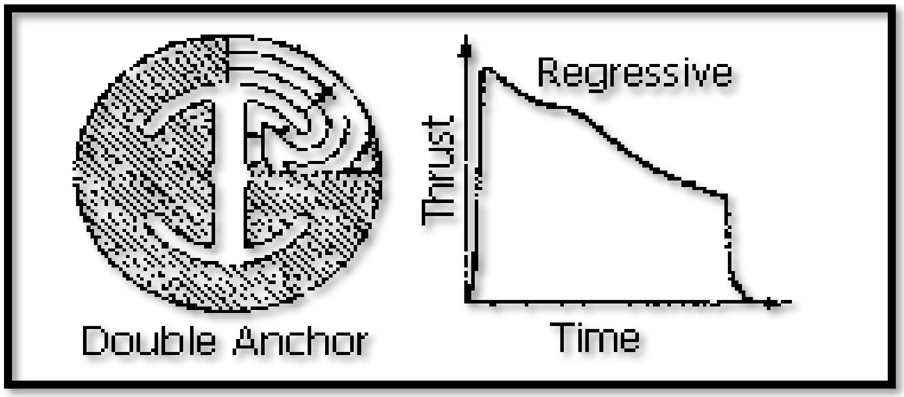

Figure 5.5 Double anchor grain

5.2 Selected Propellant Grain

On the basis of the burning patterns of grain and the thrust behavior, we selected end burn grain as our final grain geometry.

6 CHAPTER 06

SAMPLING OF GRAIN

After selecting the propellant pairs and grain geometry, we made samples of the propellant pairs with selected grain geometry and tested those samples.

6.1 Hardware

For the sampling of grain, following hardware is required:

6.1.1 Chemicals

List of the chemicals that are required to make the sample of the grains are given below:

Table 6.1 Chemicals

Chemicals	
Fuel	Boron and HTPB
Oxidizer	Ammonium Perchlorate
Curing Agent	Toluene Di-isocyanate (TDI)
Plasticizer	Dioctyl sebacate (DoS)
Binding Agent	Methyl aziridinyl phosphine oxide (MAPO)

6.1.2 Weight Balance

Digital weight balance is used to measure the weights of chemicals that are used for samples.

Figure 6.1 Weight Balance

6.1.3 Petri dishes and Beakers

Petri dishes and beakers are used for the mixing of samples.

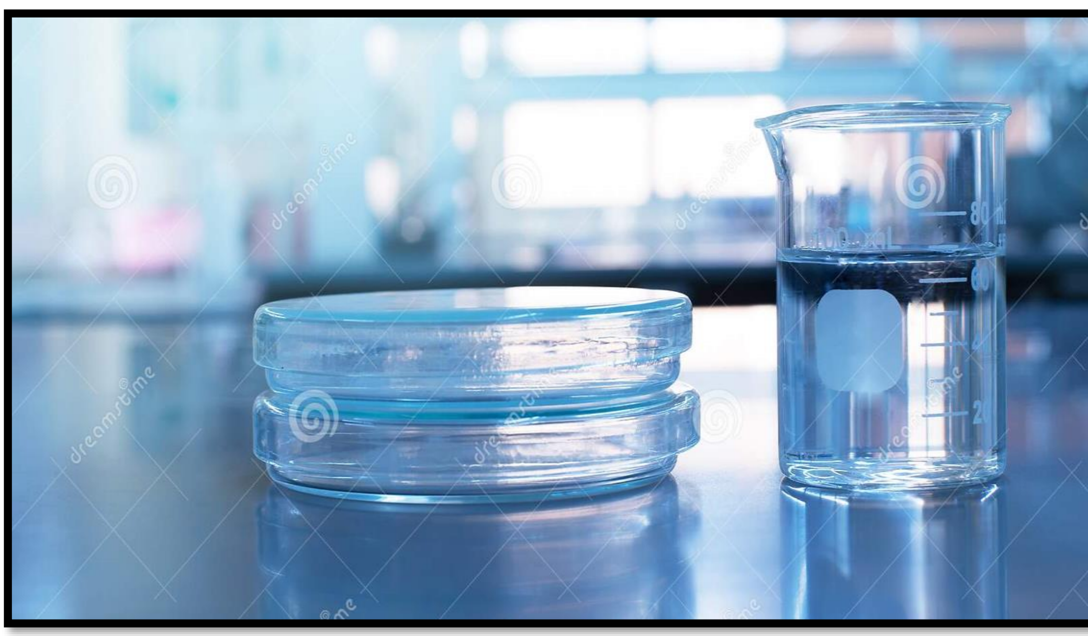

Figure 6.2 Petri dishes and Beakers

6.1.4 Mechanical Mixer and Hot plate

Mechanical mixer is used to mix all the chemicals together and hot plate is used to heat up the mixture so that the mixing is easy.

Figure 6.3 Mechanical mixer and Hot plate

6.1.5 Oven

After mixing the samples, we put the mixtures in the oven for curing.

Figure 6.4 Oven

6.1.6 Spark Plug

Spark plug is used for the testing of samples.

Figure 6.5 Spark plug

6.2 Procedure

First of all we measured the quantity of chemicals depending on their selected O/F using the digital weight balance. To mix these chemicals we used beakers, petri dishes, mechanical mixer and a hot plate. And after mixing we molded the mixture into the selected grain geometry i.e. end burn grain. Finally, we put the mixtures in oven for curing for about 7-8 days. And after the curing period we observed our grain samples and did testing.

6.3 Chemical Reaction of Mixing

6.3.1 Structural Formulae of the chemicals used

6.3.1.1 Hydroxyl-terminated polybutadiene (HTPB)

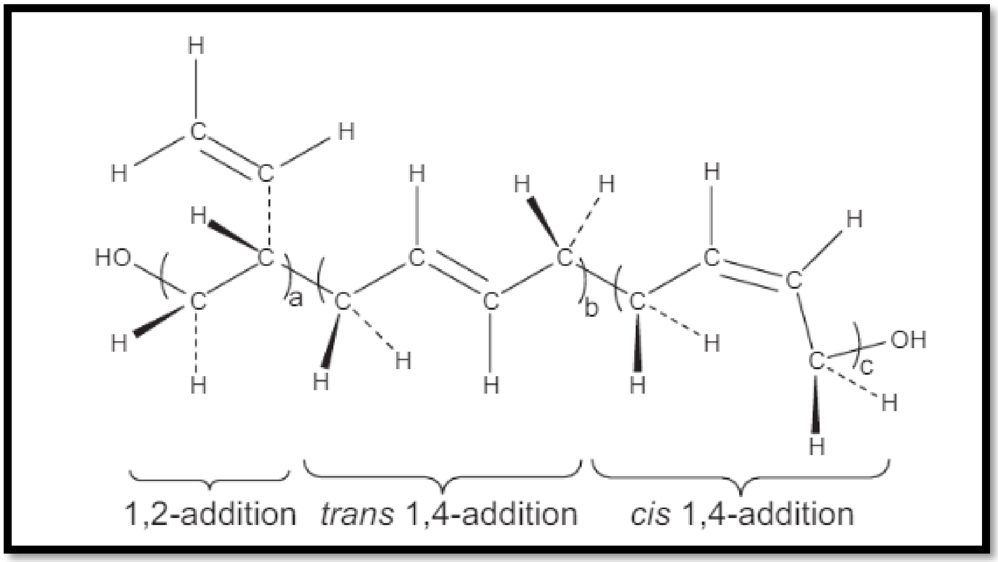

Figure 6.6 Hydroxyl-terminated polybutadiene (HTPB)

6.3.1.2 Toluene di-isocyanate (TDI)

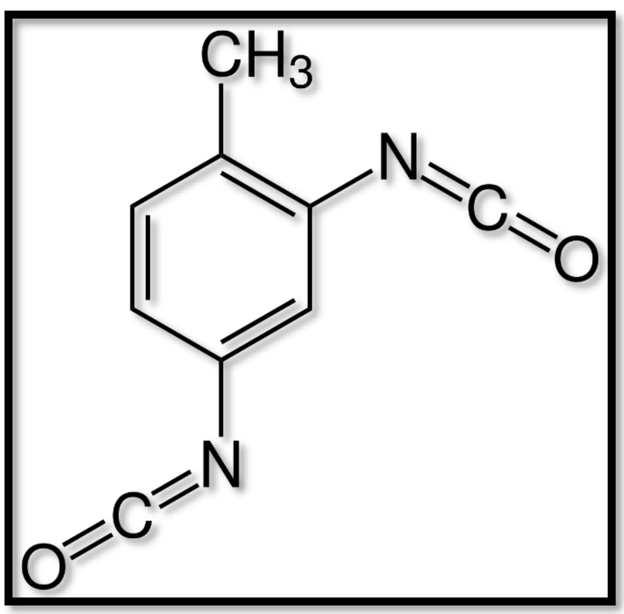

Figure 6.7 Toluene di-isocyanate (TDI)

6.3.1.3 Dioctyl sebacate (DoS)

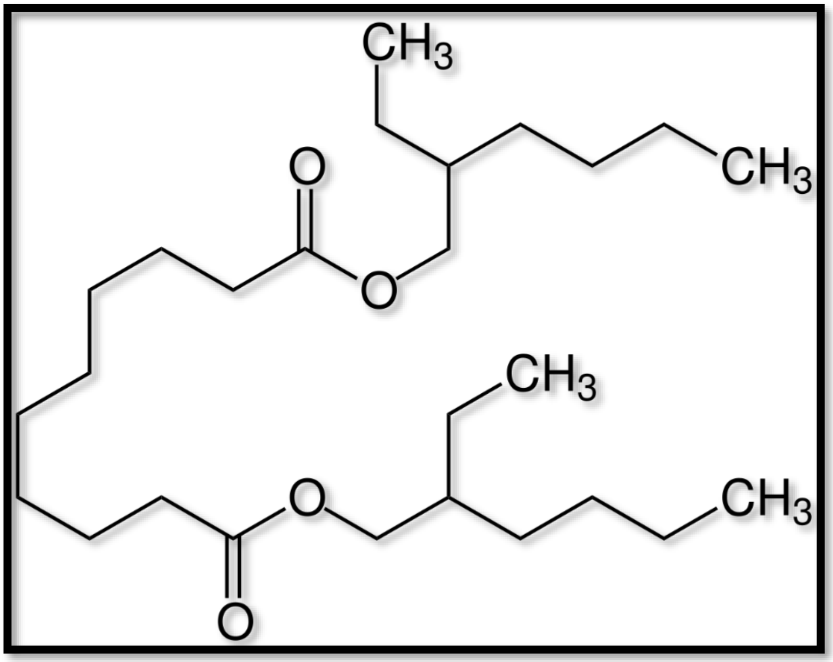

Figure 6.8 Dioctyl sebacate (DoS)

6.3.1.4 Methyl aziridinyl phosphine oxide (MAPO)

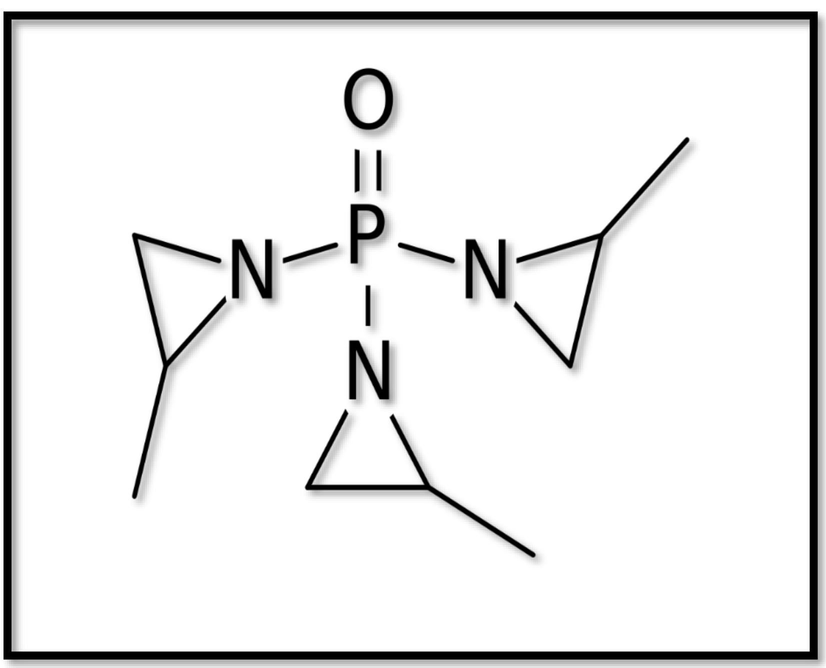

Figure 6.9 Methyl aziridinyl phosphine oxide (MAPO)

6.3.2 Chemical Reaction

Composite propellants consist of fuel and oxidizer in the form of powder that are mixed with polymeric binder to form the propellant grain. During the mixing, Hydroxyl Terminated Poly Butadiene (HTPB) reacts with Toluene Di-Isocynate (TDI) to form polyurethane (PU) network. The characteristics of polyurethane depends on the ratio of cyanate/hydroxyl (NCO/OH) groups, temperature and time of the mixing.

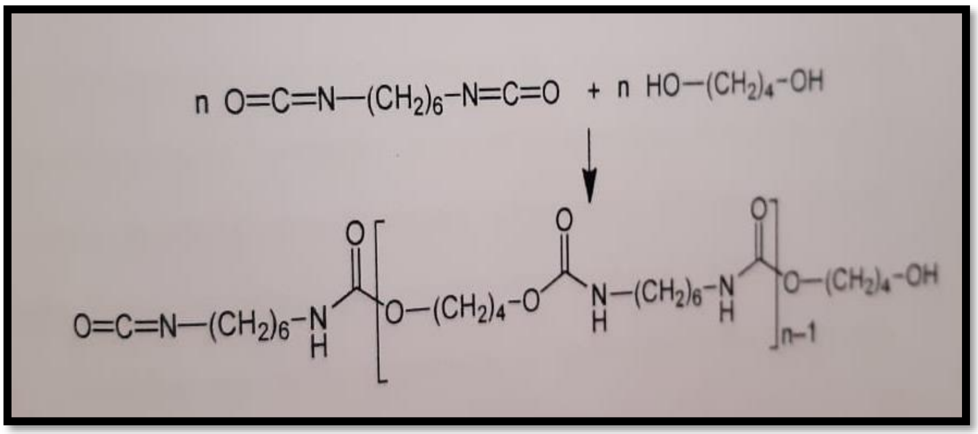

Figure 6.10 Chemical Reaction of Mixing

6.4 Observations

6.4.1 Coarse Modal

Table 6.2 Coarse Modal

Size of AP	Observation	Combustion Performance
60 µm	Segregated	Poor

6.4.1.1 Observation of Coarse Modal

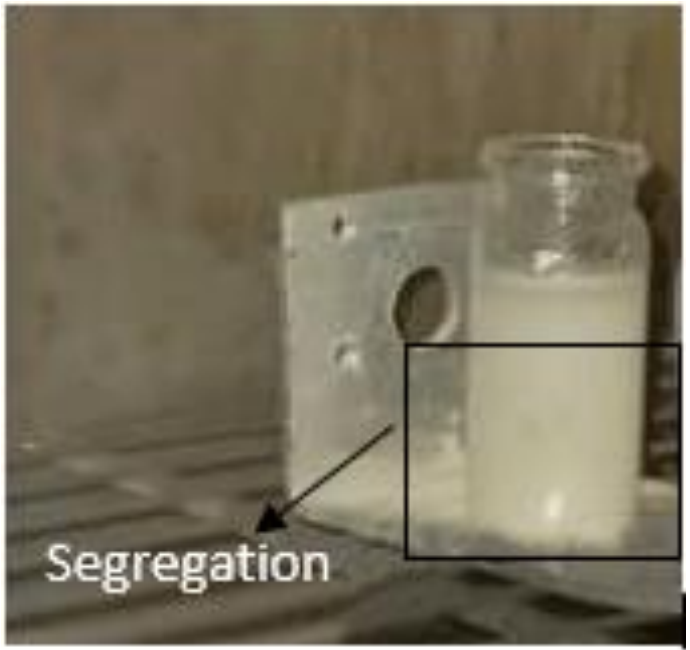

Figure 6.11 Coarse Modal

We observed that AP got segregated in the sample and was not combustible.

6.4.2 Ultra-fine Modal

After the observation of coarse modal, we made another sample with ultra-fine AP and plasticizer was also excluded this time.

Table 6.3 Ultra-fine Modal

Size of AP	Observation	Combustion Performance
10 µm	Didn’t Segregate	Good

6.4.2.1 Observation of Ultra-fine Modal

Figure 6.12 Ultra-fine Modal

It was observed that the sample did not segregate at all in the sample.

6.4.2.2 Testing of Ultra-fine Modal

Figure 6.13 Testing of Ultra-fine Modal

6.4.3 Fine Modal

Due to unavailability of 10 μm sized AP, we made another sample using fine modal of AP in which the size of AP is 40 μm.

Table 6.4 Fine Modal

Size of AP	Observation	Combustion Performance
40 μm	Segregated but not much	Fair

6.4.3.1 Observation of Fine Modal

We observed that it segregated but not as much as in the first case in which coarse tri-modal was used.

6.4.3.2 Testing of Fine Modal

We observed that it is combustible but the combustion performance is fair. For the better combustion we needed an igniter.

7 CHAPTER 07

IGNITER

Igniter is a something that is used to initiate the combustion of something.

- **Why Igniter?**

  At stoichiometric O/F, combustion generates the most heat possible, and maximum combustion efficiency is achieved. But as our composition is low temperature fuel rich so we need some type of igniter for the best combustion performance.

7.1 Selection of Ignitors

7.1.1 AP + Al + Matchstick Powder

First of all we used fine mixture of ammonium perchlorate, aluminum and matchstick powder but we observed that there was a blast.

7.1.2 Charcoal + Sulphur + AP

After the blast of AP + Al + matchstick powder, we decided to change the composition. Then we used mixture of charcoal, Sulphur and ammonium perchlorate as ignitor but it didn’t even caught fire.

7.1.3 Glycerin + Matchstick Powder

After the failure of C / S / AP, we made different composition of glycerin and matchstick powder with different ratios of glycerin. It was observed that it caught fire but the flame was not stable and it was not strong enough to start the ignition of the propellant grain.

7.1.4 Kerosene based gel + Matchstick Powder

Again after the failure we made another igniter mixture that was the combination of kerosene based gel and matchstick powder. And with this igniter mixture it was observed that it was perfect for our propellant grain.

7.1.5 Matchstick Powder

Matchstick powder was also a very good igniter. It gave stable flame and also was able to initiate the combustion in our propellant grain.

7.2 Selected Igniters

Based on the observation discussed above, we selected 2 best igniters that are suitable for our propellant grains. List of the selected propellants are given below:

Table 7.1 Selected Ignitors

Sr. no	Igniter Composition	Observations
1	Kerosene based gel + Matchstick Powder	Stable Burning
2	Matchstick Powder	Stable Burning

7.3 Schematics of Sample testing along with Ignitor

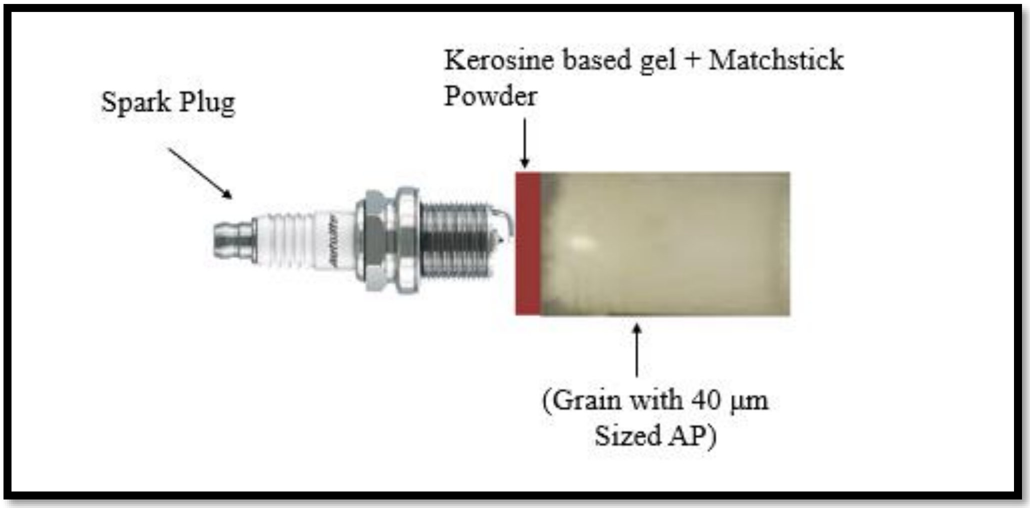

Figure 7.1 Schematic diagram for testing

7.4 Sample testing along with Igniter

The following figure shows the sample testing of sample grain along with the ignitor.

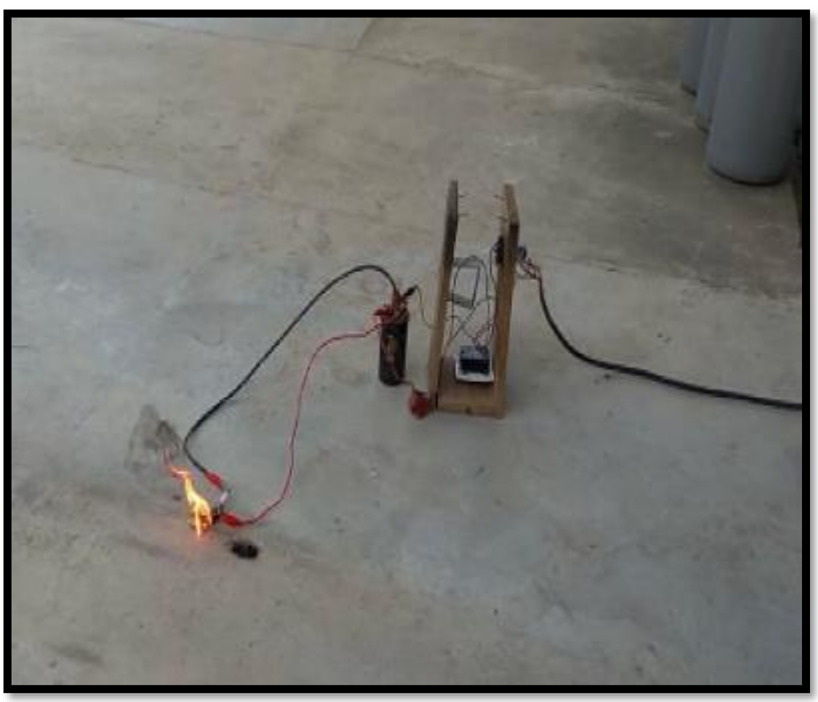

Figure 7.2 Sample testing along with Igniter

8 CHAPTER 8

GRAIN FABRICATION

This chapter is about the grain fabrication. Before the grain fabrication, a lot of testing was done for the propellant selection. Multiple tests were performed on the small level in order to pick out the best propellant that would fit all our requirements. For this purpose, initially the CProp and Propep3 software were used. A lot of propellant pairs were shortlisted. After that, the tests were performed on the basis of which a few propellant pairs were selected and shortlisted. The next step was the selection of the grain geometry. Studying from the literature review, the best and most appropriate grain geometry was selected which had good properties as well as it was easy to fabricate. After grain geometry selection, the samples of the selected propellant pairs were made. Then igniter was selected. Long story short, the best propellant pairs and igniters were selected and then we moved to the next step, which is the Grain fabrication. These were the final major samples upon which the testing was to be performed. The finalized propellant pairs were as follows:

Table 8.1 Selected Propellant

Propellant Pair	**O/F**
AP + HTPB	0.428
Boron + AP + HTPB	0.721

8.1 Dimensions

Total of the 5 grain samples were fabricated. Based upon the different mathematical formulas and MATLAB codes, total 5 samples were fabricated having the following dimensions.

Table 8.2 Dimensions

Composition	No. of samples	Length	Diameter	Weight
AP + HTPB	3	48 mm	52 mm	120 g
AP + HTPB	1	85 mm	52 mm	224 g
Boron + AP + HTPB	1	74 mm	52 mm	132 g

Note: The calculations have been done through the MATLAB codes which have been added in the report in the bibliography portion. The following formulas have been used:

$$\dot{m} = \frac{P_C A_t}{C^*}$$

Where

$\dot{m}$=Mass flow Rate

P_C=Chamber Pressure

A_t=Throat Area

C^*=Characteristic Velocity

$$\dot{m} = r\rho A_b$$

Where

$\dot{m}$=Mass flow Rate

r=Burn Rate

ρ=Density

A_b=Burn Area

The process of fabrication was carried out in such a way that the both compositions (i.e., AP+HTPB and Boron + AP + HTPB) were taken and mixed in the required proportions which were based on our MATLAB calculations. The mixing was carried out in the mechanical mixer using hot plate as shown below. For grain shape, the coca cola tin cans were used. The reason behind this is that the diameter which we calculated came out to be equal to that of diameter of cola cans. The length of each was also observed. After putting in the tin cans, these cans were put in the oven for 7 days for curing. After 7 days, these samples were taken out and were ready for testing. A lot of segregation was observed in the samples though.

Figure 8.1 Mixing of the Chemicals

8.2 Segregation of the Sample

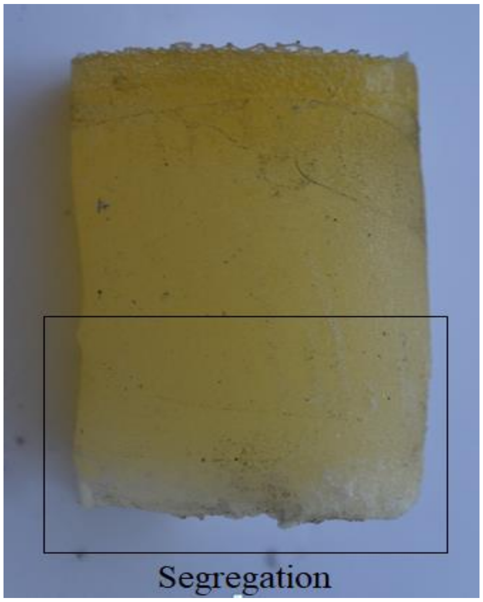

Figure 8.2 Segregation

This image shows that using 40 μm sized AP powder would result in the segregation of AP and HTPB. It was expected that some portion might remain unburned at the end of the testing in the nozzle due to bad mixing of the chemicals.

8.3 Fabricated Samples

The images of the 5 samples after fabrication are shown below:

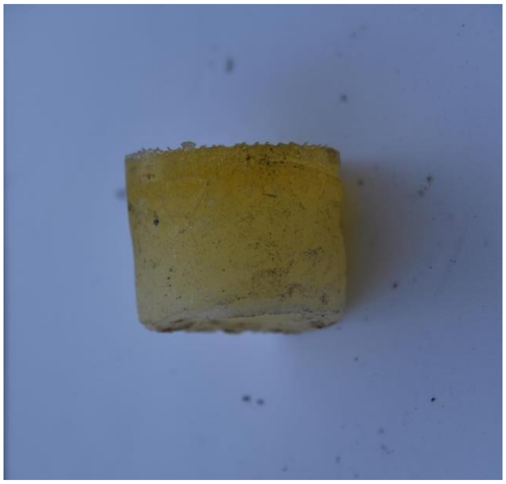

Figure 8.3 AP + HTPB (120 g)

Out of 5, 3 such samples were fabricated having the same dimensions i.e. having the length of 48 mm, diameter of 52mm and having the mass of 120 grams. The testing was carried out using these samples first followed by the boron sample and in the end another AP+HTPB composition sample having entirely different dimensions from these. The remaining samples are shown next.

Figure 8.4 Boron + AP + HTPB (132 g)

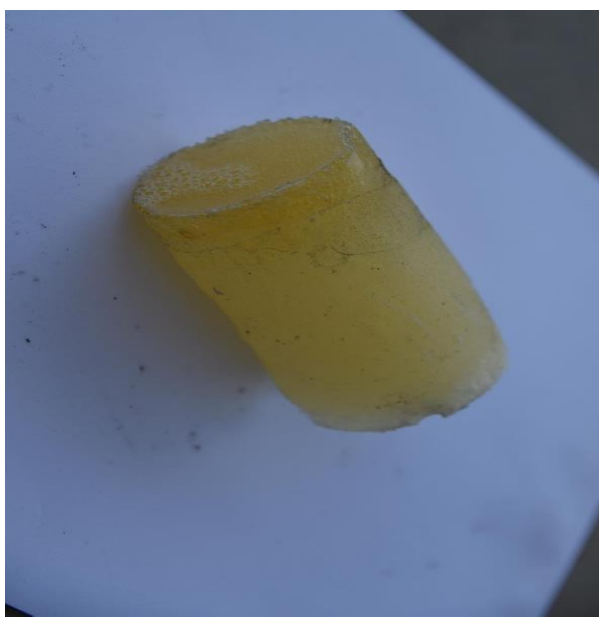

Figure 8.5 AP + HTPB (224 g)

9 CHAPTER 9

FABRICATION OF NOZZLES AND COMBUSTION CHAMBER

9.1 Nozzle Design

The converging diverging (CD) Nozzles are widely used in the rockets and proved to be best. The simple diagram of such nozzle is shown below.

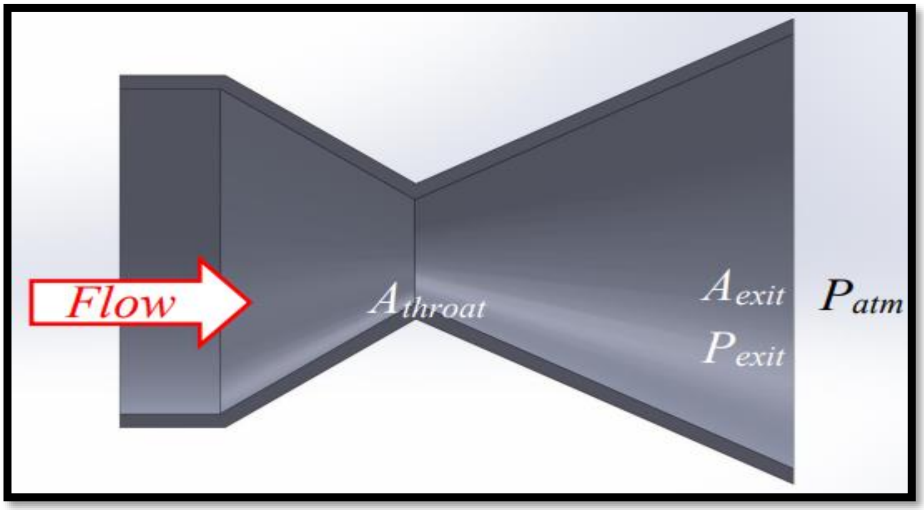

Figure 9.1 CD Nozzle

- In between the nozzle throat and the combustion chamber, the converging part of the nozzle is located. Here the mass flow rate is subsonic. For such mass flow rates, the velocity of the fluid varies inversely as the throat area of the nozzle.
- The next portion is the throat of the nozzle. Here the mass flow rate is sonic and is equal to the speed of the sound. The Mach number is 1 in this region and the flow is supposed to be choked.
- In between the nozzle throat area and the exit area, the diverging portion of the nozzle is located. Here the mass flow rate is supposed to be supersonic and Mach

number is greater than 1. So the fluid velocity and the throat size area vary directly to each other.

Based on different chamber pressure, 3 nozzles with different throat diameters are designed.

$$A_t = \frac{C * \dot{m}}{P_C}$$

- At 18 bar pressure, throat diameter is 3.5mm
- At 11 bar pressure, throat diameter is 4.5mm
- At 7.3 bar pressure, throat diameter is 5.5mm

9.1.1 2D Drawings of Nozzles

This is the 2D CATIA drawing of the Nozzle having 3.5 mm diameter throat.

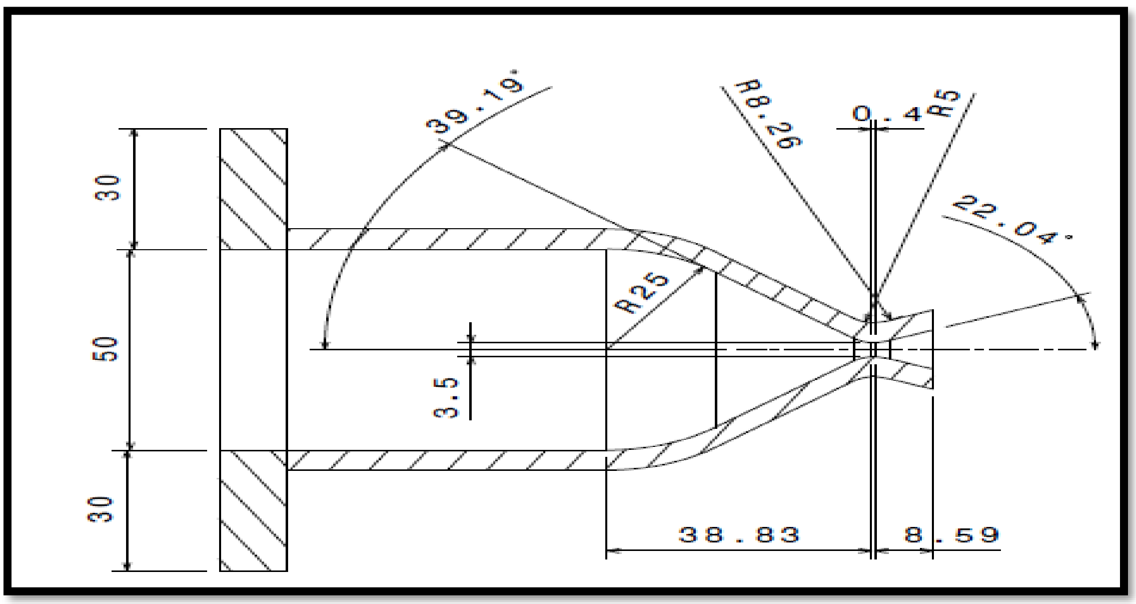

Figure 9.2 3.5 mm Throat diameter

This is the 2D CATIA drawing of the Nozzle having 4.5 mm diameter throat.

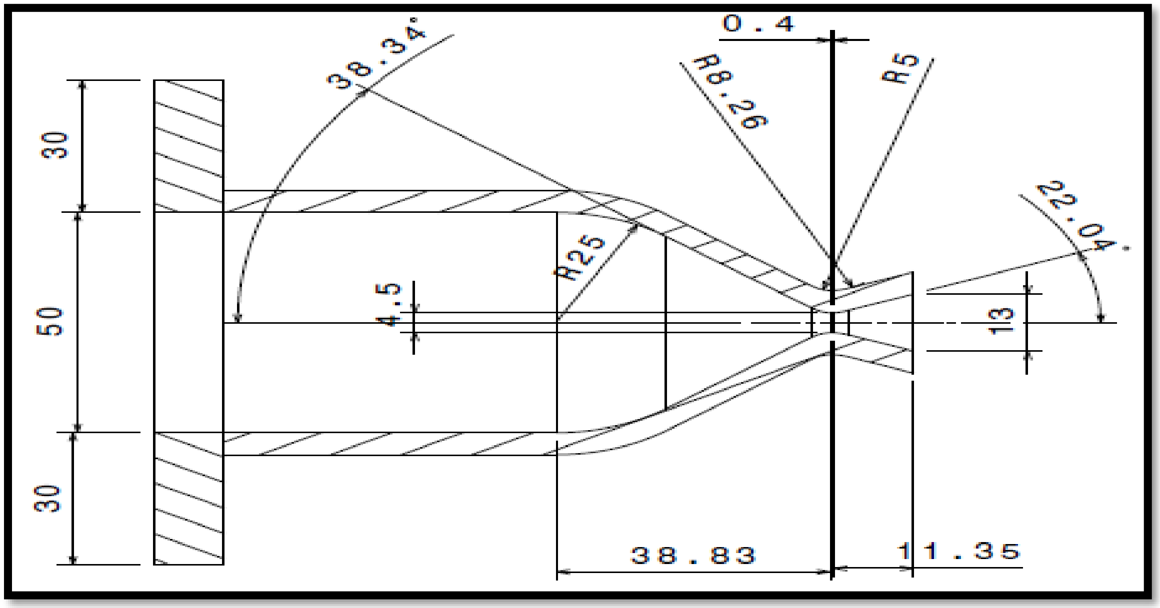

Figure 9.3 4.5 mm Throat diameter

This is the 2D CATIA drawing of the Nozzle having 4.5 mm diameter throat.

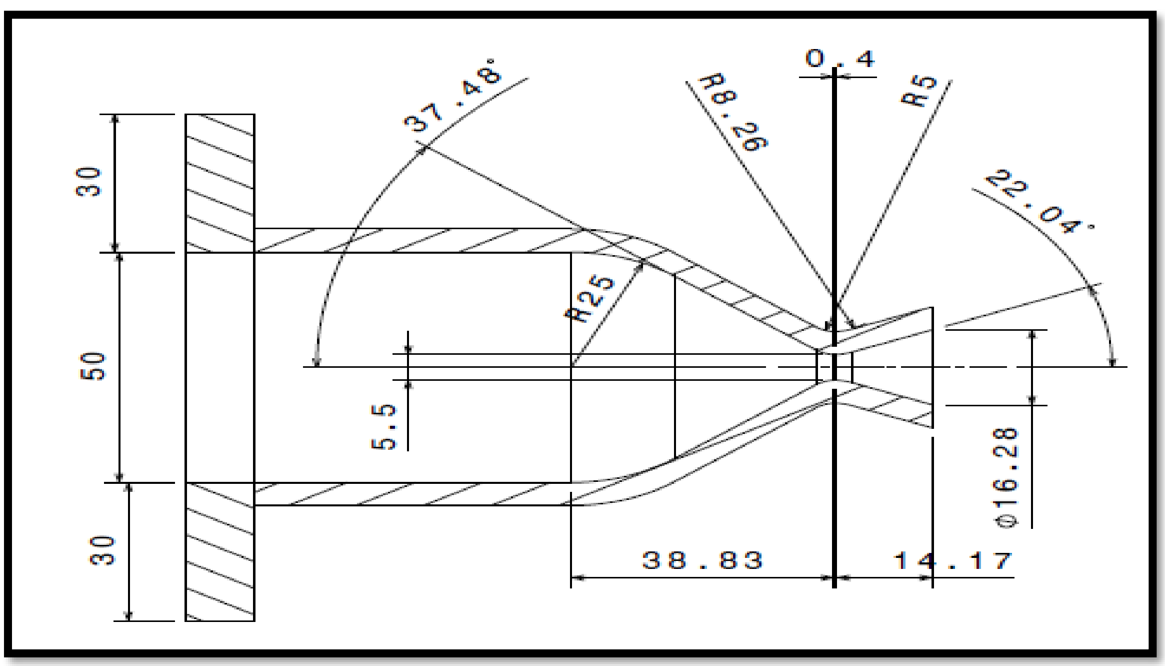

Figure 9.4 5.5 mm Throat diameter

9.1.2 Fabricated Nozzles

Figure 9.5 3.5 mm Throat diameter

Figure 9.6 4.5 mm Throat diameter

Figure 9.7 5.5 mm Throat diameter

9.2 Combustion Chamber Design

Combustion chamber is the portion in the rockets where the combustion of the propellant pair takes place. The diameter and the lengths are designed according to the dimensions of the grain designed. There are 3 different ports on the outside of the combustion chamber. A temperature port is for the measurement of the temperature. A pressure port is for the measurement of pressure. And the spark plug port for the ignition of the propellant pair. The propellant pair is placed inside the combustion chamber, where it is ignited by giving the electric supply through the ignition port. The pressure is created and temperature increases as a result. These temperature and pressure values are noted down with the help of thermocouple which is connected through the thermocouple port and pressure sensor which is connected to the pressure port respectively. The thermocouple gives the temperature values which are displayed on the computer screen using Arduino and the pressure values are displayed by using the Data Acquisition System (DAS).

9.2.1 2D Model of Combustion Chamber

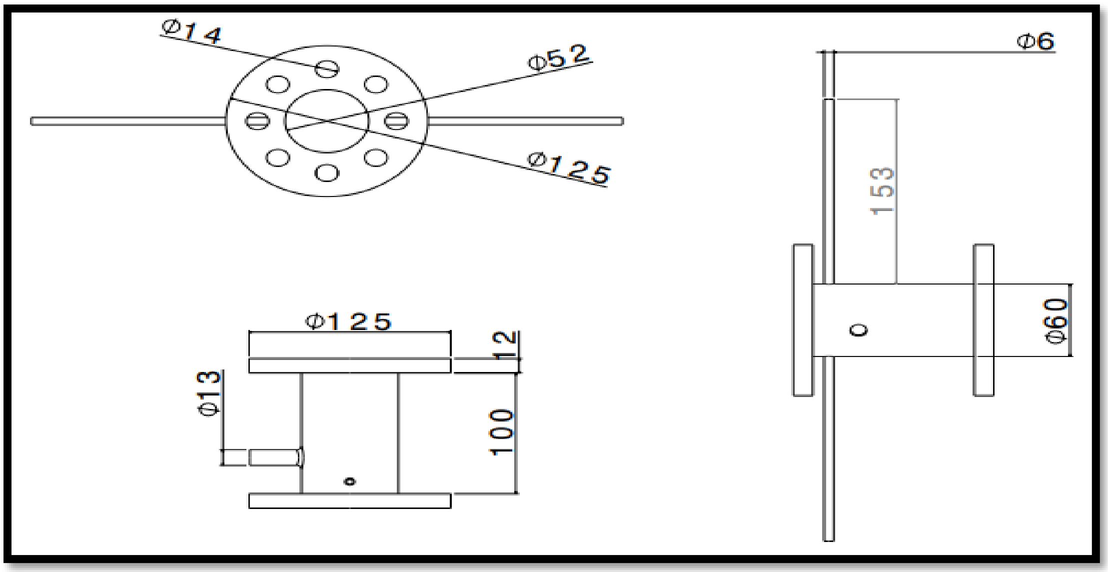

Figure 9.8 Combustion Chamber’s 2D Model

9.2.2 3D Schematic Model

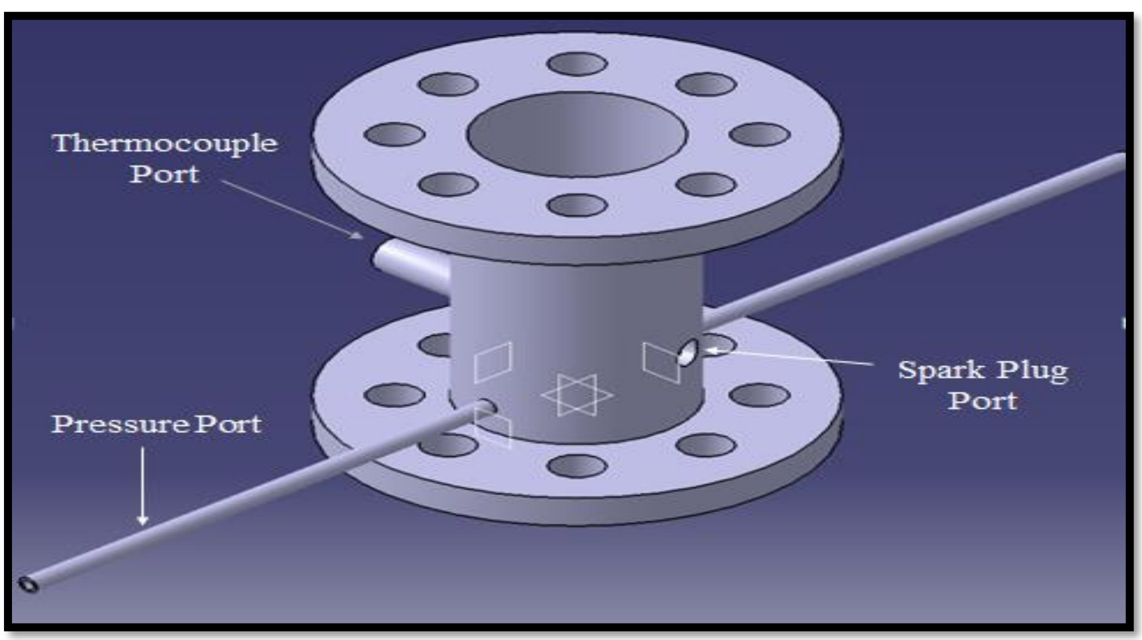

Figure 9.9 CATIA Model

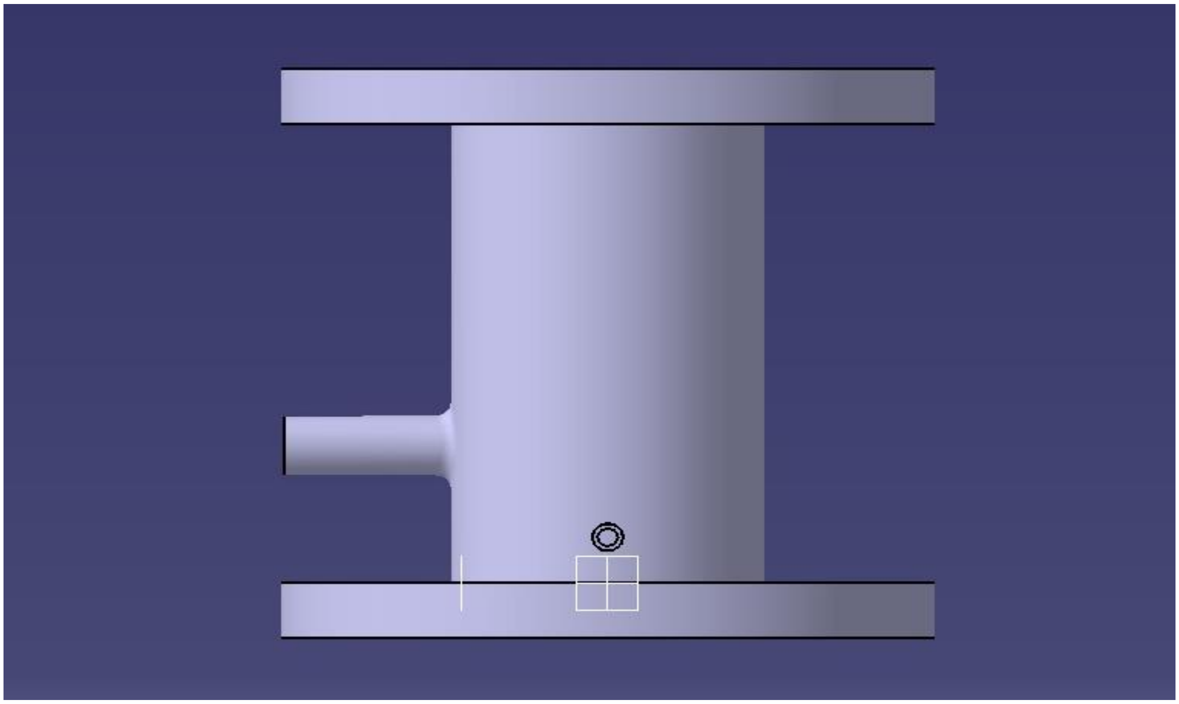

Figure 9.10 CATIA Model (Side View)

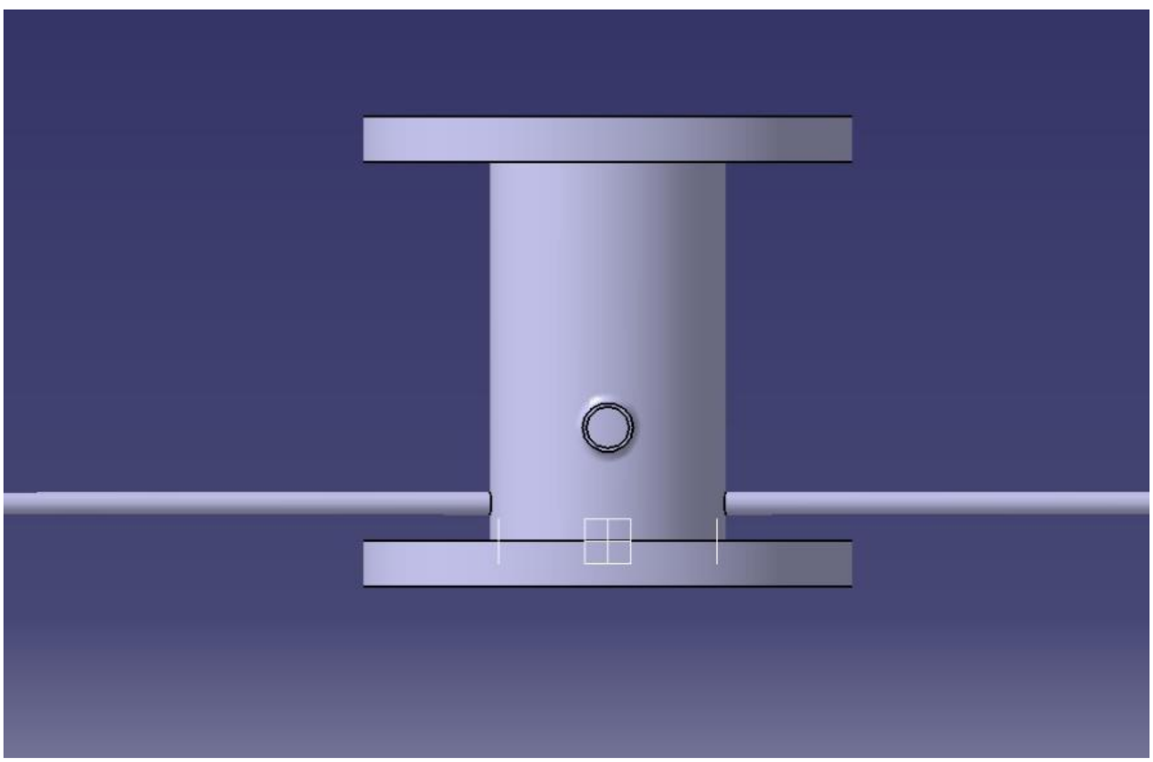

Figure 9.11 CATIA Model (Side View)

9.2.3 Fabricated Combustion Chamber

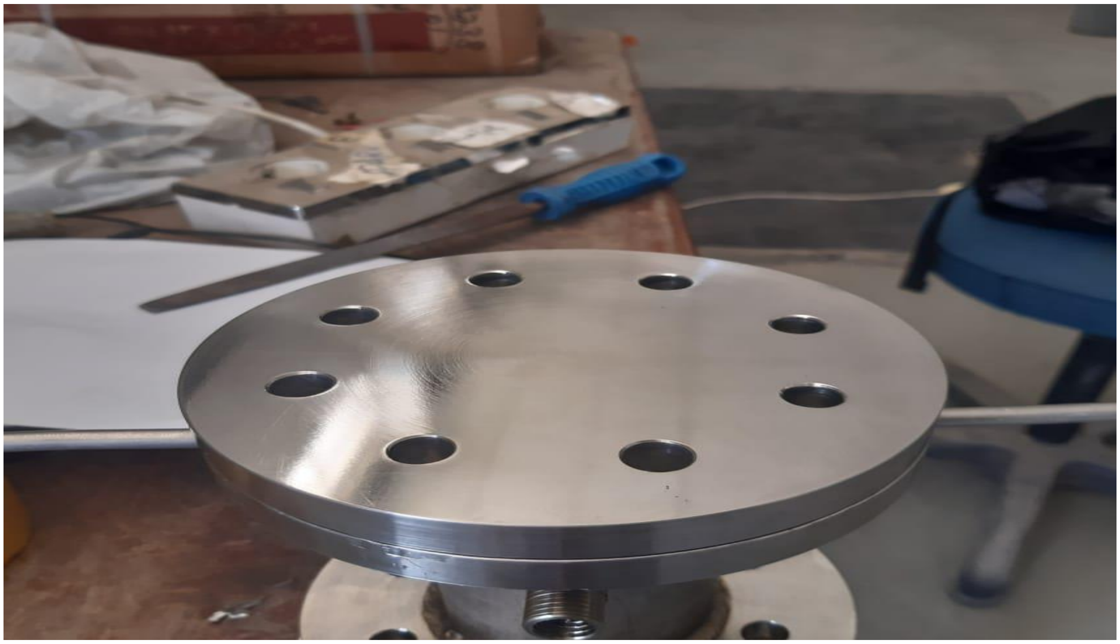

Figure 9.12 Fabricated Combustion Chamber

Figure 9.13 Fabricated Combustion Chamber

10 CHAPTER 10

TEST BED

This chapter is related to the test stand. The test stand working as well as its components will be discussed in detail. The function of the test bed is simply to conduct the testing. The test stand could have 3 orientations. These are horizontal, vertically upward and vertically downward. Each of these components has their own advantages and disadvantages. Installations of the test stand consist of:

- Propellant Pair (AP+HTPB & AP + HTPB + Boron) inside the chamber
- The combustion chamber and nozzle collectively called as Torch.
- Maximum permissible Combustion Chamber Pressure which is 25 bar
- K-type Thermocouples connected to Arduino Chip for the Temperature measurements
- Pressure sensors connected to Data Acquisition and Control System for pressure readings
- Ignition system that is electrical supply in our case

The torch which consists of a combustion chamber with the propellant inside and a nozzle above is installed in the test bed wall with the help of nuts and bolts. Proper connections of thermocouple and pressure sensor through the ports were made. The proper electrical supply was provided through the ignition port. These components in the form of a chart are shown next.

10.1 Components of the Test Bed

The following flow chart is representing the components of the test bed. Each of the components is discussed below.

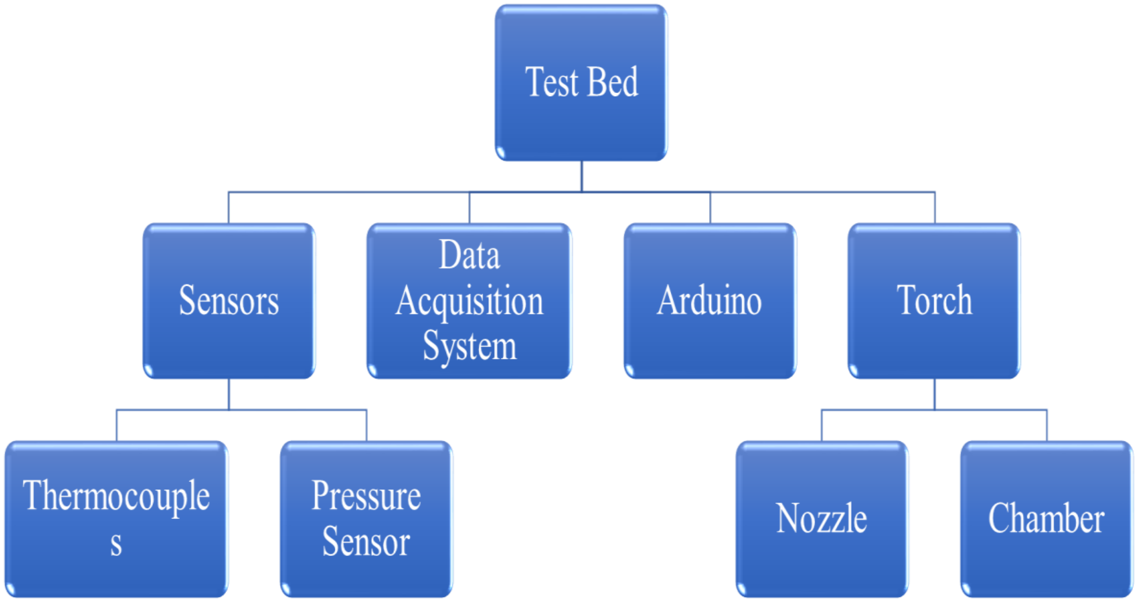

Figure 10.1 Test bed components

10.1.1 Sensors

Sensors are the devices that are used to sense the variations in the surroundings or environment and the send the signals to the electronic devices. We are using Pressure Sensors for Pressure measurement and Thermocouple for Temperature measurement.

Figure 10.2 Thermocouple

We are using the K type Thermocouple having a Range: -200 to 1260°C. We are using this thermocouple because they show a good linear behavior between the temperature and resistance. They are inexpensive and have a suitable temperature range.

Figure 10.3 Pressure Sensor

We are using the Pressure Transducer having a Range: 0 to 100 bar.

10.1.2 Data Acquisition System (DAS)

It consists of the both, hardware and software and its function is to sense and measure the physical characteristics of something in the real world and then displaying it on the screen. The Data Acquisition System (DAS) was basically used for the measurement of the Pressure. The Data Acquisition System was installed in the PC and then connected to the pressure sensors. These pressure sensors were connected to the pressure port of the Combustion Chamber and sensing the pressure as the grain continued to burn. As the pressure was built in the chamber, these pressure variations were displayed on the screen of the PC with the Data

Acquisition System (DAS). The DAS provided by the lab is shown in the picture next.

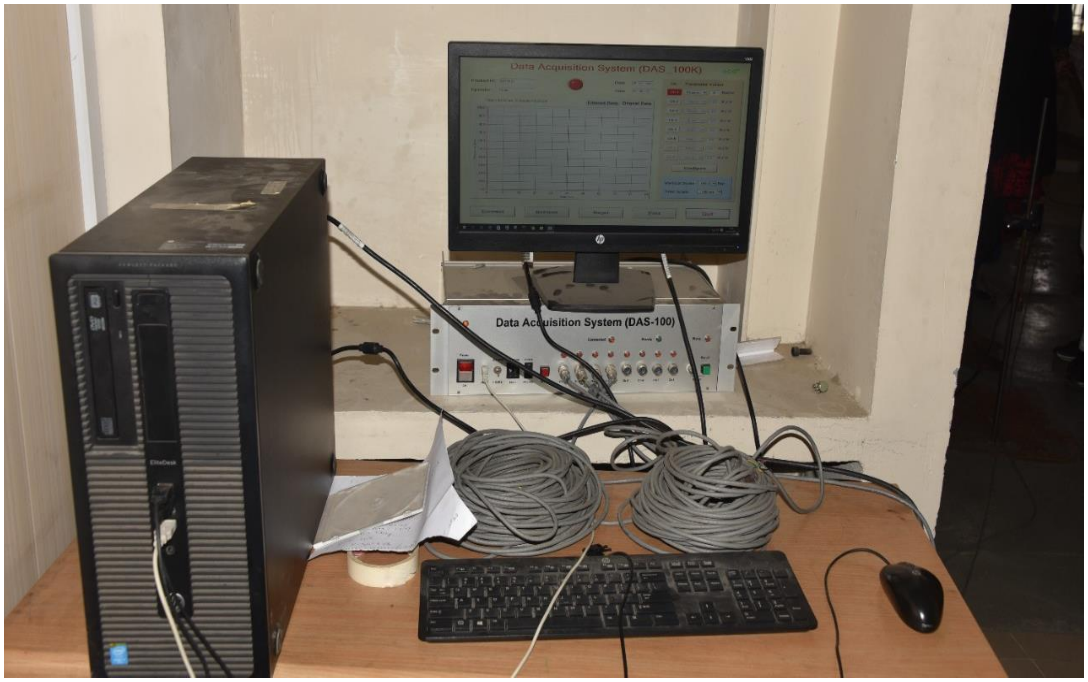

Figure 10.4 Data Acquisition System

10.1.3 Arduino

It was used for measuring temperature using thermocouple and displaying it on Arduino serial monitor. The Arduino chip was connected to the thermocouple and the thermocouple connected to the port. The other side of Arduino chip was connected to the laptop. As the temperature of the combustion chamber kept on increasing with grain burning, the thermocouple sensed that temperature change and with the help of the Arduino chip that those temperature values were displayed on the laptop screen. The figure of the Arduino chip is shown next.

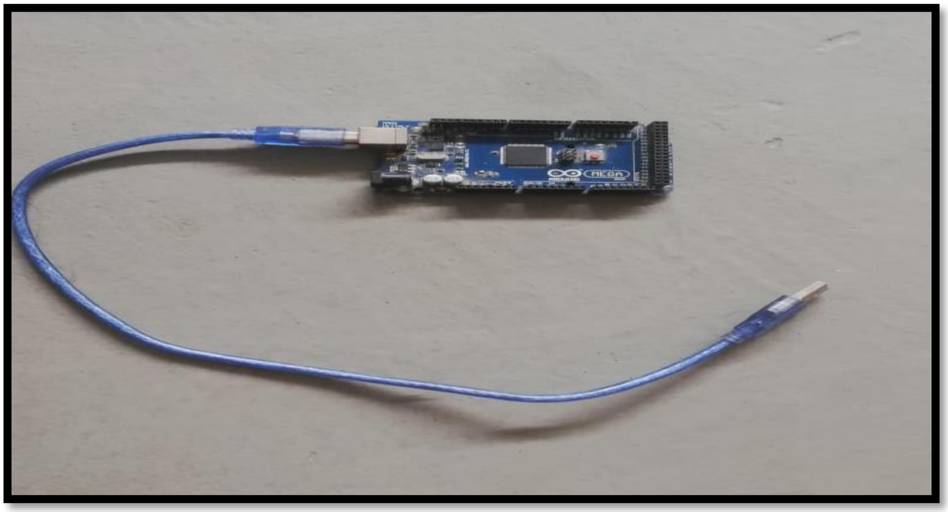

Figure 10.5 Arduino

10.2 Orientation of the Test Bed

Basically there are 3 types of the orientations used for the testing of ignition torch. These are

- Vertical orientation with the nozzle facing downwards
- Vertical orientation with the nozzle facing upwards
- Horizontal orientation

Each of these has their own advantages and disadvantages. 2 orientations were used during the testing. First was the horizontal testing and the second one was the nozzle with the face in the upward direction. These are discussed below.

10.2.1 Horizontal Testing

We performed the testing in the horizontal direction first as shown. THE GRAIN DID NOT BURN! The reasons of the failure were unknown so we tried again and again but all in vain. Several modifications were done and the tests were conducted again.

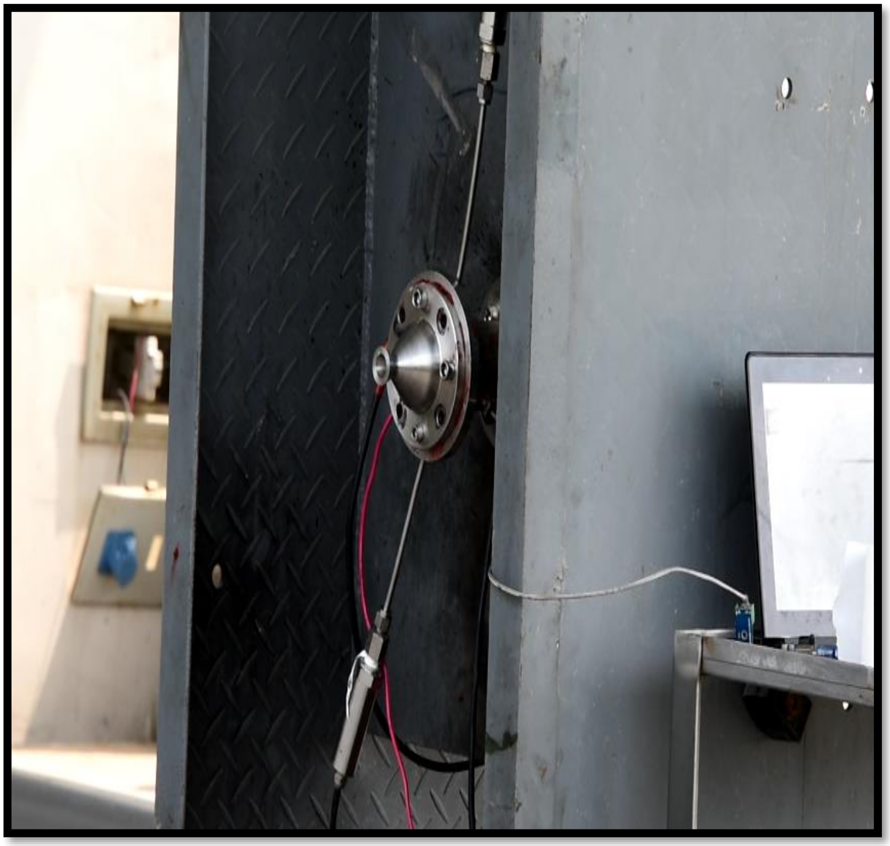

Figure 10.6 Horizontal Orientation

10.2.1.1 Modifications

Following modifications were done:

- Increased the igniter quantity
- Made sure that stickiness was enough
- Made sure that igniter is uniformly distributed over the entire grain's diameter.

Result:

THE GRAIN FAILED TO IGNITE AGAIN!!

10.2.2 Vertical Testing

We decided to change the igniter i.e., using only matchstick powder and try again.

We had to change the orientation for this purpose.

Figure 10.7 Vertical Orientation

Initially we were using the Kerosene based gel mixed with the match stick powder. After several failed attempts it was suspected that there might be some problem with the igniter. We decided to use another one. We used match stick powder instead and for that purpose we had to change the orientation of the nozzle. We made another attempt and our grain caught fire instantly.

11 CHAPTER 11

INTEGRATED TESTING

This Chapter is about the testing. Total 5 tests were being conducted. The first test was conducted using the grain composed of AP + HTPB having the length and diameter of 48 mm and 52 mm respectively. The mass was 120 kg. The nozzle being used was having the throat area of 5.5 mm. In the 2^{nd} and 3^{rd} tests, same grain having the same compositions and having same dimensions were used. The nozzle for the 2^{nd} test was of the throat area 4.5 mm and for the third one, it was 3.5 mm respectively. The data in tabular form is shown below.

Table 11.1 Test Grain Dimensions

Tests	Grain	Length	Nozzle Throat size
Test 1	AP + HTPB	48 mm	5.5 mm
Test 2	AP + HTPB	48 mm	4.5 mm
Test 3	AP + HTPB	48 mm	3.5 mm
Test 4	Boron + AP + HTPB	74 mm	5.5 mm
Test 5	AP + HTPB	85 mm	5.5 mm

11.1 TEST 1

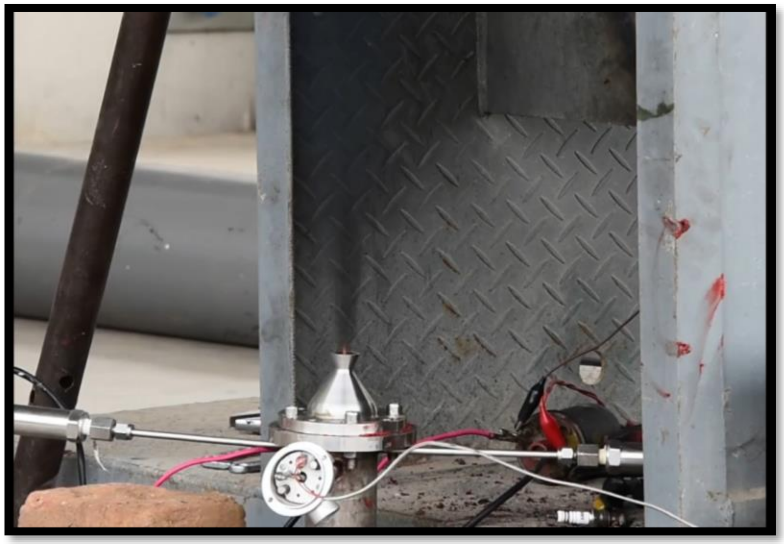

Figure 11.1 Test 1

11.1.1 Observations

The test 1 was successful with the visible flame coming out of the nozzle. The grain did not burn full though but the burning was very stable.

11.2 TEST 2

Figure 11.2 Test 2

11.2.1 Observation

In the test 2, the burning was stable but there was a little bit leakage due to the uneven bolt stress and the wrong placement of the flanges.

11.3 TEST 3

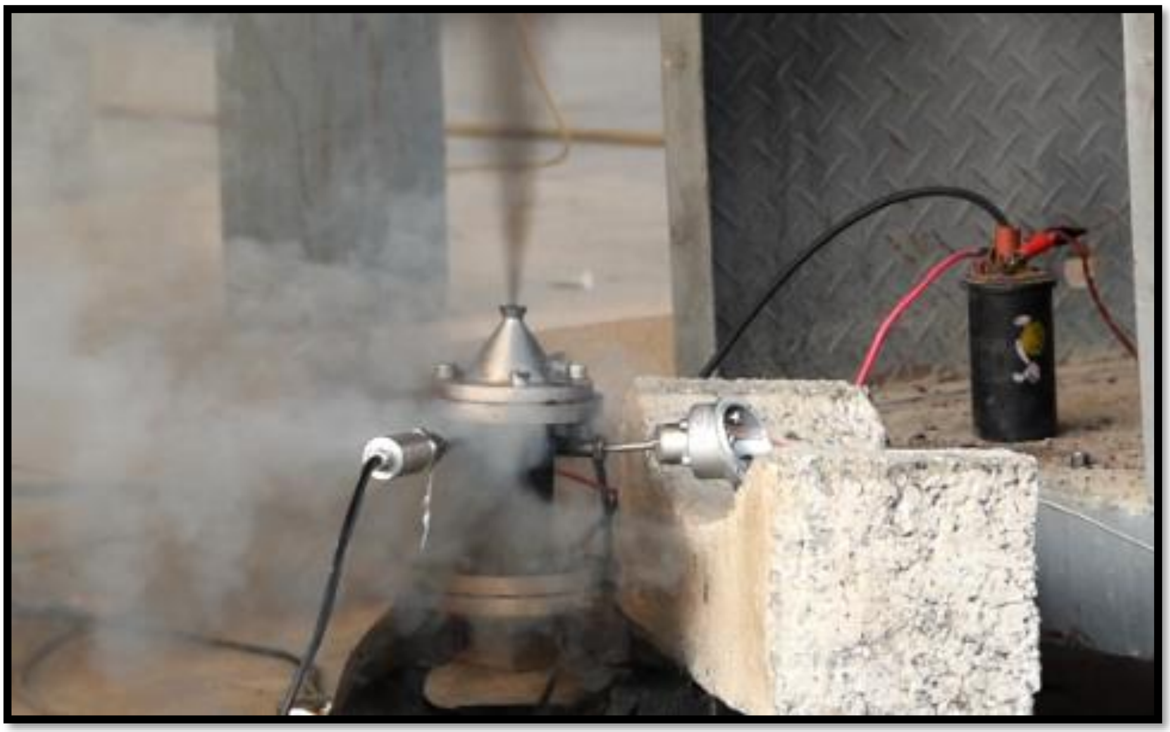

Figure 11.3 Test 3

11.3.1 Observation

In the test 3, a lot of leakage was observed due to the high pressures created as the throat diameter was small.

11.4 TEST 4

Figure 11.4 Test 4

11.4.1 Observation

In the test 4, a very smooth and stable burning was observed with a big bright flame coming out of the nozzle but a lot of residue was left behind.

11.5 TEST 5

Figure 11.5 Test 5

11.5.1 Observations

In the 5th test, the nozzle exploded due to high pressures and was stuck in the roof.

This as a failed attempt!

11.6 Nozzles after Testing

11.6.1 Externally

Figure 11.6 3.5 mm throat diameter

Figure 11.7 4.5 mm throat diameter

Figure 11.8 5.5 mm throat diameter

11.6.2 Internally

Figure 11.9 3.5 mm throat diameter

Figure 11.10 4.5 mm throat diameter

Figure 11.11 5.5 mm throat diameter

11.6.3 Observations

- In the first nozzle i.e. having the diameter of 4.5mm, there were some cracks being observed after the test. These cracks were due to the high pressures created inside the chamber.
- In the second nozzle i.e. the one having the throat diameter of 4.5 mm, there were no cracks observed.
- The third nozzle i.e. the one having the diameter of 5.5 mm exploded and stuck in the roof. Actually 3 tests were being conducted using this nozzle. The first 2 tests were successful but in the third attempt, the nozzle could not bear the enough pressure and a blast took place.

11.7 Resides

11.7.1 Test 1

Mass = 51.3 g

Throat = 5.5 mm

Figure 11.12 Test 1

11.7.2 Test 2

Mass = 51.7 g

Throat = 4.5 mm

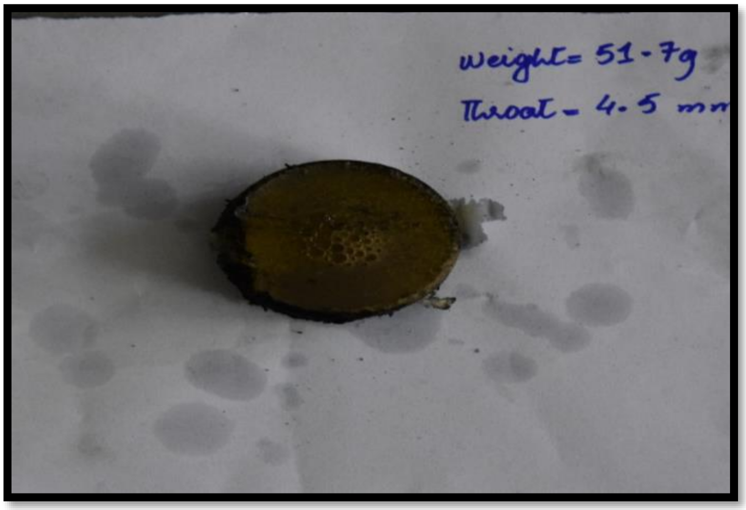

Figure 11.13 Test 2

11.7.3 Test 3

Mass = 33.7 g

Throat = 3.5 mm

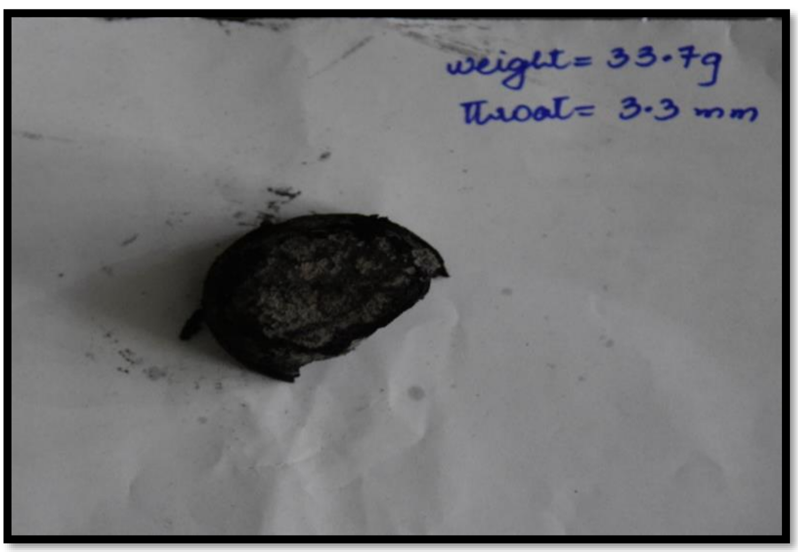

Figure 11.14 Test 3

11.7.4 Test 4

Mass = 101.10 g

Throat = 5.5 mm

Figure 11.15 Test 4

12 CHAPTER 12

RESULTS

12.1 Mass Flow Rate Calculation

Table 12.1 Results

Test	Burnt mass (kg)	Burn time (s)	Mass flow rates (kg/s)
Test 1	0.066 kg	30	0.0022
Test 2	0.072 kg	10	0.0072
Test 3	0.084 kg	11	0.0077
Test 4	0.028 kg	6	0.0048

Where

• Burnt Mass = Total Mass of the grain – Residue Weight

• Burnt Time = Recorded

$$\dot{m} = \frac{m_{burnt}}{t}$$

12.2 Density calculation

Table 12.2 Density Calculation

Test	**Burnt Length (mm)**	**Density (kg/m3)**
Test 1	21	1481.08
Test 2	23	1492.6
Test 3	27	1666.47
Test 4	14	972.5

Where

- Burn Length = Length of the grain – Length of Residue
- Density = $\rho = \frac{m}{L * A_b}$

12.3 Burn Rate Calculation

Table 12.3 Burn Rate Calculations

Mass Flow Rate	Density	Burn Rate
0.0022	1481.08	0.0007
0.0072	1492.6	0.002273
0.0077	1666.47	0.002177

Where

- $\boldsymbol{r} = \frac{\dot{m}}{\rho A_b}$
- $\boldsymbol{A_b}$=0.002122 m^2

12.4 Pressure Readings

Here is the comparison between the pressure values that we calculated and those obtained from Data Acquisition System (DAS)

Table 12.4 Pressure Values

Pressure Calculated (Expected)	Experimentally Determined
7.3 bar	5 bar
11 bar	9 bar
18.1 bar	13 bar

12.5 Graphs

Following is the comparison of the experimental graph with the one obtained from literature.

12.5.1 Literature Graph

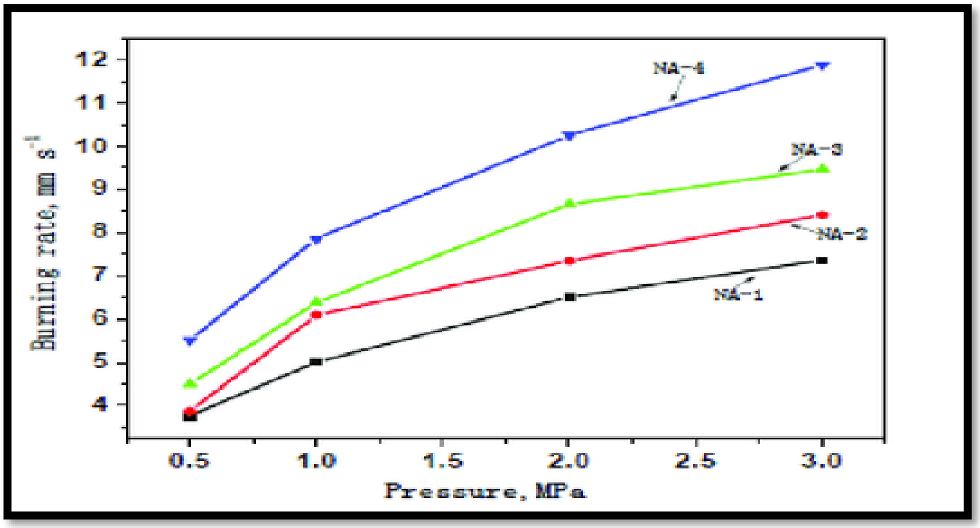

Figure 12.1 Burn Rate Graph (Literature)

12.5.2 Experimental Graph

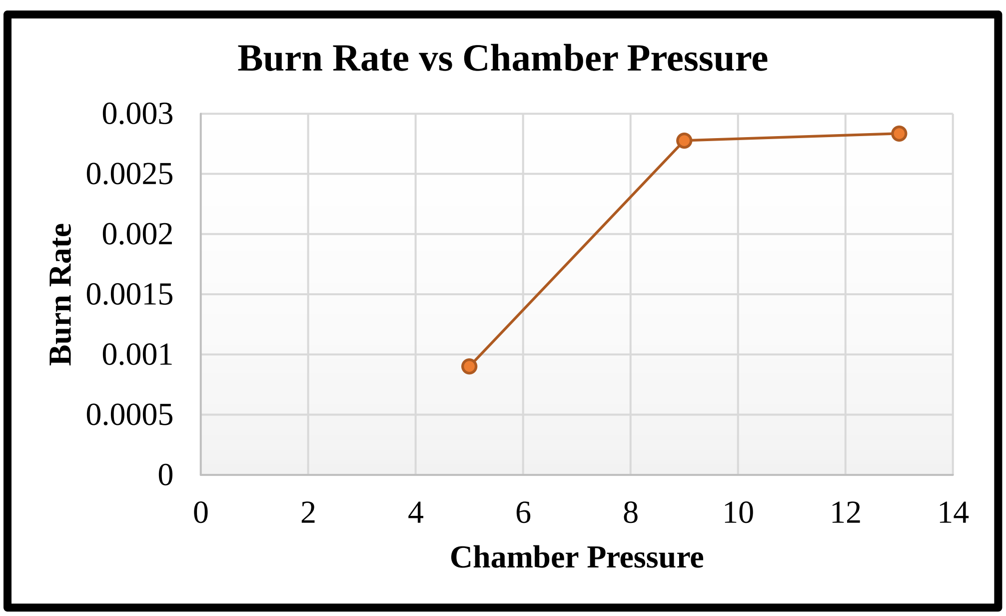

Figure 12.2 Burn Rate Graph (Experimental)

12.5.3 Comments

As we can see that the graph obtained from the experimental work is approximately same as that from the literature. This indicates that the burn rate obtained experimentally is correct. The brown line in the experimental graph is exactly equal to that of the literature.

On the other hand, the blue line in the experimental graph has been obtained from different MATLAB codes through curve fitting. We would obtain an equation that would be useful to obtain the burn rate exponent and burn rate coefficient in the following formula.

$$r = aP_c^n$$

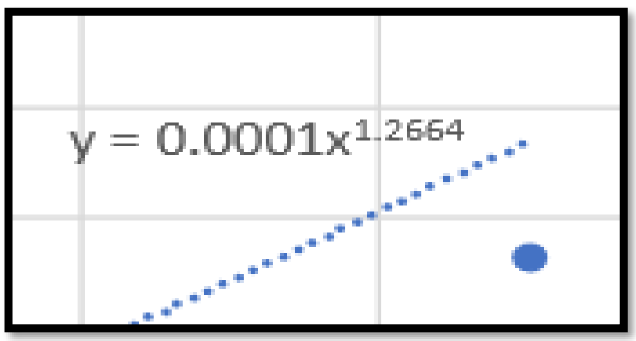

Figure 12.3 Value obtained from graph

By comparing the values in the graph with the above formula, we obtain the burn Coefficient and Burn Exponent as below:

n = 1.2664

a = 0.0001

Now for any Combustion Pressure, we can calculate the burn rate for the AP + HTPB composition.

12.6 Temperature Results

Table 12.5 Temperature Measurement

Test	Average Temperature
1	Too short to measure
2	Too short to measure
3	Too short to measure
4	212℃
5	Blast

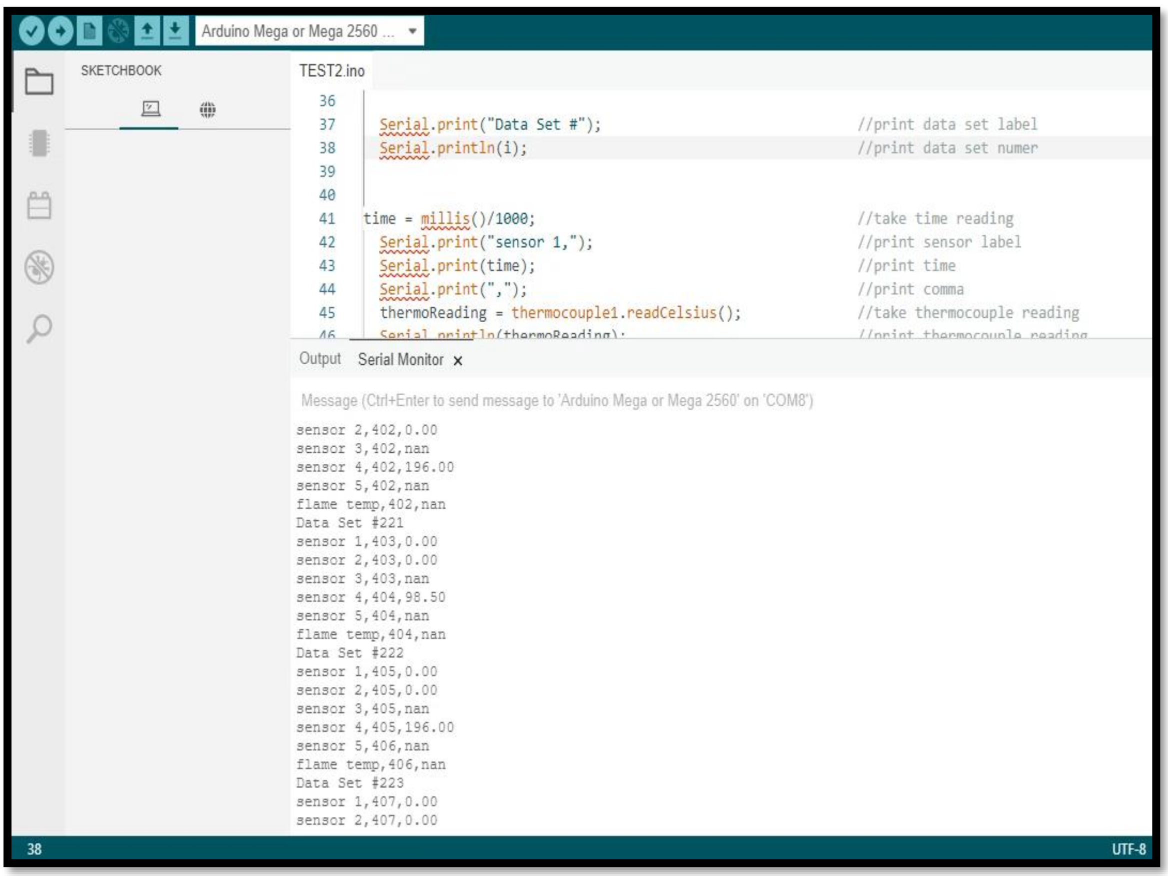

Figure 12.4 Temperature Values

13 CHAPTER 13

FUTURE WORK

As our project was to design and develop a low temperature solid propellant ignition torch, for that ignition our first step was to select our propellant pair which upon burning gives the temperature of about 700-1000 K and after selecting the propellant pair that is perfect for the requirements that are needed for our ignition torch, we have to process that propellant pair to form the low temperature solid / composite propellant grain. This low temperature solid / composite propellant grain can be used for different applications.

13.1 Ignition of LPRE System

Low temperature solid propellant is used to form the low temperature solid propellant based ignition torch that is used to initiate the combustion in liquid propellant rocket engine (LPRE).

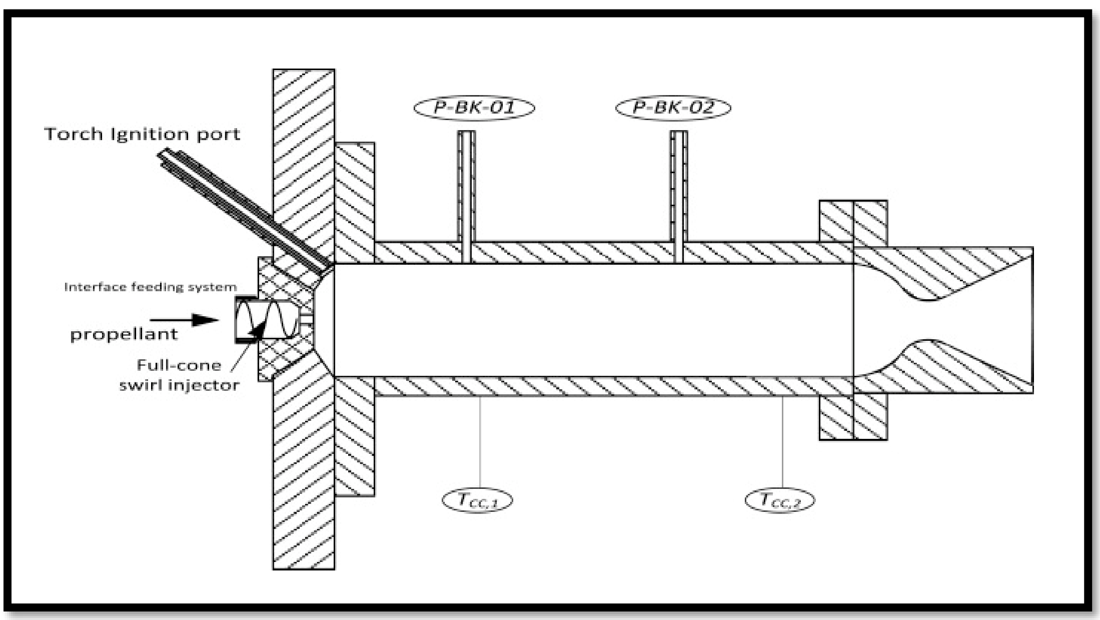

Figure 13.1 LPRE System

13.2 Kick Starter to start Turbine in LPRE

Low temperature solid propellant grain can also be used as kick starter in order to start turbine of LPRE.

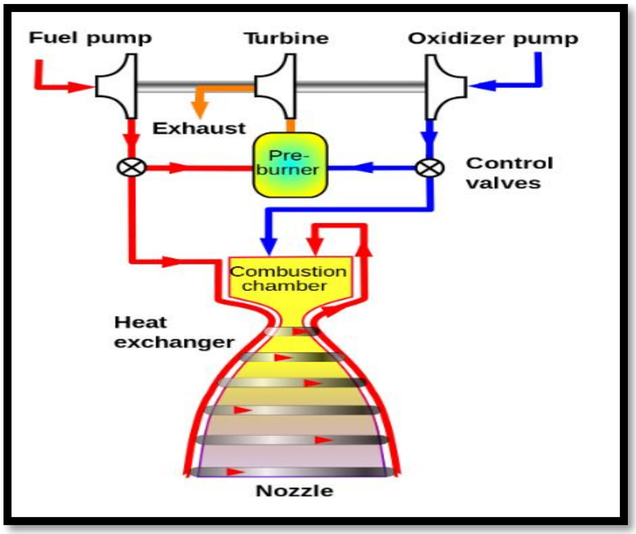

Figure 13.2 Liquid Propellant Rocket Engine

13.3 Primary combustion in Ramjet

Low temperature solid propellant can also be used in the ramjet for primary combustion as fuel rich propellant is used in ramjet for primary combustion.

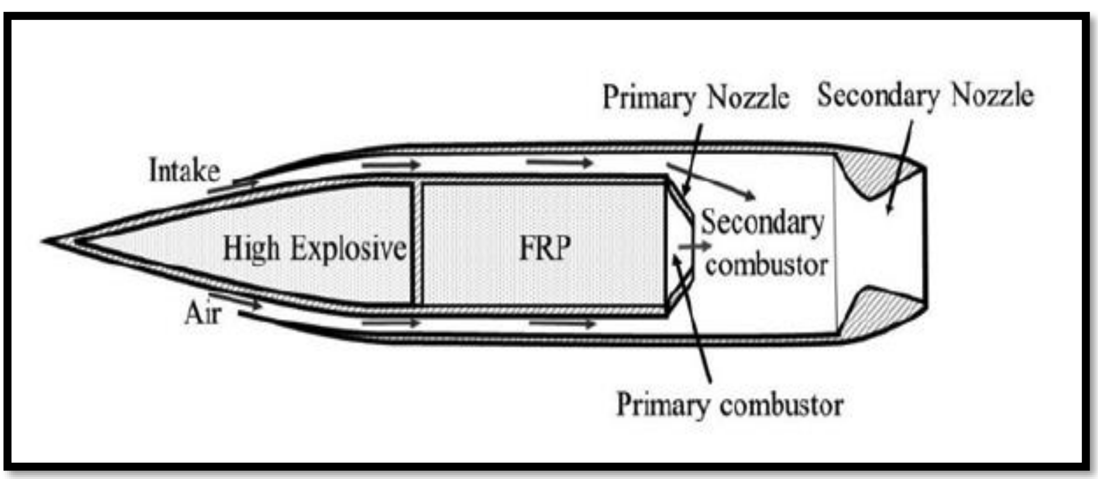

Figure 13.3 Ramjet

CONCLUSION

As our project is the designing and development of low temperature solid propellant based ignitor, it is shown from the results that we achieved our goal.

As our testing was successful, we conclude that the propellant pairs we selected for our grain can be used for ignition of LPRE. As our propellant grain is low temperature solid / composite based gain, it has some future perspectives and applications such as it can be used for primary combustion in ramjet and it can also used as kick starter to start the turbine in LPRE.

APPENDICES

Appendix A

Appendix A consists of the MATLAB codes.

Radius of Throat

```
Burnrate=0.0056;

density=1092.1;

C_star=1580;

P_c=1500000;

r_b=0.025;

A_b=3.14*((r_b)^2)

A_t=(Burnrate*A_b*density*C_star)/(P_c)

r_t=(A_t/3.14)^(0.5)
```

Chamber Pressure

```
Burnrate=0.0056;

density=1092.1;

C_star=1580;

r_b=0.0245;

A_b=3.14*((r_b)^2)

r_t=0.005;

A_t=3.14*((r_t)^2)

P_c=(Burnrate*A_b*density*C_star)/(A_t)
```

Burn Radius

```
Burnrate=0.0056;

density=1092.1;

C_star=1580;

r_t=0.00175;

P_c=1500000;

A_t=3.14*((r_t)^2)

A_b=(P_c*A_t)/(Burnrate*density*C_star)

r_b=(A_b/3.14)^(0.5)
```

Thrust

```
Isp=137;

m_dot=0.0185;

T=Isp*m_dot
```

Mass Flow Rate

```
P_c=1.8939e+06;

r_t=0.00175;

A_t=3.14*((r_t)^2)

C_star=1024.5;

m_dot=(P_c*A_t)/C_star
```

Length of Grain

```
m_dot=0.0178;

t=25;

m=m_dot*t

density=1092.1;
```

```
A_b=0.0019;
L=m/(density*A_b)
```

Burn Time

```
L=0.100;
density=1092.1;
A_b=0.0008123;
m=L*(density*A_b)
m_dot=0.0077;
t=m/m_dot
```

Curve fit

```
x=input('Enter the value of x : ');
y=input('Enter the value of y : ');
n=length(x);
X=log(x)
Y=log(y)

sumX=0;
sumY=0;
sumXY=0;
sumX2=0;
for i=1:n
    sumX=sumX+X(i);
    sumY=sumY+Y(i);
    sumXY=sumXY+X(i)*Y(i);
```

```
    sumX2=sumX2+X(i)*X(i);
end
d=[sumX n;sumX2 sumX];
da=[sumY n;sumXY sumX];
db=[sumX sumY;sumX2 sumXY];
a1=det(da)/det(d)
b1=det(db)/det(d)
b=a1
a=exp(b1)

fprintf('The equation of line is Y = %of*x^%of',a,b)
```

Appendix B

References

1. https://en.wikipedia.org/wiki/Liquid-propellant_rocket
2. https://www.hq.nasa.gov/pao/History/conghand/propelnt.htm
3. https://www.grc.nasa.gov/WWW/k-12/airplane/lrockth.html
4. http://www.ijmetmr.com/olseptember2016/MadhaviThanniru-SAlka-DrMSatyanarayanaGupta-135.pdf
5. https://rafafusutur.weebly.com/uploads/1/3/4/8/134858683/2905602.pdf
6. https://upcommons.upc.edu/handle/2117/180778
7. https://worldwidescience.org/topicpages/l/liquid-fueled+rocket+engines.html
8. https://link.springer.com/book/10.1007%2F978-1-4471-6796-9
9. https://arc.aiaa.org/doi/10.2514/1.B34996
10. http://www.zamandayolculuk.com/html-3/roketmotors.htm
11. http://kuncupmekar.xyz/xgt6t6x/3xi9xp2.php?khplopegu=adc-ic-arduino
12. https://www.science.gov/topicpages/l/liquid+propellant+rockets.html
13. https://arc.aiaa.org/doi/10.2514/1.B35384
14. https://www.amherst.edu/academiclife/departments/courses/1112F/MATH/MATH-111-1112F?a11y=0