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# A THEORETICAL AND EXPERIMENTSAL STUDY OF PYROTECHNIC IGNITER FOR SOLID ROCKET MOTER APPLICATION

A thesis submitted

In Partial Fulfillment of the Requirements

for the

**Degree of Masters of Technology**

By

Semayat Fanta Herano



To the

DEPARTMENT AEROSPACE ENGINEERING

Defense University College of Engineering Office of Postgraduate Programs and Research, Debrezeit (Bishoftu), Ethiopia

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**Defense University, College of Engineering**
**Office of Postgraduate Programs and Research**

M-Tech Thesis on

# A theoretical and Experimental Study of Pyrotechnic Igniter for Solid Rocket Motor Application

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# A theoretical and Experimental Study of Pyrotechnic Igniter for Solid Rocket Motor Application

Thesis submitted to the office of postgraduate programs and research at Defence University, College of Engineering in partial fulfillment of the requirement of degree of masters of technology (M/Tech) in Aerospace Engineering.

Thesis submitted by: SEMAYAT FANTA HERANO
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January, 2014

# DECLARATION

I hereby declare that the work which is being presented in this thesis entitled "A theoretical and Experimental Study of Pyrotechnic Igniter for Solid Rocket Motor Application" submitted for masters of technology (M/Tech) degree is original work of my own and has not been submitted and presented for any degree and all the resource of materials used for the thesis have been duly acknowledged.

Name of student: Semayat Fanta Herano

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Date: 12/01/2014

Modified July, 2021

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# CERTIFICATE

This is to certify that the thesis entitled "A theoretical and an experimental study of pyrotechnic igniter for solid rocket motor application" is the work carried out by Semayat Fanta Herano a student of M-Tech, Defense university college of Engineering, Debrezeit (Bishoftu), in the year 2012-2014. In partial fulfillment of the requirement for the award of the Degree of M/Tech of Aerospace engineering and that the thesis has not formed the basis for the award previously of any degree, diploma, associate ship, fellowship or any other similar rule.

**Supervisor:** Prof. G.C Pant (Dr.)

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**Date:** January, 2014

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# A theoretical and Experimental Study of Pyrotechnic Igniter for Solid Rocket Motor Application

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## ABSTRACT

The use of pyrotechnics for solid rocket motor (SRM) ignition is the most important aspect for the development of rocket technology. The design and construction of appropriate ignition system is one of the most important innovative steps for the development of rocket technology. In Solid rocket motor, once the propellant start burning it will not terminate and is not used for further application. Therefore, it is good practice to study the ignition system characteristics and its performance related parameters before the occurrence of catastrophic failure of the whole rocket. In this thesis, a detailed theoretical and experimental study of solid rocket motor igniters characteristics have been conducted. An experimental synthesize of black powder ignition charge from sulfur (10%), charcoal (15%), and potassium nitrate (75%) using a traditional boiling method and is tested for its ballistic performance using bulk burning method. From the test we analyzed the ballistic performance like burning rate, the amount of pressure and temperature developed from particular igniter charge and compared it with commercially manufactured ignition charge. The mathematical modeling of pyrotechnic ignition and the heat transfer from the igniter material to the solid propellant surface have been modeled using ANSYS finite element modeling software for chemical kinetics CHEMKIN. A numerical simulation of internal ballistic parameter of black powder pyrotechnics like thrust (F), combustion chamber pressure (Pc), burning rate ($r_b$), and burn area ratio (Kn) have been studied using BurnSim simulation software and the boundary layer modeling of energy transfer by chemical reaction from the igniter material to the propellant uninhibited surface have been studied using CHEMkin. The result obtained from ANSYS is verified with the theoretical and the experimental results for the pyrotechnic chemical under our prime concern. In general, the thesis provides a very clear road map to solve the problem related to ignition of solid propellant rockets. Thus, it is highly demanded in the area of aerospace engineering particularly in the development of missiles and rockets in the scope of national level and to emerge the idea for fellow engineers, initiate them for further research work and to indigenize (own) the technology of missiles and rockets. Finally, the design and construction of pyrotechnic igniter for solid rocket motor have been performed.

*Keywords:* Burning rate, Ignition, performance, propellant, pyrotechnics igniter, solid rocket

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## LIST OF ACRONYMS AND ABBREVIATION

| ABBREVIATION | MEANINGS |
|---|---|
| BP | Black Powder |
| CDF | Confined detonating fuse |
| CV | Closed vessel |
| EED | Electro-explosive devices |
| EPDM | Ethylene Propylene Diene Monomer |
| ETA | Explosive transfer assembly |
| HMX | Cyclo-Tetra-Methylene-Tetra-Nitramine |
| IANS | Idaho section of the American nuclear society |
| MTV | Mg–Teflon-vision |
| NASA | National Aeronautical Space Administration |
| NIATT | National institute for advanced transportation technology |
| NSI | NASA Standard Initiator |
| PEC | Plasticized ethyl cellulose |
| PETN | Penta-Erythritol-Tetra-Nitrate |
| PTFE | Poly-Tetra-Fluro-Ethylene |
| RDX | Cyclotrimethylenetrinitramine |
| SRM | Solid rocket motor |
| TBI | Through Bulkhead Initiator |

# CHAPTER ONE

## 1. INTRODUCTION

### 1.1 Background of the study

The fundamental function of an igniter in rocket motor (SRM) is to enable the exposed surface of solid propellant of rocket motor to a thermal state that results in a sustainable combustion of a propellant within a prescribed ignition time or delay. It is observed that for optimum solid rocket propellant ignition process a proper interaction of fundamental parameters such as temperature (T), pressure (P) and time (t) are required. Similarly, the chemical composition of propellant and its grain size and shape also plays a major role in ignition performance. Based on the above parameter igniters are classified in to various types. The most significant classification of igniters is based on the energy release system, which produces the required amount of pressure, temperature and heat flux required for combustion of a propellant in SRM. The two basic classifications of ignitors for SRM are pyrotechnic and pyrogen igniters.

The pyrotechnic types of igniters are thermo-chemical device containing a pyrotechnic charges (compositions), that used to ignite other materials which are difficult to ignite. Such materials may include rocket propellants, thermites, and gas generators [1], [2], [3]. Pyrotechnic igniters consist of pyrotechnic charges in the form of powder, granules, or pellets as the main charge. Pyrotechnic compositions contain fuel and oxidizer which are elements, alloys or compounds. Frequently used elemental fuels are metallic powders of aluminum, magnesium, titanium, iron, manganese, tungsten, boron, etc. compounds used as fuels are hydrocarbon, carbohydrates, sulfides of arsenic and antimony [4]. The oxidizers used includes metallic oxides, metallic peroxides, nitrates, chlorates, and chromates of alkali and alkaline earth metals. In pyrotechnic composition the fuel produces a significant quantity of hot particles that promote the ignition and oxidizers used may be potassium perchlorate or potassium nitrate. The charge is contained in vented (perforated) tubes called igniter hardware.

Pyrotechnic initiators are usually controlled electrically (electro-pyrotechnic initiators), using a heated bridge wire [5], [6]. Electrical ignitors are resembling to blasting cap (detonators) except in that there is no intention to produce a shock wave. The main advantages of pyrotechnic devices over other devices are [7], [8].

- The high power to weight ratio,
- It is highly reliable,

- Very small in size,
- Requires low operating current,
- Simple electrical circuit requirement,
- Economical and reasonably low cost,
- Ability to produce more energy in short time (impulse) and
- Precisely controllable force.

Another advantageous feature of this device is the possibility of providing time delays by placing elements with fixed burning time delay trains in the explosive devices themselves.

Pyrotechnics composition contain the energy desired to perform an intended function within a given small volumes in a combustion chamber. Initiation inputs are the only external energies to devices can be precisely established to prevent unintentional initiation or startups, and also to produce satisfactory initiation energy. Pyrotechnics uses highly energetic solid propellant compositions and required to be highly stable under high thermal and vacuum conditions. Pyrotechnics are basically used for solid propellant rocket ignition startup due to the following characteristics[9]:

- Exclusive Features
- Single shoot
- Functional checking before flight is not possible
- Very short-duration of ignition,
- Very sensitive regarding safety
- It contains explosive charges

Pyrogen igniters are small rocket motors, which are designed in same principles as SRM and consist of a fast-burning cast propellant grain, which is almost similar to the main charge. Hence, their ballistics can be predetermined from the known parameters and they function for longer durations and more reproducibly than pyrotechnic igniters do. Initiation of the propellant grain produces energetic hot gases which can ignites the main motor propellant. An ignition charge, in addition to the main charge, consists of an initiator charge and a booster charge in it. There are also igniters used in liquid rocket engines and for other applications. These include Spark Torch igniter, Catalytic igniter, Hypergolic igniter, Laser igniters and also others.

## 1.2 Statement of the problem

The research of pyrotechnic igniter of solid rocket motor (SRM) is concerned to fulfill the demand of young growing industries in developing countries like Ethiopia, in the area of newly emerging technology of aerospace engineering, particularly rocket and missile technology. The thesis is mainly intended:

- To eliminate the foreign exchange expended to import the rocket,
- To design, develop and construct appropriate ignition system for SRM,
- To owe the rocket technology in the country,
- To motivate, and promote Aerospace technology.

## 1.3 Objective of thesis

### 1.3.1 General objective

- The main objective of this thesis is to conduct a detailed theoretical and experimental study on pyrotechnic igniter particularly black powder chemical composition as well as an investigation of the influence of grain size on its burning rate, and also for its optimum performance for SRM startup or ignition.

### 1.3.2 Specific objectives

- Originating the idea in the development of anti-tank guided missile ignition systems and guided weapon technology with in the country.
- Instigating the young Engineering graduates of the DEC thereby create synergy in the technological development of missile and aerospace industry with in the nation.
- Laying roadmap for the design, development and research work for rockets, missiles and related guided weapons ignition technologies with in the homeland for interested researchers and scientists.
- To owe/or transfer technologies and design footsteps of rockets/missiles ignition system design for fellow engineers.
- To make a clear theoretical base for different types of igniters used in missile system, and through study on pyrotechnic type igniters for SRM application; conducting an experimental analysis of its different grain size, chemical composition and ballistic performance.

## 1.4 Scope of the Study

The scope of the thesis includes the following important topics:

1. Theoretical study of pyrotechnic igniter and its composition
2. Experimental preparation of ignition charge of SRM for double base propellants
3. Testing the prepared BP charge for its performance
4. Mathematically modeling the ignition energy transfer from igniter to propellant surface.
5. Designing and constructing the igniter using experimentally prepared BP charge and multi-perforated ignition charge

**1.5 Methodology**

1. Literature review and data collection regarding different types of igniters and pyrotechnics, thereby focusing on pyrotechnic igniter and its composition.
2. Collecting and interpreting the data from the NASA data manual/sheets and other aerospace relate books, journals, publications and exploring internet.
3. Physical observation for related technological items which exist in Ambo chemical and ammunition industry for 122 mm rocket motor and its igniter.
4. Identifying and procuring different chemicals, equipments, tools and laboratory setups required for experiment.
5. Conducting experiment on different composition of chemicals used to make pyrotechnic igniter charge specifically black powder ingredients.
6. Synthesizing ignition charge of different grain size like course, medium and fine grains in conventional technique.
7. Testing the compositions using bulk burning rate test method and conventional CCV test method for their ballistic performance
8. Comparing the test result with commercially manufactured ignition charge.
9. Designing the pyrotechnic igniter for the proposed thesis of my relative graduate of aerospace engineering for the given combustion chamber free volume using the synthesized black powder.
10. Finally, discussion and analysis of the results and then based on the result recommendation and conclusion was made for the thesis work.

**1.5 Importance of the thesis in the context of current status**

Now a day our country is in rapid development in every sector of economy specifically the industrial sector takes prominent part. The success of this plan can be achieved through multidirectional contribution of the nations. Thus, the research work on the modern solid rocket motor igniter is very vital and be studied with in this thesis work.

### 1.7 Expected outcome of the thesis and contribution to aerospace industry

The guided missiles/rocket enables the defense (military) forces to deliver munitions rapidly to a selected target at a distance. It is considered an effective means to conduct a wide variety of military missions ranging from the denying of enemy communications and supply routes to establishing ground/air superiority of a country. Due to this mission flexibility, missiles particularly the guided missiles have attained outstanding level of importance in military applications and consequently it gets great attention in recent research and development programs. To attain the mission requirements a precisely controllable and consistent design of ignition system is required. For this reason, an appropriate ignition system design and experimental work have been conducted in this thesis work. At the end of this thesis work the industry in Ethiopian national defense put a milestone for the rocket technology, which requires an excellent ignition system with predetermined combustion of pyrotechnic propellant, will benefit to the maximum level, with ignition related problems of solid rocket motor.

### 1.8 Thesis organization

The thesis is organized in seven chapters. Chapter-1 deals with the preliminary introduction of the thesis. Chapter-2 Provides the background study of the rocket propulsion element and brief literature review. Chapter-3 deals with solid propellant rocket motor ignition theories and analytical design requirements. Chapter-4 design of pyrotechnic igniter and its components for solid rocket motor application. Chapter-5 deals with experimental study of pyrotechnic compositions its safety precautions and testing. Chapter-6 provides a numerical simulation of internal ballistic parameter and boundary layer modelling of solid rocket motor pyrotechnic ignition charge. The last chapter concludes the work done in this thesis and also recommends for future work to be done.

# CHAPTER TWO

# LITRATURE REVIEW

## 2.1 Introduction

Pyrotechnics is the art of using chemically generated light, heat, or sound for entertainment, convenience, or military purpose. Pyrotechnics in terms of manufacturing firework refers to the general discipline of civilian pyrotechnics, which encompasses firework, matches, and devices such as highway flares, flower bombs, automotive airbag inflators, thematic welding kits, and items for theatrical effect. Military pyrotechnics includes a wide range of devices for illuminating, signaling, incineration, igniter compositions, and smoke and gas generation types. In aerospace industry pyrotechnics are refer to a wide-ranging family of devices utilizing propellant, explosives and pyrotechnic compositions to achieve; motor propellant initiation, component release, discard, valving, switching, time delay, and actuation functions.

## 2.2 Uses of pyrotechnics

Although pyrotechnics were not important before World War I (WWI), the increased technical requirement of modern warfare necessitated the extensive use of signal and illuminating compositions. During World War II (WW II) further development of such compositions for aerial observation, photography, and bombing purpose has been achieved. Now a day pyrotechnics are used not only for lighting but also for heat, smoke, and sound and for initiating ignition of solid rocket motors. The most important uses are in projectiles, flares, photoflash cartridge and bombs, signals, tracers, simulated ammunition, and target identification bombs. Physically, pyrotechnics are mixture of finely powdered element and compounds, which are generally compressed in a candle form.

## 2.3 Solid rocket motor and its igniter

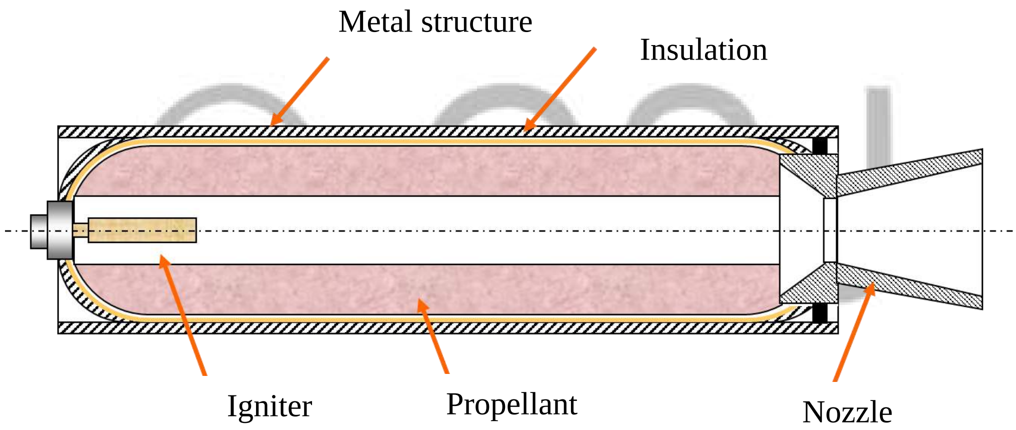
The force needed to propel rocket (SRM) is primely obtain from the combustion of a propellant at prescribed pressure, temperature condition. Thus, the fundamental use of igniter in rocket propulsion is to induce a combustion reaction of a solid propellant in a precisely controlled manner at a restricted burn rate. A designer of SRM ignition system must be able to understand the requirements of particular type of igniters. Lack of theoretical knowledge is considered as great obstacle to meet the requirements at low costs with reliable design procedure. Therefore, it has been rely on an empirically derived formulations that cannot effectively consist and coordinate all relevant design variables and are not suitable for design optimization[9],[10].

### 2.3.1 Constructional feature of SRM

A solid rocket motor (SRM) is constructed from the following main parts of the rocket[11], [12]: Solid rocket motor case (RMC), insulation, igniter, nozzle and solid propellant.

#### 2.3.1.1 Rocket motor casing (RMC)

It is a cylindrical structural part which encloses the propellant grain, solid propellant igniter and insulating material[13]. The solid propellant combustion process takes place inside the combustion chamber with in motor casing. RMC required to resist internal pressure that resulting from the solid propellant combustion, which is estimated as 3.00 MPa to 30.00 MPa, designed with an appropriate safety factor. RMC is most frequently constructed from metal materials of high strength steels and recently from composite materials. In designing RMC, we have to know the effect of stresses induced in a casing from combustion chamber pressure and the thermal stresses, stresses due to bending loads and inertial forces while determining the required thickness of the casing and determining material of the motor casing.




(a) Sectional view of rocket motor and its components

(b) Full representation of 3-D view of SRM

Figure 2.1 Constructional feature of typical solid rocket

### 2.3.1.2 Insulation

An insulation in SRM is a layer of heat protection material placed in between the internal surface of the casing material and exposed external surface of the burning propellant. The use of insulator material is just to prevent the casing from attainment of temperature that can damage its structural integrity[14],[15], [16]. The high temperature of propellant combustion gases inside SRM may ranging from 2,000 $^0$K to 3,500 $^0$K, which needs a thermal protection system of subcomponents of the SRM. Usually, insulator materials are characterized by very low thermal conductivity, good capacity of ablative cooling and high heat capacity. The common thermal insulation materials in SRM casing application includes Ethylene-Propylene-Diene-Monomer (EPDM) with reinforcing materials.

### 2.3.1.3 An igniter

It is one of an essential part of SRM construction, which is secured in the rocket motor to achieve the ignition process in SRM. Basically, an igniter induces the combustion reaction inside combustion chamber of SRM in a controlled manner by producing sufficient amount of heat flux. A rocket motor igniter provides the necessary quantity of heat to ignite or initiate the rocket motor propellant[17]. The SRM igniter uses an electrical system (EED) to stimulate the ignition of ignitor charge, which in turn ignites a propellant grain[17].

An ignition system provides sufficient energy to a solid rocket propellant non-inhibited or exposed surface to initiate stable combustion[2]. The charge of ignitor requires a tremendous amount of specific energy, and designed to release hot gases or a solid particles of ignition charge. The heat releasing compositions used in a pyrotechnic ignitor includes black powder (BP), metal-oxidants and solid propellant. The igniter, which is a pyrotechnic device, starts the rocket operating when an electrical signal is received.

### 2.3.1.4 Rocket nozzle

The high pressure and temperature gases of combustion products of rocket motor are ejected through a converging-diverging section of a rocket motor called a nozzle. Inside a motor the chemical reaction take place to produce chemical energy of the propellant and then converted to kinetic energy that propels the motor known as the thrust [18],[19].

The proper selection of material for nozzle is a significant step of design of rocket motor, particularly for the nozzle throat where an erosive hot particle flow will take place. Some of the materials used for nozzle throat include refractory metal, and composites of carbon or graphite that can resist erosive burning effects.

### 2.3.1.5 Solid propellants

It is a cast in with various geometric configuration or propellant grain. The two main categories of solid propellant grains configurations are case bonded and free-standing grain configuration.

A case-bonded configuration is made by directly casting the grain into the motor case, which is already made with thermal insulation material.

In a free-standing configuration, the grains are not directly cast into the motor case. Instead, the propellant is pre-casted in some special mold. Once the curing process of the cast is completed, the grain is extracted from the mold. Therefore, the grains are then loaded to the insulated motor case on the assembly line. This type of configurations are called cartridge-loaded grains configuration. The geometric design of a grain configuration defines the performance of a given solid propellant type and nozzle design.

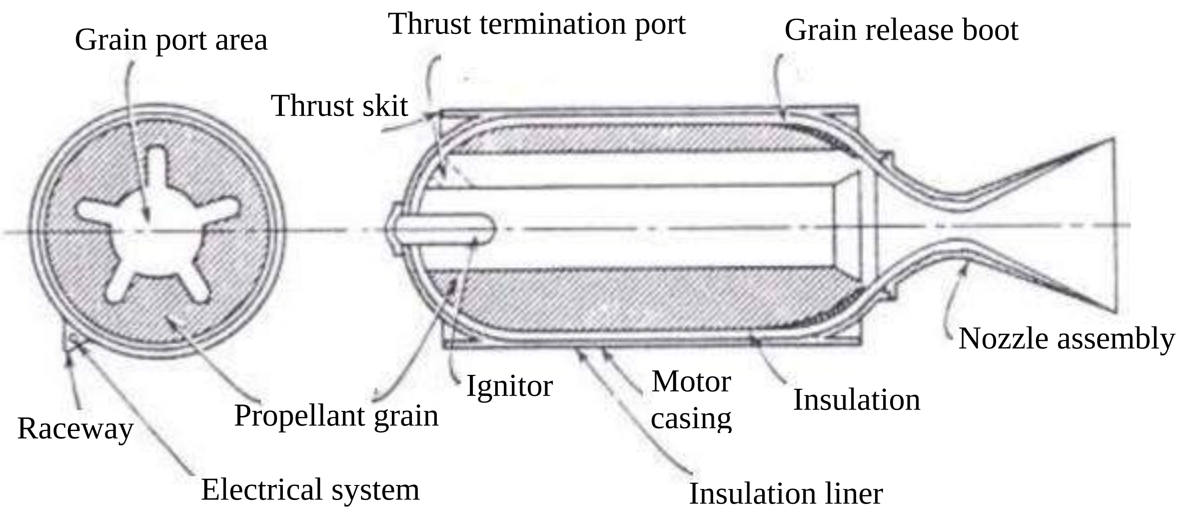



Figure 2.2 Generic SRM components and its cross-sectional view

The propellant in SRM burns at the proper rate known as burn rate in order to maintain the desired amount of thrust profile and need to have structural continuity to resist the pressure load and acceleration introduced during ignition operation. The propellants are classified into two categories: Double base propellant (DBP), and Composite propellants (CP)[20], [21].

In DBP the fuel and an oxidizer composition are mixed in a molecular level. The primary ingredients in these types of propellants are nitrocellulose (NC) dissolved in nitroglycerine (NG) with minor additives. Both NC and NG ingredients are explosives containing fuel and oxidizer within molecular structure. DBP have been used in military applications (primarily for the use of ballistic missiles)[20],[21].

The second general type of solid propellant type is composite propellant (CP). CP is a heterogeneous mixture of fuel, oxidizer and binder. Fuels are generally metallic powders and oxidizers are crystalline materials. Aluminum (Al) being the most common metallic powder fuel while ammonium perchlorate (AP) is the most popular crystalline oxidizer. The chemical formula for AP is $NH_4ClO_4$.The binder materials are rubber-based material that serves to hold the mixture together in a cohesive grain. The binder material includes hydroxyl-terminated polybutadiene (HTPB) and polybutadiene nitrile (PBAN). To improve the ballistic performance of the propellant, small amounts of highly energetic materials such as “Her Majesty's Explosive” (HMX) have been added [21].

### 2.3.2 Solid propellant burning rates

The burning rates of solid propellant used in SRM are a function of many parameters such as chamber pressure Pc and temperature Tc. Robert's law expresses the dependency of propellant burn rate on combustion chamber pressure as $r_b = ap_c^n$. where $r_b$ is the burn rate (cm/s or mm/s or in/s), ‘a’ is the burn rate coefficient, and ‘n’ is the burn rate exponent[20]. Table 2.1 gives the values of constants for particular propellants.

Table 2.1 Characteristics and values of constants for common propellant formulations.

| Combination | Density (Kg/m$^3$) | $C^*$(m/s) | Temperature T (K) | Pressure $P_c$ (MPa) | coefficient a | exponent n |
|---|---|---|---|---|---|---|
| X | 1840.0 | 1542.0 | 3635.0 | 2.75–7.00 | 0.416 | 0.32 |
| Y | 1800.0 | 1528.0 | 3395.0 | 2.75–5.00 | 0.400 | 0.31 |
| Z | 1760.0 | 1570.0 | 3393.0 | 2.75–7.00 | 0.562 | 0.36 |

The ingredients of X, Y and Z in Table 2.1

| TP-H-1202 | Al (%) | AP (%) | HMX (%) | HTPB (%) | PBAN (%) | Application |
|---|---|---|---|---|---|---|
| X | 21 | 57 | 12 | 10 | - | Star 63D |
| Y | 18 | 71 | - | 11 | - | Star 37 |
| Z | 16 | 70 | - | - | 14 | Titan IV |

### 2.3.3 General requirements of SRM propellant igniter

1. The temperature of the surface of propellant must be increased above its auto-ignition level of temperature.
2. The pressure in combustion chamber should be increased beyond the minimum pressure needed for stable burning of particular propellant.

3. Ignition delay, from the point of application of electrical pulse to the point where 10% of the peak pressure is attained in a combustion chamber should be in a specified limit.
4. Ignition interval, from 10 % to 90 % of motor peak pressure, should be short enough or else heat transfer will remove more heat than that is generated by the igniter gases.
5. The rate of pressure rises (dp/dt) in a motor combustion chamber during ignition transient period should not be excessively high leading to undesirable peaks loads.
6. Igniter should meet the requirements of size, weight and interface constraints.
7. Igniter should satisfy the intended mission, and shelf life or storage requirements.
8. Mode of initiation and electrical characteristics should be as specified.

**2.3.4 Classification of SRM Igniters**

Ignitors for rocket propulsion purpose are classified according to various bases:

1. Classification based on the mounting location of igniter [22]
2. Classification based on the energy released system. [22]

**2.3.4.1 Classification of SRM ignitor based on Mounting Locations**

- Head-end mounted igniter
- Aft-end/nozzle-end/externally mounted igniter
- Toroidal igniter
- Grain mounted igniter

The following figure (Figure 2.3) illustrates an alternative location of igniter in SRM.

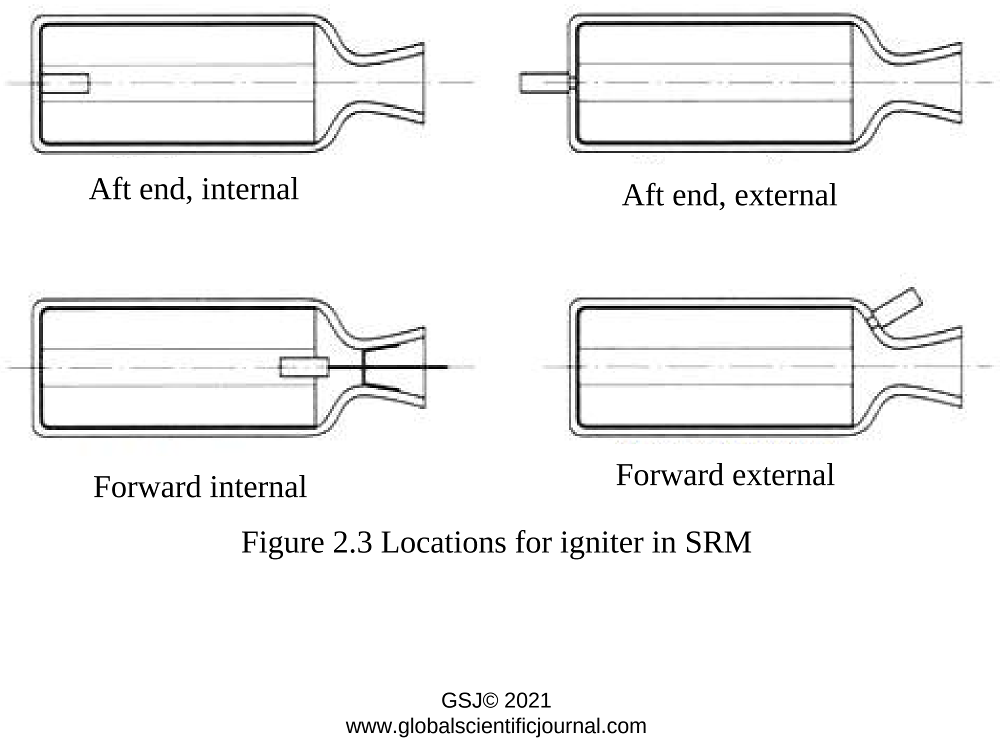



Figure 2.3 Locations for igniter in SRM

The propellant mass of igniter is assumed to be smaller than 1.0 % of propellant mass of main charge and it should burn at low chamber pressure or at low specific impulse $I_{sp}$. Propellant charges are generally fitted with head end ignition system, but it adds to undesirable head weight after combustion. In addition, igniter casing can damage propellant bore and structurally it is unsafe to keep igniter at head end side. In some designs, head ends are closed and safety prevents placement of igniter at head end. Recent trend is to use aft end or nozzle end ignition systems. In this case, igniter is structurally separated from the motor casing. It is ejected as soon as initiation of propellant is completed. This type of ignition system needs higher igniter charge, as loss of unburnt igniter charge is higher. This suppresses ignition peaks and is preferred now a day for staged rockets, where it can be mounted at the top of jettisoned stage for initiation of next stage.

When an igniter is placed on the forward end, the gas flow over the surface of propellant facilitates ignition process. When it is mounted at aft end, there exist a gas motion near the forward end. If igniter is mounted on the nozzle, the hardware and support of an igniter discarded immediately after the igniter has consumed its propellant. The two basic types of ignitors in this regard: pyrotechnic and pyrogen igniters; as discussed below in section 2.4.3.2.

### 2.3.4.2 Classification based on Energy Release System

SRM are ignited using ether a pyrotechnic or a pyrogen igniter. The pyrotechnic igniters act directly onto the propellant surface of the SRM with very hot particles which in turn, initiate/ignite the solid propellant. The pyrogen igniters is applicable for very large rocket motors such as ballistic missiles. The propulsive force (thrust) of a rocket is resulting from the combustion of propellant at high pressure and temperature[23].

#### i. Pyrotechnic igniter

It is defined as a SRM igniter employing a solid explosive charges or energetic materials usually propellant which is capable of providing energy to burn large surfaces within short burning period[23], [24]. Pyrotechnic ignitor consists of pyrotechnic chemicals or charges in the form of various size and shape as powder, granules, or pellets as main charge. The powders are the finer mesh sizes, while granules are larger mesh size. The trend is away from the use of powders as the main charge because of their tendency towards brisance or shattering power and excessive ignition shock. Pellets are generally preferred due to their ballistic reproducibility and ability to obtain longer and more controllable burning time compared to powder charges. Pellets are produced from same mix as powders, but with addition of a binder to facilitate granulation and pelletizing.

Pyrotechnic compositions contain fuel and oxidizer which are elements, alloys or compounds. Frequently used elemental fuels are metallic powders of aluminum, magnesium, titanium, iron, manganese, tungsten, boron, etc. compounds used as fuels are hydrocarbon, picrate's, carbohydrates, sulphides of arsenic and antimony, etc. The oxidizers used are easily reducible metallic oxides or peroxides, nitrates, chlorates, and chromates of alkali and alkaline earth metals. The charge is contained in vented or perforated tubes. The initiation is generally through electrical means.

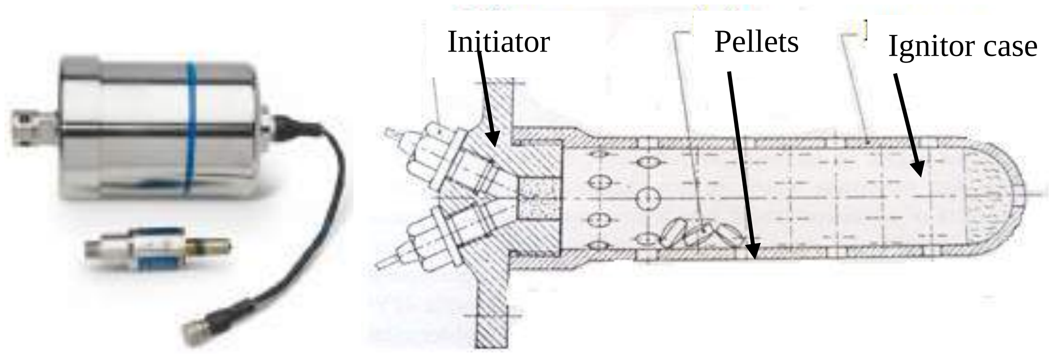



Figure 2.4 Pyrotechnic igniter

Burning process is performed in stages; the first stage, when an electrical signal is received from electric circuit, the igniter releases small amount of energy of sensitive powdered pyrotechnic (BP) housed within the initiator called squib (or the primer charge); in the next stage, the booster charge is ignited by heat released from the primer charge (squib); and the final stage, the main ignition charge of rocket propellants is ignited with stable rate[23], [24]

Proper selection of igniter charge is based on available propellant type, a rocket motor characteristic, and ignition transient requirements. Table 2.2 shows an important characteristic of some common pyrotechnic materials used as main charge.

**Table 2.2 Common properties of pyrotechnic materials used as main charge**

| Composition | Calorific value (MJ/kg) | Ignition temperature $T_{ig}$ ($^0$C) | Pressure 0.4g/48cc (MPa) |
|---|---|---|---|
| B/KNO3 | 7.95 | 520 | 2.84 |
| Al/NH4ClO4 | 10.75 | 370 | 5.39 |
| Al/KClO4 | 10.67 | 370 | 5.39 |
| Ti/KClO4 | 7.62 | 560 | 4.02 |
| Ti/CuO | 3.10 | 750 | 0.69 |

| | | | |
|---|---|---|---|
| Zr/KNO3 | 4.48 | 620 | 1.67 |
| Zr/KClO4 | 6.07 | 500 | 3.24 |
| ZrH2/KClO4 | 5.69 | 550 | 2.26 |

### ii. Pyrogen igniters

Pyrogen igniter designed in the same principles as pyrotechnic ignitor for a small rocket motor application and consists of a cast propellant grain of fast-burning type as the main charge[23].

**Table 2.3Comparison of pyrotechnic and pyrogen igniter**

| Types of ignitor | Pyrotechnic igniter | Pyrogen igniter |
|---|---|---|
| Charge/ configuration | Powder/pellet/or granule type pyrotechnic charge used as main charge in vented or perforated containers | Fast burning propellant grains cast in metal /composite case with single/multiple nozzles. |
| Action time | Short (around 100 ms) | The Long is from 250 to 1000ms |
| Repeatability | Moderate control only possible | Close control only possible by varying surface area and geometry |
| Size and cost | Lower cost, Suitable for small motors, if the motor size is large, the quantity of charge required for initial port pressurization will be large and necessitates elaborate hardware | Higher cost. But for large motors, propellant cost offsets the increased hardware and labor cost |
| Rate of pressure rise | Very high and can cause ignition shock | Very low |

## CHAPTER THREE

## SOLID PROPELLANT ROCKET MOTOR IGNITION THEORIES AND ANALYTICAL DESIGN REQUIRMENTS

### 3.1 Introduction

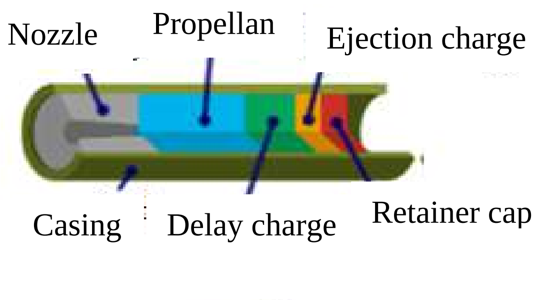
Ignition of rocket motor is an important and vital event in the combustion of solid propellants. It is a transient phenomenon leading to steady state combustion of propellant [2]. An igniter should provide optimum energy to raise the surface temperature of propellant grain from ambient temperature to its ignition temperature. It should pressurize the initial free volume of the motor to a pressure level well above the minimum pressure required for steady state combustion of propellant without exceeding maximum expected operating pressure limit of the motor. The rate of pressurization should be smooth to avoid pressure peak and instability. Ignition delay should be with in specific limits. Moreover, igniters should be easy to assemble and economical to produce.

Ignition involves the transfer of heat or thermal energy from suitable source; that is the ignition charge to the propellant till steady state combustion condition is achieved. The time taken to this event to happen is called "ignition delay". In solid propulsion, energy is transferred from a pyrotechnic igniter, may be black powder, gun powder or any other composition having high heat flux to the propellant surface. In the family of solid propellants, while double base propellant (DBP) needs comparatively lower energy for ignition, composite propellants however need higher energy in terms of heat flux. A double base propellant gets ignited with small quantity of black powder (potassium nitrate + sulfur + charcoal) of different sizes ($G_{12}$ to $G_{40}$) by means of electric match. The device which contains ignition material and match inside a container made from aluminum or tine material is called igniter.

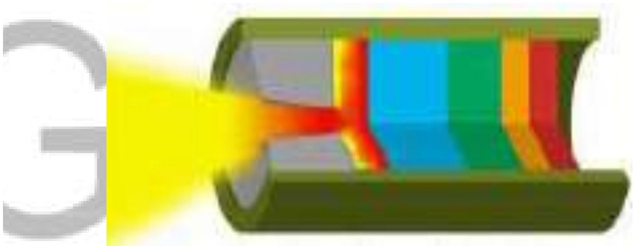
Generally, energy is transferred to the propellant surface by all three mechanisms of energy transfer namely, conduction, convection and radiation. The impingement of hot solid particles from the burning igniter is effective in igniting the propellant surface. $KNO_3$, sulfur, carbon along with binders are used for composite propellant ignition. These gasless igniters have a high reaction temperature and produces hot particles, which transfer thermal energy by both direct impact and radiation[25],[26].

### 3.2 Ignition sub events of SRM propellant

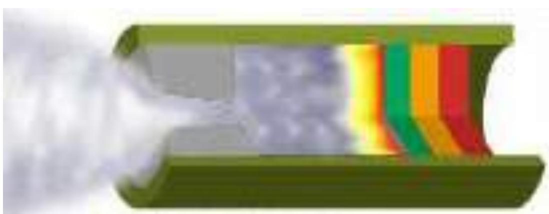
Ignition of solid propellant rockets has a series of complex chemical processes[27],[28]. It is a fast, short lived transient heat transfer phenomenon, which starts with triggering of electric pulse and terminates at the point of time matching with the establishment of stable combustion front at the propellant surface. During this short period several events take place simultaneously like initiation of igniter composition, creation of hot igniter gases with in-built solid unburnt igniter charges, filling of rocket chamber free volume by igniter gases, heating of propellant surface to self-ignition temperature, establishment of flame front at the propellant surface, flame spreading and establishment of stable self-sustained burning front at the propellant surfaces. Although, these events do not occur in tandem, a scheme to predict ignition delay, ignition pressure peaks, kinks and other abnormalities need theoretical studies. Overall, it is a heat transfer phenomenon but role of fluid mechanics, phase change, computational fluid dynamics (CFD), and chemical kinetics cannot be neglected[29].



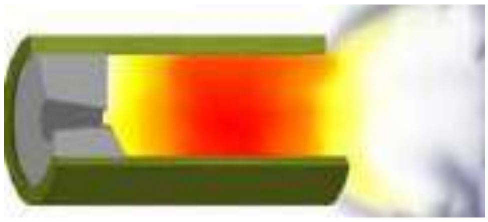

(a) SRM diagram



(b) Motor boosts the rocket in to sky



(c) Delay is activated



(d) Ejection charge is activated

Figure 3.1 The diagram illustrates the working principle of

### 3.3 Igniter composition based on the type of propellant used in SRM

The following table relates the type of igniter material for the selected type of propellant and also shows the Propellant characteristics for design of particular igniter. Table 3.1 shows the components of ignitor based on propellant type used in the ignition process.

**Table 3.1** Prepared igniter composition based on propellant type

| Type of propellant | Ignition temperature (°c) | Stable combustion pressure (Kg/cm$^2$) | Type of igniter prepared |
|---|---|---|---|
| Double base propellant (DBP) | 165 | 35 | black powder |
| Composite propellant (CP) | 240 | 15 | Metal/oxidizer |
| Composite modified double base propellant (CMDB) | 175 | 20 | Metal/oxidizer |

Igniter composition is obtained in various forms like powder, pellet or their combinations. A typical igniter composition contains fuel, oxidizer and binder. Fuel should have high heat of combustion, physical and chemical stability in the operating temperature range of -40°c to +60°c. It should be non-hygroscopic and easily pulverizable. It should be readily oxidized and combustion products should produce desired effect. Ingredients must be readily available, stable in operating temperature range and non-hygroscopic. Binder should reduce sensitivity towards impact and friction and increase mechanical properties of produced pellets. It must be compatible with other fuel and oxidizer and should give sufficient wetting to the igniter ingredients for processing in the granular form. For reproducibility, it must be thermoplastic in nature. The following shows different types of black powder used as ignition charge in solid rocket motor propellant[30],[31].

Figure 3.2 Different size Black powder used as ignition charge in SRM

Igniter compositions typically contain magnesium (Mg) or boron (B) powder with potassium nitrate ($KNO_3$) in processed form. For igniting cordite or plastic propellants, Mg/$KNO_3$ based composition, which gives little ignition shock, is preferred. In general, for double based propellants, igniter compositions producing hot gases only are prepared while for composite propellant initiation; hot particles in the streams of igniter combustion products are desired. For smaller rockets, pyrotechnic compositions are sufficient to produce high temperature gases at desired pressure level in the chamber free volume but for large size booster applications, another smaller rocket is used for initiation of main charge. This system is called pyrogen ignition system, which is initiated by pyrotechnic ignition system. An ignition process has been studied by a number of investigators. Most of early ignition studies were carried out on gem primers. Different propellant compositions ignite differently. In general, ignition delay is less for fast burning double base propellants and longer for low burning compositions.

**3.4 Ignition theory**

In thermal ignition theory a materials are supposed to ignite when the exposed surface reaches the ignition temperature[32]. By calculating the surface temperature versus time, the time to ignition can be easily obtained [33], [34]. A number of attempts have been made in the past to establish a satisfactory ignition theory. Igniter design becomes very critical due to the fact that this ignition related processes have not been clearly understood and mismatch of systems may lead to ignition delay, pressure peaks, propellant chuffing, and kinks or in some cases extinction of charges also. For theoretical understanding of behavior of igniters, the following theories have been made and are very helpful [35]:

**3.4.1 Hot-spot theory**

During ignition of a reactive material, the energy from chemical reaction and the thermal energy of combustion process is converted to heat and sound in localized regions in a combustion chamber, that is called “hot spots” [36]. If heat is placed into a small volume of reactive material, the material starts to decompose. The rate of decomposition is proportional to the amount of temperature. Thus, the higher the temperature in a local volume, the faster the decomposition reaction. The increase in temperature increases the reaction rate and heat is produced even faster. Thus, an accelerating and self- sustaining reaction has been started. This in turn spreads to the surrounding materials. This is called the hot-spot theory of initiation.

3.4.2 **Deflagration to detonation theory** (DDT)

At face of propellant surface heat is being received from the burning reaction, by radiation, causing the surface to melt. The melted propellant receiving still more heat, then boils and evaporates. During both the melting and vaporization stages, the propellant begins to decompose. The decomposition products react with each other in the flame region, and here the combustion becomes complete. The product gases from the hot combustion flow away from the surface through nozzle. As long as the flame continuous to radiate at the same rate, the boiling continuous at the same rate as does the vaporization and decomposition. The entire process then maintains a steady rate, propagating its way in to the propellant material at a constant velocity[37],[38]..

### 3.4.3 Burning rate theory

Burning Rate Theories Based on Combustion Reaction Rates. The ballistic properties of solid propellent are divided into two distinct areas the magnitude of the available energy of the system and the rate at which the energy is released; that is, the burning rate[39],[40], [41]. The mathematical relation between burning rate and the motor combustion chamber pressure is governed by the following equation,

$$r_b = a p_c^n \tag{3.1}$$

The relation in Equation (3.1) is formulated by St. Robert's and is a propellant burn rate law and can be plotted by using MAT LAB simulation software for a pressure of 0 Psi to 1000 Psi and the pressure coefficient a = 0.436 (in/sec)/(Psi$^n$), exponent n = 0.165 is as in the following

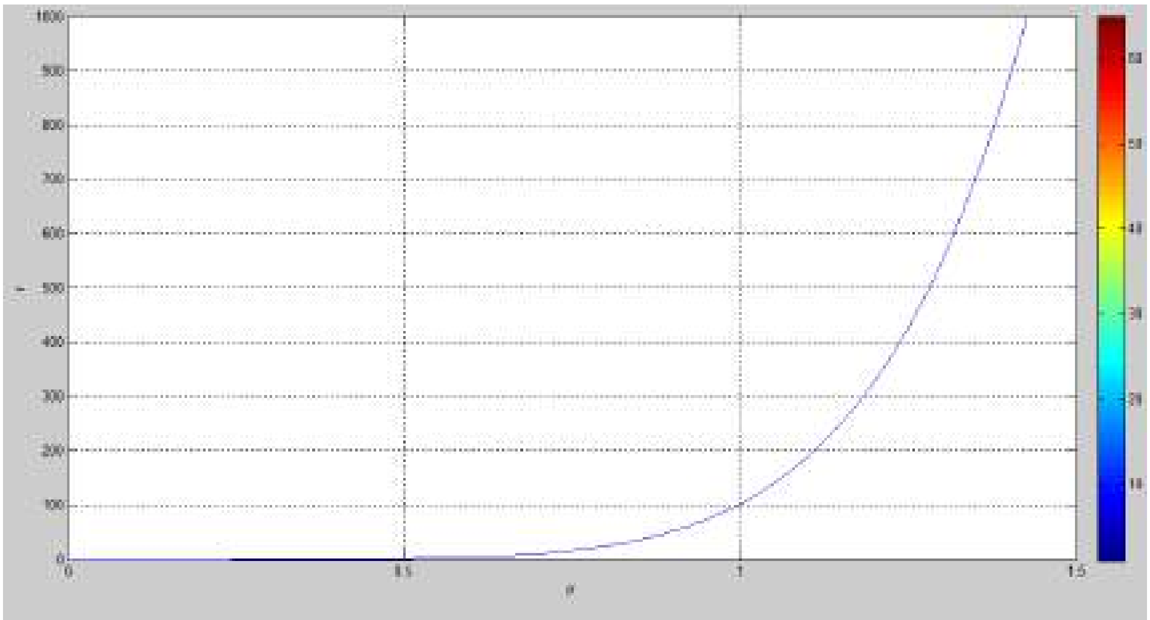


Figure 3.3 MATLAB simulation for combustion chamber pressure (Pc) versus burning rate ($r_b$) for particular black powder ignition charge.

The relation in Equation (3.1) can be also rewritten as:

$$r_b = r_b\left(T_{ref}\right).\exp\left(0.01\sigma_p\right).\left(T - T_{ref}\right) \tag{3.2}$$

The empirical expression in Equation (3.2) gives the burning rate of a particular propellant. The values for constant “a” and exponent “n” are derived from “strand burner tests” that can be performed by small sub-scale burning rate test motor firing at different operating pressures. The normal burning rate coefficients and pressure exponents of gun powder for various applications is 0.436 (in/sec)/(Psi$^n$) and 0.165 respectively. The sensitivity of $r_b$ to solid propellant can be defined in terms of a temperature coefficients:

$$\sigma_p = \frac{1}{r_b}\left[\frac{\delta r_b}{\delta T}\right]p \tag{3.3}$$

$$\pi_k = \frac{1}{p}\left[\frac{\delta p}{\delta T}\right]k \tag{3.4}$$

In the use of solid propellant rocket, the whole propellant chamber must be built to contain the maximum pressure of the burning program. If any part of the burning program is below the require amount of chamber pressure, the penalty is incurred in the resulting impulse compared with the achievable mass ratio of the motor, the mass ratio is being limited by the required hardware. Therefore, the critical problem in the use of solid propellant rocket for long range flight reduces to the prediction of the burning program of the propellant. This program is arranged by grain configuration. If it is designed properly, the success of motor depends entirely upon the designer's ability to predict the burning rate inherent in the propellant compound as modified by propellant temperature and chamber pressure in accordance with an empirical burning rate formulation that fits for many propellants:

$$r = bp^n e^{\alpha\left(T_0^{'} - T_0\right)} \tag{3.5}$$

Where the parameters $r$ is burning rate (in/sec), $b$ is constant, $p$ is chamber pressure, $n$ is pressure dependency exponent, $T_0^{'}$ is standard propellant temperature, $T_0$ is actual propellant temperature, and $\alpha$ is temperature sensitivity of burning rate.

The properties $n$ and $\alpha$ are usually constant over the normal range of operating condition. An improved solid propellant should have the following characteristic features

a. Required burning rate range
b. Reliability of burning rate
c. Low- and high-pressure exponents as desired
d. Low temperature sensitivity
e. Smooth ignition
f. High transport efficiency of the product
g. Freedom from unstable burning
h. Freedom from transition to detonation

### 3.4.4 Analytical model theories

The three models of ignition theories referred to as solid-phase theory, heterogeneous-phase theory, and gaseous-phase ignition theories. The basic differences in between ignition theories or models is on the location of existence of exothermic reaction with respect to the non-inhibited propellant surface and the physical state of the reacting compositions.

### 3.4.4.1 Solid phase theory

In solid phase theory it is assumed that propellants undergo exothermic reaction in solid phase and does not considers the heat release and diffusion in the gas phase. Making the classical assumption of one dimensional (1D) heat flow in semi-infinite solid, the expression for thermal heating is given by:

$$\rho c\left(\frac{\partial T}{\partial t}\right)=k\left(\frac{\partial^2 T}{\partial x^2}\right)+pQZ\exp\left(-\frac{E}{RT}\right) \tag{3.6}$$

Where ρ is solid state density of propellant (gm/cm$^3$), C is specific heat at constant pressure (Cal/gm-$^o$C), T is temperature ($^o$K), t is time (s), K is coefficient of thermal conductivity (Cal/cm-sec-$^o$C), Q is heat of reaction per unit mass (Cal/gm), Z is pre-exponential factor (1/s), E is energy of activation (Cal/mol), R is universal gas constant (Cal/$^o$k-mol), and X is distance from gas-solid interface (cm).

In recent studies, some terms have been included to the Equation (3.6) to incorporate factors that influence the energy accumulation rate as:

$$\rho c\left(\frac{\partial T}{\partial t}\right)=k\left(\frac{\partial^2 T}{\partial x^2}\right)+pcr\left(\frac{\partial T}{\partial x}\right)+\beta\dot{q}\exp\left(-\beta x\right)+pQZ\exp\left(-\frac{E}{RT}\right) \tag{3.7}$$

The components of equation (3.7) are $pcr\left(\frac{\partial T}{\partial x}\right)$ is surface regression effect due to ingredient reaction, $\beta\dot{q}\exp\left(-\beta x\right)$ is Energy absorption due to optical transparency, r is a linear regression rate of solid propellant surface (cm/s), β is Extinction coefficient for radiant transmission (1/cm), and $\dot{q}$ energy flux per unit area (Cal/cm$^2$/s)

### 3.4.4.2 Gas-phase theory

The gas-phase theory postulates that the ignition process is controlled by reactions between fuel and oxidizer that has evaporated, possibly including atmospheric oxygen. A 1-D analytical model depicting this theory with the exothermic reaction rate being dependent on the fuel-oxidizer concentrations and the gas temperature. The PDE describing the mass and energy transfer of the reaction are given as: The PDE describing the mass diffusion

$$\frac{\partial C_f}{\partial t} = K_f\left(\frac{\partial^2 C_f}{\partial x^2}\right) - C_f C_0 Z \exp(-\frac{E}{RT}) \quad (3.8)$$

$$\frac{\partial C_0}{\partial t} = K_0\left(\frac{\partial^2 C_0}{\partial x^2}\right) - C_f C_0 Z \exp(-\frac{E}{RT}) \quad (3.9)$$

- The PDE describing energy diffusion:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2}\right) + \left(\frac{Q}{\rho C}\right) C_f C_0 Z \exp(-\frac{E}{RT}) \quad (3.10)$$

Where $C_f$ is a concentration of reactants in fuel (gm/cm$^3$), $C_0$ is a concentration of reactants in oxidizer (gm/cm$^3$), $K_0$ is mass diffusivity (cm$^2$/sec), and $\alpha$ is thermal diffusivity (cm$^2$/sec)

### 3.4.4.3 Heterogeneous phase theory

This theory consists of one-dimensional model with mass flow and energy diffusion into semi-infinite oxidizing gas domain and heat conduction into a semi-infinite solid. The surface reaction, which provides the total available energy, is assumed to be rate dependent as a function of temperature, as described by an Arrhenius type relationship. This theory is mathematically expressed as:

$$\left(\frac{\partial T_c}{\partial t}\right) = \alpha_c\left(\frac{\partial^2 T_C}{\partial x^2}\right) \quad (3.11)$$

$$\left(\frac{\partial T_g}{\partial t}\right) = \alpha_g\left(\frac{\partial^2 T_g}{\partial x^2}\right) \quad (3.12)$$

$$\left(\frac{\partial C_0}{\partial t}\right) = K_0\left(\frac{\partial^2 C_0}{\partial x^2}\right) \quad (3.13)$$

$$\left(\frac{\partial C_p}{\partial t}\right) = K_p\left(\frac{\partial^2 C_0}{\partial x^2}\right) \quad (3.14)$$

Where p = refers to the products of combustion, c = the condensed phase, g = the gas phase.

### 3.5 Selection criterion for propellant ignition

An ignition is determined by the surface temperature reached after ignition delay time $t_{ign}$ from the beginning of its heating with $t_{ign}$ being dependent on intensity of the heat exchange. In reality the transfer of energy to surface of the propellant being analyzed from the ignition gases takes place with the help of:

- Mechanism of free and forced convection
- The radiation of hot ignition gases and the hot solid particles of the igniter charges
- Collision of hot particles of the igniter charge with the non-inhibited surface of propellant which is being ignited
- The thermal conduction in places of contact between solid particles of the igniter charge and the grains of propellant being ignited.

The ignition delay ($t_{ign}$) is the time from the start of burning an igniter until the time at which the chamber pressure reaches 10% of the maximum chamber pressure have been recorded in the closed vessel experiment test (see Figure 3.4).

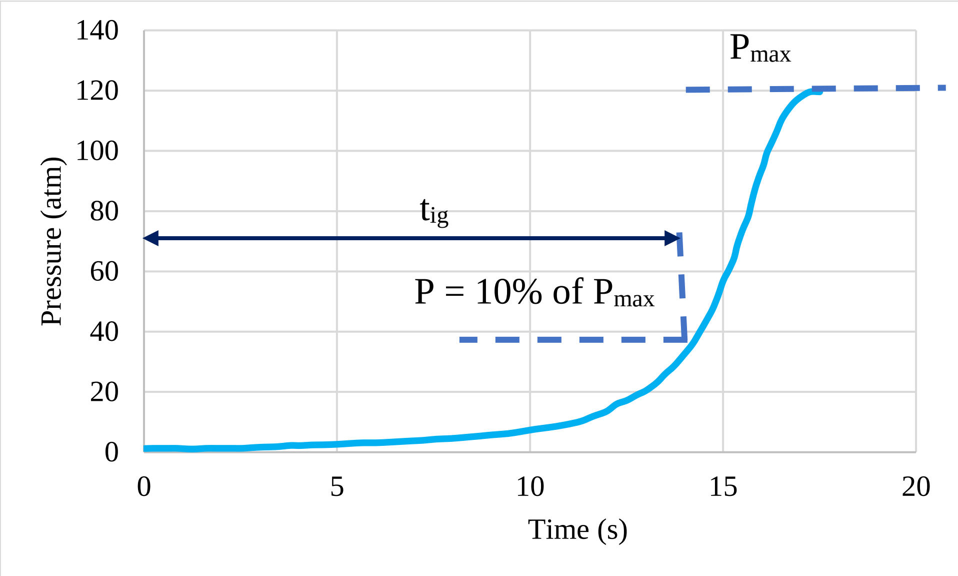



Figure 3.4 Pressure (P) verses ignition time ($t_{ig}$) graph

### 3.6 Igniter qualification

Amount of heat evolved by the combustion of pyrotechnic composition is experimentally determined by burning the composition in bomb calorimeter and is theoretically calculated by Hess law. For experimental determination, a certain weighted amount of composition is burnt in bomb calorimeter, placed in a water bath and calval is determined by rise in temperature of water. Bruceton stair case method and Julius peter apparatus determines impact and friction sensitivities respectively [8]. The properties of some of the typical igniter compositions are given in the table 3.2.

Table 3.2 Properties of typical igniter compositions

| No | Type of igniter | Cal-val (Cal/g) | Solid: Gas | Application |
|---|---|---|---|---|
| 1 | Black powder | 730 | 60 : 40 | Double base propellants |
| 2 | Mg-$KNO_3$-PEC | 2100 | 97 : 03 | Composite propellants |
| 3 | B-$KNO_3$-PEC | 1700 | 97 : 03 | CMDB and high altitude |
| 4 | Al-$KClO_4$ | 2550 | 93 : 07 | Composite propellants |
| 5 | Al-$NH_4ClO_4$ | 2570 | 80 : 20 | Composite propellants |
| 6 | Mg-PTFE | 2200 | 93 : 07 | High energy and fuel rich propellants |

# CHAPTER FOUR

# DESIGN OF PYROTECHNIC IGNITER AND ITS COMPONENTS FOR SOLID ROCKET MOTOR APPLICATION

## 4.1 Introduction

The theories of ignition heat transfer from ignitor charge to main propellant surface, the propellant burning, the ignition flame spreading over propellant surface, deflagration phenomenon and filling chamber with hot gases are some of the aspects in the design of pyrotechnic igniters. In general, the numerical models of the physical phenomenon and chemical processes considered in the design of igniters are not complete and accurate. The exact mathematical analysis of SRM igniter is heavily depends on an experimental result, including past successes and failures with full scale motors. In this thesis the effect of some of the important parameters has been predicted, for using data from previously developed SRMs.

## 4.2 Design Requirements

The main task of SRM ignition system designers is determination of an appropriate types of system to be used for a specific rocket application. It is important to assume and evaluate the factors influencing the design and construction. The main factors under this aspect includes:

- The required ballistic performance
- The system interface and
- The operating environment

### 4.2.1 The ballistic performance

The ballistic performance includes ignition transient characteristics, ignition times, and the level of shock wave outputs. Restrictions on these features are decided based on the end use requirements. Thus, it may be stated in many ways as:

1. The time required to attain a given performance level, usually taken at 10 % of maximum chamber pressure and attaining 75 % of average thrust.
2. The envelope of thrust versus time, pressure versus time, or impulse versus time.
3. The limit on thrust rate on set or pressurization

The anticipated mission may require an intentional delay of time in between an application of activating energy (ignition pulse) and motor propellant ignition by the igniter. This delay time may variety from a few milli-seconds (ms) to several seconds (s). These ignition delay systems are made as an integral part of the igniter.

With a defined performance parameter, designer of particular ignition system have to evaluate the effect of motor design characteristics on the selection of the types of igniter. These includes the configuration of SRM (internal), the grain design (size, shape and geometry), propellant material properties, and the type of nozzle end.

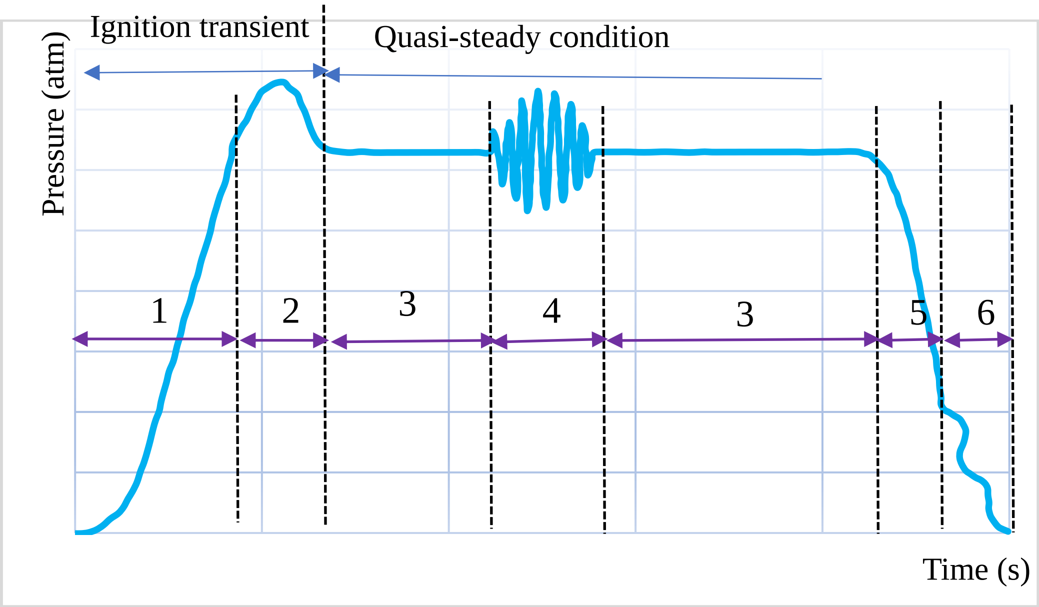



Figure 4.1 Burning rate and the ballistic performance of the propellant

The numbered regions in Figure 4.2 represents:

1. Ignition unsteady non-linear burning rate
2. Pressure overshoot Steady state erosive burning
3. Normal steady state burning
4. Instability (Acoustic) unsteady linear burning rate
5. Pressure decrease unsteady non-linear burning rate
6. Instability (Volume or L) unsteady linear burning rate

### 4.2.2 Ignition transient of SRM

During ignition transient process, unexpected variation in the flow conditions within the combustion chamber may happen, which is obviously caused due to the presence of violent chamber pressurization. Subsequently, a high static and dynamic structural and thermal loads on the motor and the launcher system in general, have been considered for many launch mission failures. The some of the examples of launch mission failure ever happened includes the failure of Challenger SRMU-PQM1[42]. An ignition transient of solid propellant rocket (SPR) is defined as the time interval between initiation of first electric signal for motor start-up to the attainment of the steady design operative condition of the motor chamber. These can be categorized into four distinct phases (See Figure 4.3):

1. An electric delay phase: which indicates the delay between the application of electrical signal to the start-up of the igniter charge in a motor. It takes only few milliseconds.
2. Induction interval phase: which is an interval between the start-up of the motor igniter charge to the first detection of flame on main charge of propellant surface (i.e. exposed surface). The interval is approximated as 1/5 of the ignition transient.
3. Flame spreading phase: which is an interval between the first detection of flame on the propellant surface to the instant of a complete ignition of the main propellant charge. It takes approximated 1/5 of the ignition transient period.
4. Chamber filling phase: which is an interval between the complete ignition of the main propellant charge (grain) to an attainment of an equilibrium condition of the chamber. It takes about 3/5 of the whole ignition transient period, pressure rises by a factor of 5.

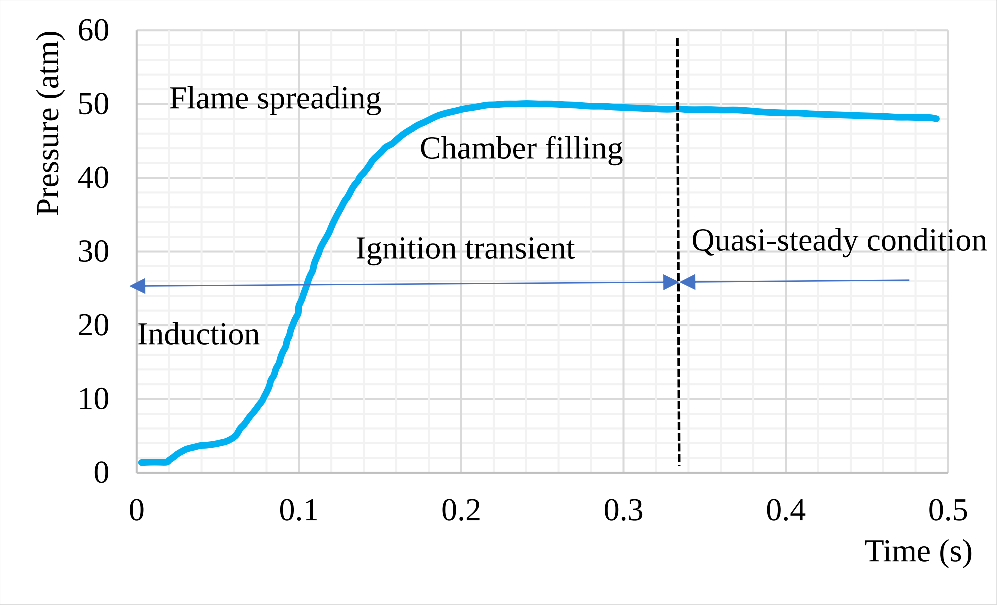



Figure 4.2 The ignition transient intervals of SRM

**4.2.3 System Interface**

The restrictions on physical component size, its specific weight and geometric configuration are imposed on the design of SRM to ensure precise fit with other component parts. These system restrictions affect igniter characteristics, like the mating parts with electrical ignition start-up system or other means of enhancing the fire to igniter, attachments to safe arm actuation methods involved and also restrict the size or location of external igniter components.

### 4.2.4 Environmental condition

The environmental condition in the sense of SRM igniter design includes the storage conditions of the igniter materials, the use environment, and also the removal polices which are usually are detailed at the beginning of its design effort.

## 4.3 Design of rocket motor case

A rocket motor case (RMC) is a structure or simply a container which is capable of holding various subsystems of the rocket as we have discussed in Chapter-3 of this thesis. The rocket motor structure should satisfy the suitable stability condition of the vehicle against the random variations of system parameters. The RMC must possess a higher strength-to-weight ratio to satisfy mission requirements of the rocket. RMC is a fundamental component of a rocket that can influence an overall performance of the flight of a vehicle.

Typically, RMC is an energy transfer system, on which the chemical energy in a propellant is converted into thermal energy, which is accompanied with high temperature and pressure producing gases accelerating through the nozzle. In a nozzle of rocket motor, an internal energy (IE) of the combustion product of a propellant is directly converted to energy which produce the motion of vehicle (kinetic energy (KE)), that generates the propulsive force of a rocket.

In SRM, a solid fuel and solid oxidizer are mixed into a single solid propellant grain. Thus, SRM are a commonly used types of rockets when compared with the liquid or hybrid propellant rocket motors. This is because of its tailored design, manufacturing easiness, economical and also highly reliable when compared with other types of rockets.

### 4.3.1 Material for the SRC

The solid rocket motor case (RMC) should be designed to have high strength with lightweight since the combustion takes place inside the casing can producing an operating temperature of minimum 2,000˚C to 3,500˚C and pressure of minimum 3.00 MPa to 30.00 MPa. The materials for RMC are mainly divided into two categories:

1. Metallic materials of high strength alloys of steel, aluminum or titanium.
2. Advance composites of carbon, Armide (Kevlar), Glass fiber reinforced polymeric matrix composites. Composites are used in the majority of the recent RMC due to its high specific properties, impact strength and the flexibility to design.

### 4.3.2 Operational loads expected on RMC

The fundamental use of RMC is maintaining the stability of all rocket components during propulsion and thereby enhancing the rocket to produce required amount of thrust force.

Producing required thrust is a function of many factors, such as the size of motor i.e. the diameter of motor (maximum caliber), the length of motor, the geometric shape propellant and the type of propellant material. These factors can also be affected by the value of internal pressure in a combustion chamber and the thermal loading generates thrust (i.e. thrust in axial direction). The structure of RMC is usually subjected to loads such as dynamic pressure loads, aerodynamic loads, thrust loads in axial direction, thermal loads and spinning load (centrifugal force) which helps in a spin stabilization while in flight[43].

#### 4.3.2.1 Pressure loads

The RMC is a highly loaded structure with subjected to loads such as the combustion chamber pressure $P_c$, thermal load due to high temperature in a combustion chamber and thrust load in axial direction in which the pressure value is computed based on the propellant charge type and its geometry[43].. The design value of pressure ($P_d$) in RMC is given by:

$$p_d = 1.3 * P_c e^{\left(\frac{45K_T}{1-n}\right)} \tag{4.1}$$

Where Pc is pressure at working level, $K_T$ is the propellant temperature sensitivity parameter, n is a pressure index parameter.

The design pressure is used in the computation of axial loads and circumferential hoop loads:

$$F_{hoop} = \frac{p_d d}{2}; \quad F_{axial} = \frac{p_d d}{4} \tag{4.2}$$

Where $F_{hoop}$ is the hoop load per unit length, Fa is the axial load per unit length; and d is the mean diameter of the casing.

#### 4.3.2.2 Thermal loads

High temperature gases (estimated as 2,000 $^0$C to 3,500 $^0$C) are generated inside the combustion chamber due to the combustion process that take place inside the SRM. It is important to use high temperature resistance material for the wall of RMC, since it serves as insulator or protector of the internal surface of RMC wall and not allowing the heat to outer surface. There exists the heat transfer between wall layers of the RMC, that induces a thermal stress in the casing material. The thermal stresses induced in RMC can be expressed as:

$$\sigma_{Th} = \frac{\alpha E \Delta T}{2(1-\gamma)} \tag{4.3}$$

Terameters α is thermal expansion coefficient, E is modulus of elasticity of material of casing, and ΔT is the temperature variation between an outer and an inner layer of the RMC wall.

To computer the thickness of insulation wall of RMC an empirical relation is developed as:

$$\left(\frac{T_{in}}{d_{in}}\right) = 6.139x10^{-7} e^{k_{in}} p_d^{0.15} T_{in}^{1.04} \quad (4.4)$$

where the thickness of insulation material is a function of caliber diameter ($d_{in}$), temperature inside the chamber ($T_{in}$), value of pressure at design point ($p_d$) and the value of thermal conductivity of material of insulating wall ($K_{in}$).

#### 4.3.2.3 Thrust loads

Thrust load is expressed as the axial component of force that obtain from the ejection of accelerating hot gases particles of a combustion product through the converging-diverging section of the rocket motor called the nozzle. Thrust can be easily computed according to the following formula:

$$T_{th} = P_c A_{cr} C_f \quad (4.5)$$

Where $A_{cr}$ is Critical area of the nozzle, Pc is combustion chamber pressure at normal temperature and Cf is Coefficient of thrust that vary between (1.40: 1.70).

#### 4.3.2.4 Centrifugal force

While flying, the rocket spines with angular velocity ω to achieve a spin stabilization. Thus, a centrifugal force obtained from the rotation about longitudinal axis, can be computed by:

$$F_c = \frac{m\omega^2 d}{2}; \quad \omega = 2\pi n, \quad m = \rho At \quad (4.6)$$

Where m element mass, ω is angular velocity, n is the number of revolutions in second, ρ is density of structural material, A is cross-sectional area of motor casing, t is thickness of casing

The centrifugal force generates load in the circumferential direction called hoop direction and is computed using the formula:

$$\sigma_{hoop} = \rho\pi^2 d^2 N^2 \quad (4.7)$$

Where N is number of spins per minute, d is caliber size of casing, ρ is density of structural material.

### 4.3.3 Material selection for RMC structure

The selection of material for RMC is a challenging task to the design engineers in a particular field of the rocket science. The selection of material for a rocket casing should be based on specific parameters such as higher specific strength and stiffness, low weight, tailored design, machinability, availability, easiness for service conditions in high temperature and pressure. Based on the above requirements we have two important class of material for RMC application.

#### 4.3.3.1 Conventional metallic materials

The metallic materials that we use conventionally include temper steel, Ni-Cr-Mo-V, aluminum, titanium alloys and also maraging steel are the most common material used in materials of RMC. Temper steel is used due to its high strength and easy availability of design data (or material properties) and easy manufacturing process. Another most commonly used conventional material for RMC is Ni-Cr-Mo-V. Ni-Cr-Mo-possess high fracture toughness that provides excellent leaked proof property for the material. The alloy of aluminum and titanium provide high strength ranging up to 1,600 MPa. Maraging steel is an alloy of steel of new generation type that consists very low carbon. The strength of maraging steel is estimated about 300 kPsi. This type of steel is very expensive and used only in critical regions of the rocket motor. The following table illustrates some of important metal materials for RMC purpose.

Table 4.1 Conventional metallic materials used in SRM and their properties

| Material properties | 15CDV6 | Modified 15CDV6 | Maraging steel (MDN-250) | Cobalt free mild steel | 3Ni-Cr-2Si |
|---|---|---|---|---|---|
| UTS (MPa) | 980.0 | 1600.0 | 1750.0 | 1765.0 | 1950.0 |
| Yield strength (MPa) | 835.0 | 1470.0 | 1680.0 | 1725.0 | 1650.0 |
| Elongation (%) | 10.0 | 8.0 | 10.0 | 5.0 | 10.0 |
| Fracture toughness (MPa/m) | 100-120.0 | 90-100.0 | 80.0 | 90.0 | 80-90.0 |
| Weld efficiency (%) | 12.80 | 21.70 | 23.10 | | 25.60 |

#### 4.3.3.2 composites for RMC

Composites are a recent synthesized material consist of at least two or more physically/chemically distinct phases of materials with entirely different mechanical properties combined to form a new material system with highly improved aggregate properties. The major constituents in an advanced composite material include fibers (carbon, Armide (Kevlar), glass, boron etc.) and matrix (metal, polymer and ceramic) materials which are combined in an appropriate ratio of volume fraction. Therefore, a composite material can be classified either based on reinforcement fibers or the matrix material used in a composition. The overall properties of the fiber reinforced composite structure mainly depend on the properties of reinforcing phase of material. The matrix material also plays great role in a composite unit by holding the fiber in proper orientation and protecting it from external environment, providing toughness to the structure, transfer forces between lamina layers, increase the ability to resist a crack propagation.

#### 4.3.3.3 Standard organizations for the design calculation of pressure vessel of RMC

The RMC is expected to have lightweight combined with enough strength in order to achieve the required flight parameters such as long flight range and to carry maximum payload. The use of advanced composites instead of conventional metallic materials enables the weight reduction of the RMC design.

The RMC can be considered as a pressure vessel (PV) subjected to an internal pressure. Actually, the design of PV is highly complex task and depends on many factors. Some of the factors include the material selected for casing, the number of thermal loads, pressure load. The design of pressure vessel should be performed based on several international standard codes. The well recognize standard codes employed in the design pressure vessel are SME, IS, GB150 and ISO. ISO has developed a new international standard code for pressure vessels design. These standard organizations are all based on several experimentation. Based on experimental verification a design factor of safety is given as 1.5 to 4.5 for material of casing.

### 4.3.4 SRM Hardware design

A general procedure for the design of RMC and hardware components includes the determination of following quantities:

1. thickness ($t_c$) of the rocket motor casing shell
2. head end dome thickness and nozzle end dome thickness
3. thickness of the flange for the bolted joints and.
4. toque required for tightening the bolts.

#### 4.3.4.1 Design inputs

Consider the motor maximum diameter 20 cm and expected operating pressure 150 Ksi which normally can be obtained from the ballistic design. The hardware design is performed based on the pressure vessel code of standard organizations. SRM hardware consists of the following basic structural components which should be considered in the design:

i) Cylindrical shaped RMC
ii) Domes ate nozzle end and head end
iii) Flanges at nozzle end and head end
iv) The nozzle sections
v) The end cover and
vi) The bolted joints

#### 4.3.4.1 Material selection

From Table 4.1 we selected a maraging steel of grade MDN-250. It is characterized by high specific strength, easily available, and with well-established fabrication technology. maraging steel of grade MDN-250 has been widely used in a structure used in space technology and defense programs. The chemical composition of the material is as given in Table 4.2.

**Table 4. 2** The percentage weight (WT.) of chemical composition of MDN-250 steel

| Elements | C | Mn | Si | Ni | Mo | Co | Ti |
|---|---|---|---|---|---|---|---|
| Wt. (%) | 0.03 | 0.10 | 0.10 | 17-19 | 4.6-5.2 | 7.0-8.5 | 0.3-0.5 |

**Table 4. 3** Factor of safety selection criteria:

| Factor of safety | $N_{Y.S}$ | $N_{UTS}$ |
|---|---|---|
| Value | 1.33 | 1.50 |

Where $N_{Y.S}$ represents factor of safety on yield strength and $N_{UTS}$ is factor of safety on UTS. The selection of above vales of factor of safety is based on AVP-32 and MIL standards chosen.

#### Calculating the yield and ultimate stresses:

The allowable yield stress:

$$\sigma_{yield} = \frac{Y.S}{N_{Y.S}} = \frac{1680}{1.33} = 1263.20 MPa \tag{4.8}$$

Allowable ultimate tensile stress:

$$\sigma_{Ult} = \frac{UTS}{N_{UTS}} = \frac{1750}{1.50} = 1166.67 MPa \tag{4.9}$$

The lowest of the above two allowable stresses $\sigma_{Ult} = 1166.67 MPa$ is taken for design.

### Summary of design inputs for motor case design

**Table 4. 4 The inputs for SRM casing design.**

| Material | d | MEOP | UTS | Y.S | $N_{Y.S}$ | $N_{UTS}$ |
|---|---|---|---|---|---|---|
| Maraging steel (MDN-250) | 20 cm | 1500 MPa | 1750 MPa | 1680 MPa | 1.33 | 1.50 |

Where d represents motor outer diameter, $P_{MEOP}$ maximum operating pressure. Additional inputs include weld efficiency = 0.90, bi-axial gain =1.10 and mis-match factor=1.15.

### Design computation of RMC

The thickness of RMC is computed based on a code developed by ASME for high pressure vessel design known as high pressure vessel design code [44],[45]. Considering the weld configuration of the casing consists of thread joint and the inside and out outside of the casing joined with butt weld. Thus, the weld efficiency is assumed as 0.9 (90%). Now from this point of view, the Minimum thickness of the shell is computed according to ASME pressure vessel code as:

$$t = \frac{p*d*Mismatchfactor}{biaxial\ gain*2\left(SE-0.6P\right)} = 2.0mm \qquad (4.10)$$



The cylinder is supposed to be made from rolled and welded shell or sheet. In the case of using rolled or welled sheet, we must consider the weld efficiency (E) and mismatch factors during the computation of thickness of the casing. The allowable strength (S) = UTS/F.S

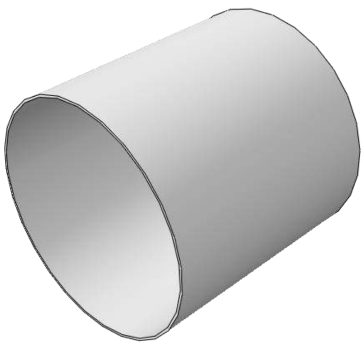


**Figure 4. 3 The casing of SRM**

### Thickness of head end and nozzle end domes:

From the various domes shape available such as Tori-spherical, ellipsoidal, hemispherical, etc which are applicable in the design of pressure vessel. The Tori-spherical dome is taken here because of easy fabrication. It is considered to be manufacture from forged rod of 20 cm diameter. The optimum parameters here include crown radius (R) =15 cm, Knuckle radius (r)= 0.15R (15% of R) = 2.25 cm, the ratio of crown to Knuckle radius (R/r) = 0.66 cm

$$t = \frac{P*R*M}{2.0\left(SE-0.1P\right)} = 1.39 \qquad (4.11)$$

Where

$$M = 0.25*\left(3+\sqrt{\frac{R}{r}}\right) = 0.25*\left(3+\sqrt{6.6}\right) = 1.4 \qquad (4.12)$$

The Schneider's approach is implemented to compute the thickness of flanges, the number and diameter of socket head bolts (SHB). Considering 12.9 grade SHB for the design.

The head end opening diameter = 33.3 cm, MEOP = 150 MPa, factor of safety = 1.50, number of studs assumed = 24, size of bolt M 6 x 1.0.

The number of bolts per millimeter of stud in a circumference of circle: N = 24/468 = 0.050.

The circumferential pitch (p) = π x 149/ (24 x 10) = 2.43

The minimum required area per bolt:

$$A = \frac{PR_m^2\left(1.0+ {l}/{b_{\max}}\right)}{2\sigma_{bolt}N\left(R_m+l\right)} = 35.9\ mm^2. \qquad (4.13)$$

From standard of bolt M 6.00 x 1.00 (a metric bolt of with nominal diameter 6.00 mm and pitch 1.00 mm) with a cross-sectional area equals to 36.60 $mm^2$ is selected.

Where $\sigma_{bolt}$ = yield strength of the bolt material and is 1080 MPa

The flange thickness can be computed using the following empirical relation:

$$t = 1.1R_m\left[\frac{3.0pl}{\sigma_f\left(1-Nd\right)\left(R_m+l\right)}\right] = 7.22\ mm \qquad (4.14)$$

That is 8.00 mm thickness is selected from a standard.

### The maximum stresses on each bolt due to preload and pressure load

The stress due to preload = 40 % $\sigma_{yield\_bolt}$ = 360.00 MPa

The stress due to pressure load = 113.00 MPa

Total stress on each bolt = stress due to preload + stress due to pressure load = 473.00 MPa

The safety factor for each bolt considered 2.0 on the yield strength of bolt material

## The thickness of cover ate head end

The thickness of head end can be same as the flange thickness, the thickness has to be calculated by using flat plate closure with bolted joint formula and higher one has to be finalized. Flat plate with bolted joint formula given in pressure vessel code is

$$t = d\sqrt{\frac{C*P}{S*E} + \frac{1.9*W*hg}{S*E*d^3}} \quad (4.15)$$

$$\Rightarrow t = 80\sqrt{\frac{0.3*1.5*2.0}{175*1.0} + \frac{1.9*7540*6.0*2.0}{175*1.0*80^3}} = 11.10mm$$

Where d is the diameter of head end up to the center of 'O' ring is taken to be 80 mm,

C = 0.30, the pressure P = 150 MPa, E = 1, $h_g$= 10.5 mm and

$$W = P*A = P*\frac{\pi}{4}d^2 = \frac{\pi}{4}*150*156^2 = 356.7kN \quad (4.16)$$

## Design of rocket Nozzle

Nozzle is a convergent-divergent section of rocket motor through which high pressure hot gas accelerate to produce propulsive force. Nozzle is fabricated from forged and rolled rod of diameter 20 cm. The diameter of nozzle throat 3.50 cm, Nozzle exit diameter 10.5 cm, and the convergent diameter: 20 cm and the calculated divergent area ratio: 9

## The thickness of Nozzle convergent section:

The thickness of convergent section of rocket nozzle is calculated employing the conical shell formula from pressure vessel standard

$$t = \frac{1}{2}\frac{P*d}{\cos\alpha\left(\eta_{weld}\left(UTS/F.S\right) - 0.6*P\right)} = 1.5mm \quad (4.17)$$

Where α == 55°, which is half of cone included angle

**The metal backup thickness at a throat:**

The pressure at throat (Pt) is approximately equal to 0.54 times chamber pressure (Pc).

$$t = \frac{1}{2}\frac{P_t*d}{\cos\alpha\left(\eta_{weld}\left(UTS/F.S\right) - 0.6*P_t\right)} = 0.32mm \quad (4.18)$$

The thickness selected from standard 1.0 mm (according to pressure vessel design), the diameter of throat back up d = 35 mm, the throat pressure Pt = 0.54*Pc = 810 MPa

**The thickness of nozzle divergent section:**

The thickness of divergent section of nozzle is given using conical shell formula as:

$$t = \frac{1}{2}\frac{P_t * d}{\cos\alpha\left(\eta_{weld}\left(UTS / F.S\right) - 0.6 * P_t\right)} = 0.7mm \quad (4.19)$$

The thickness selected from standard 1.0 mm, $\alpha = 14^0$ (half of the included angle of the cone)

### 4.5 The components of SRM igniter

The constituents of SRM igniter includes the fuel, oxidizers, binders and curing agents and also additives in some cases. The fuel in ignitor construction includes powdered Al, B, Mg; the oxidizers include $KNO_3$, $KClO_3$, $KClO_4$, $NH_4ClO_4$, $NH_4NO_3$ while Plastized-Ethyl Cellulose is used as a binder which reduces sensitivity[2]. The main components of SRM ignitor consist:

1. Initiation system,
2. Energy release system,
3. Hardware and
4. Other components that physically contain both the initiation and energy release systems that provide appropriate system for mounting.



#### 4.5.1 Initiation systems and initiators

An initiation system and initiator are capable to initiating energy input in rocket system may be either of electrical, mechanical, laser, and semi-conductor bridge wire (SCB) or a combination of these systems.

##### 4.5.1.1 Electrical initiator:

These are electro-explosive devices (EED) and are fall into two categories: hot wire initiator and exploding bridge wire initiator[46]. EED are commonly used on rockets, missiles, launch vehicles, spacecraft for the initiation of motor ignition and other propulsive elements, and also for actuation of mechanisms such as separation devices, cutters, pin pullers, or isolation valves. The initiator takes an electrical input or pulse and provides work in the form of a pyrotechnic output or ignition initiation.

Figure 4.4 Hot wire electrical ignitor

### 4.5.1.2 Hot wire initiator

Hot wire ignitor is the most common type and consists of a squib and relay charge, which constitutes an ignition cartridge[47]. The squib consists of a small resistance wire (12-125µm diameter) attached between terminals, on which a resistive heating raises the local temperature sufficient enough to cause deflagration of the heat sensitive prim charge in contact with it to give a flash of flame. The relay charge, which is adjacent to the primer, picks up the flash and produces a hot flame, which becomes the energy source for subsequent energy release system. Ignition cartridges generally incorporate glass to metal seals for the terminal pins for leak tightness and electrical isolation. Fig 4.4 shows electrical initiator for ignition of solid rocket motor propellant.

Hot wire material selection is based on compatibility with pyrotechnic materials. Nichrome that is nickel chromium, and iridium, are usually used. The relay charge is an intimate mix of Pyrotechnic powders of metal such as boron, magnesium, titanium, and aluminum and strong oxidizers like potassium nitrate, potassium chlorate, and cupric oxide. In this thesis we used the gun powder which is the mixture of potassium nitrate, sulfur and charcoal.

### 4.5.1.3 Exploding bridge wire initiator

Exploding bridge wire initiator uses Gold/Platinum wires primarily for their low specific resistance and inertness, in contrast with high resistance wire used in hot wire initiators. The charge pressed against the bridge wire is high explosive, usually PETN, or RDX. Operating voltages are of very high magnitude compared to the hot wire type, and functioning delay is very much less in the order of micro seconds. Electrical firing system characteristics according to NASA standard initiator (NSI):

- It should deliver reliable electrical energy to initiator
- Enable the use of direct current
- Make use of capacitor discharge
- It must protect against inadvertent initiation

- It should shield against lightning, static electricity, radio frequency
- It must have a two fault tolerant switches that is ON/OFF
- It must control or sequence firing commands
- It should provide electrical isolation from other electrical circuits
- Designed with high safety consideration, that is an ultimate connection to the device
- There should be an access to remove shield from device and install final connector
- Predictable ignition delay for recommended firing energy

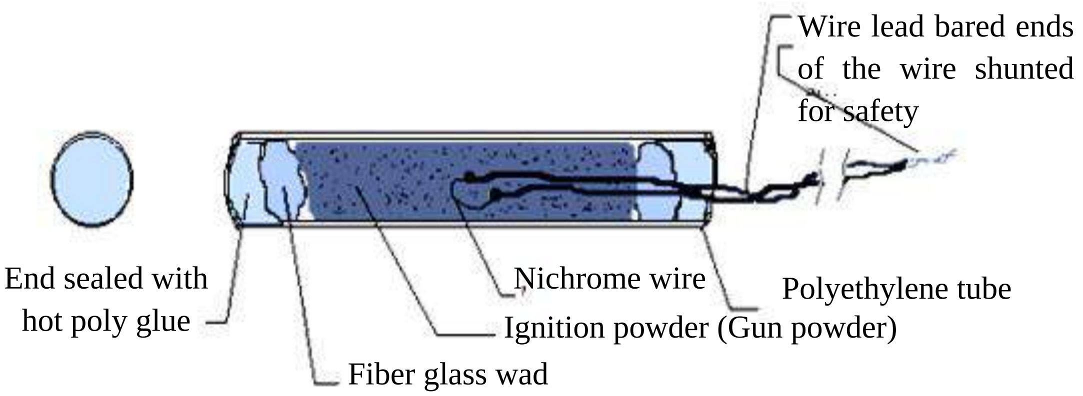



Figure 4.5 Hot wire initiator

The pyrotechnic ignitor (hotwire igniters) used in this work consist a header, a bridgewire, and a gun powder based pyrotechnic charge as shown in Figure 4.5 and Figure 4.6

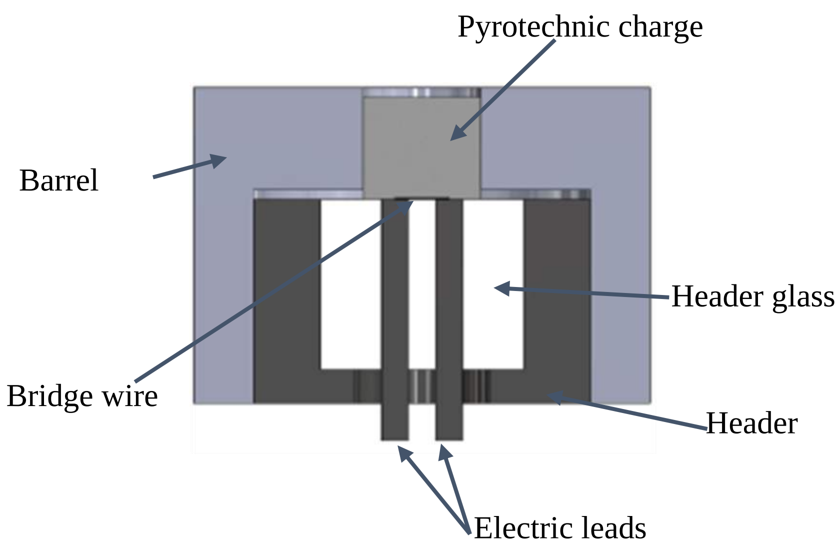



Figure 4.6 Components of hot wire ignitor

**4.5.1.2 Mechanical initiator**

These are not used extensively in aerospace technology, but in isolated cases. A typical device is the percussion initiator, consisting of metal cup into which initiating charge is loaded.

#### 4.5.1.3 Through Bulkhead Initiator (TBI)

TBI is a SRM propellant initiation device that employs a shock input stimulus where the contributor (donor) charge initiates and transfers a shock wave through an adjacent structural bulkhead with sufficient intensity to cause the initiation of a receptor charge on the opposite side of the bulkhead[48]. TBI is a mechanical device, made from steel material, containing an explosive charge on either side, which are called donor and acceptor charges as shown in Figure 4.7. The donor charge on, on initiation produces a high velocity shock wave, which is transmitted through-the-bulkhead and produces initiation of acceptor without affecting the integrity of the bulkhead structure[49]. The donor charge is initiated using a confined detonating fuse (CDF) in the form of a flexible explosive transfer assembly (ETA) which transmits the explosive stimulus at a speed of 7.0 km/s-8.0 km/s (which is known as a velocity of detonation) and confines all products of detonation.

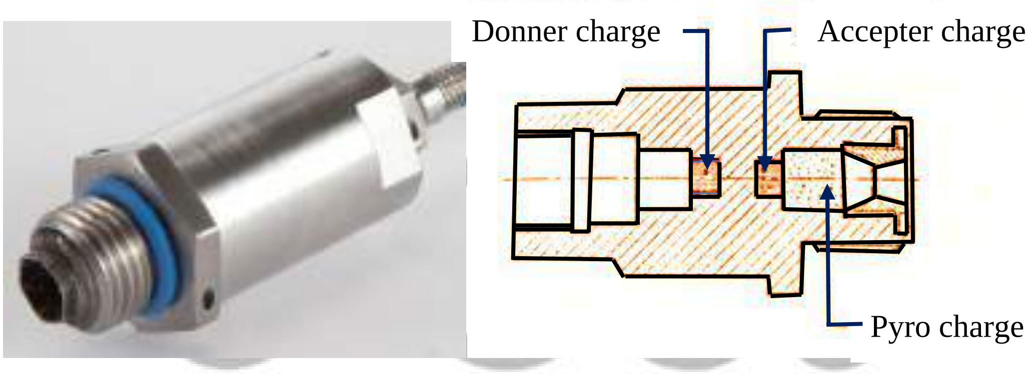



Figure 4.7 Through bulk-head initiator

#### 4.5.1.4 Hypergolic initiation

Another method of initiation is by injecting a hypergolic fluid, such as chlorine tri-fluoride into the propellant chamber to cause ignition[50].

#### 4.5.1.5 Laser Initiator

This is relatively new concept and has recently made its entry in aerospace applications. Basically, in this initiator, a laser beam is used for initiation of explosive charge (either pyrotechnic charge or secondary high explosives). This consists of a laser firing unit and laser beam from the unit is transmitted through a fiber optic cables and a sealed optic window of the device to directly initiate the explosive material. As the laser is insensitive to stray electrostatic discharges, the system is highly safe from accidental initiation when compared to other type of initiators. Also, it can be used for direct initiation of high explosive charges in launch vehicles.

### 4.5.1.6 Semiconductor Bridge Initiator (SCB)

Semiconductor Bridge is a recent innovation. This consists of a doped poly silicon layer formed on a silicon substrate over which aluminum lands are provided. The lands provide a means of electrical connection to the bridge. A current pulse through SCB causes the bridge to burst into bridge plasma discharge in microseconds, which transfer the energy to the charge.

### 4.5.2 Energy Release System

Energy release system provides heat and pressure to the motor propellant necessary to ignite it and to produce sustained combustion within the required time limit. The pyrotechnic igniter usually has pelleted/ powdered pyrotechnic charge as the energy release system. In this particular thesis we used a black powder charge of different grain size. The detail discussion of this part will be presented in preceding section using ANSYS software called CHEMKINE modeling tool.

### 4.5.3 Hardware components

This consists of the structural and inert components that the initiation and release systems, contains and releases the combustion products, and provides means of interfacing with the motor. This also includes fasteners, thermal insulation and sealing elements. Typically, in a pyrotechnic igniter, the components are metallic head end adapter, a vented/perforated case, and sealing elements. Igniter case can be either of metal or composite material such as fiber glass. Composite cases have the advantages of very high specific strength and get progressively consumed during motor action.

### 4.6 Design and construction of igniters

The design of igniters for rockets has been more of art than a science. It has been a practice in the development of a new rocket that space requirements for propellant, grain support, nozzle, fins, and grid are carefully designed and then whatever space is left for igniter. The igniter design is influenced by the size and shape of propellant charge, its composition, location of igniter in the rocket motor chamber, and amount of free volume inside the combustion chamber.

Metal oxidants are replaced by black powder in new ignition systems. Igniter containers in early days were made of cotton cloth. However, due to its hygroscopicity of black powder and other igniter compositions, containers suited for hermetic sealing have been used. Plastic containers, used in the beginning, were relatively inexpensive and could be sealed and made in any desired shape or size. However, most of the materials were brittle and were susceptible to breakage during rough handling. Moreover, these containers absorb NG in double base propellants. Tin containers were used for artillery rockets. This type of containers works by a violent rupture of the containers or by blowing off of the cover.

The ignition devices generally follow the contour of containers. However, their shapes are controlled by their location in rocket chamber. For most of the rockets, it has been found advantageous to locate the igniter at the head end. The reaction products of the igniters are expected to sweep over the entire length of propellant charge. However, some rockets have nozzle end igniters and few others have internal igniters. Fin stabilized rockets generally have large length to diameter ratio and hence there is no problem in utilizing internal space at the head end for the igniter. In large rockets, igniter can be located at the center of the head closure or it could be in the form of torus or ring.

### 4.6.1 Inputs for igniter Design

The following inputs are necessary while designing pyrotechnic igniters for SRM[51]:

- Free volume of motor
- Initial and total surface area and grain geometry
- Maximum operating pressure of motor
- Motor port and throat area
- Minimum ignition energy of propellant
- Location of igniter
- Nozzle closure effects
- Permissible ignition delay
- Pressure-time requirements; and
- Motor ignition altitude/environments



### 4.6.2 Estimation of charge quantity

Charge quantity is estimated from the equations as in the follow steps. Pressure generated by the pyrotechnics igniter is designed to be 40-60 % of the maximum operating pressure of the motor. Figure 4.4 shown below illustrates the Model of the igniter charge flow through SRM

Further, charge quantity can be related to the motor free volume, by the equation:

$$M_{ig} = KV^{n} \tag{4.1}$$

Where: $M_{ig}$ is in g and V in inch$^3$

i. The motor chamber free volume V:

The total free volume of the combustion chamber is estimated for particularly selected propellant having length l = 330 mm and diameter d = 105 mm is:

$$V = V_0 + 10\%(V_0) = V_0 + 0.1V_0 \quad (4.2)$$

$$\Rightarrow V = 1.1 * \frac{\pi}{4} d^2 * l = 1.1 * \frac{\pi}{4} * 105^2 * 330 = 4{,}143{,}222.5\, mm^3$$

$$M_{ig} + M_p = M_n + M_c \quad (4.3)$$

Where: $V_o$ is the volume of solid propellant used in solid rocket motor

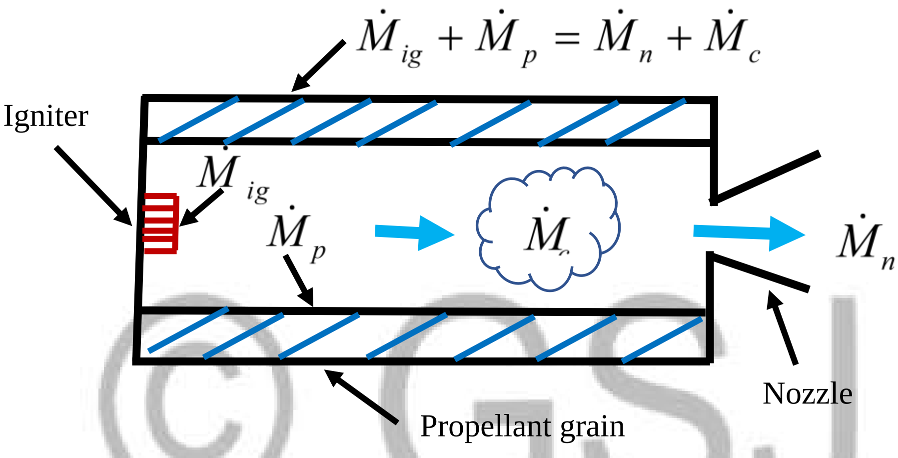



Figure 4.8 Model of the igniter charge flow through SRM

If an igniter has been already developed for particular motor, for motors having the same propellant and grain geometry but different in size, Equation (4.2) can be used by applying the values estimated for K and n. The typical; values of K and n are 0.5 and 0.7 respectively. But the volume V in the above is given in $mm^3$ and has to be converted to $in^3$ using the following relation:

$$V = \frac{4{,}143{,}222.5\, mm^3}{25.4\, mm^3} * 1in^3 = 353\, in^3$$

ii. The mass of igniter $M_{ig}$ from Equation (4.1):

$$M_{ig} = KV^n = 0.5 * 353^{0.7} = 24\, gm$$

The ignition energy varies from 84 $kJ/m^2$ to 420 $kJ/m^2$ and the average value is computed as:

$$q = \frac{\sum_{i=1}^{n} q}{n} = \frac{84 + 420}{2} = 252\ kj / m^2 \quad (4.4)$$

The pellet density $\rho_{ig}$ is 1630 Kg/m$^3$ for the selected type of igniter charge.

iii. The volume of pellet $V_{pellet}$:

$$V_{pellet} = \frac{\pi}{4} d_{pellet}^2 h \quad (4.5)$$

Since the diameter of pellet ranges from 6 mm to 10 mm. let the diameter of pellet $d_{pellet}$ = 6 mm and height or length h = 4 mm

i. For d = 6 mm: $V_{pellet} = \frac{\pi}{4} d_{pellet}^2 h = \frac{\pi}{4} * 6^2 * 4 = 113\ mm^3$

ii. For d = 10 mm: $V_{pellet} = \frac{\pi}{4} d_{pellet}^2 h = \frac{\pi}{4} * 10^2 * 4 = 313.145\ mm^3$

iv. The weight of pellet $W_{pellet}$

$$W_{pellet} = V_{pellet}\ \rho_{pellet} \quad (4.6)$$

$$\Rightarrow W_{pellet} = 113\ mm^3 * 1.63 * 10^3 \left( \frac{1000 gm}{1000^3 mm^3} \right) = 0.185\ gm$$

v. The number of pellets $N_{pellet}$ is:

$$N_{pellet} = \frac{M_{pellet}}{W_{pellet}} \quad (4.7)$$

$$\Rightarrow N_{pellet} = \frac{M_{pellet}}{W_{pellet}} = \frac{10 gm}{0.185 gn} = 54$$

Since the weight of pellet for initiation purpose is estimated as 2/5 the total weight of igniter, that is (2/3*24= 9.6 gm). Once igniter charge weight is computed, the rest of dimensional details that related to the pellets and igniter tubes are fixed based on the following assumptions:

1. Attrition of pellets should be less than 4 %. This can be achieved by selecting suitable crush strength of pellets and packing of pellets within the igniter tube.

$$V_{tube} = 1.4\left(N_{pellet}\right)\left(V_{pellet}\right) \tag{4.8}$$

$$\Rightarrow V_{tube} = 1.4 * 54 * 113 = 8551\, mm^3$$

2. The pellet dimensions control the igniter burning time. The igniter burning time, in turn, is fixed based on:

   i. Threshold ignition energy requirement which varies in the range of 84 - 420 KJ/$m^2$;

   ii. Whether the motor is ground lit or air lit

   iii. Based on the nature of combustion products of igniter charge (percentage of condensed phase).

   iv. Aspirin-shaped pellets are generally used.

   v. Pellet density is fixed based on the crush strength requirements, which is dictated by environmental considerations.

   vi. Pellet diameters generally range from 6 to 10 mm and density, 1.6x $10^3$ kg/$m^3$ approximately.

3. Vent or perforated area of an igniter should be least 40% of total surface area of igniter.

4. Size of openings in the igniter tube should be small enough to hold the pellets until 75% of the pellets weight is consumed or ignited.

5. Other igniter's tube dimensions are fixed based on motor port and head end opening in the case of internal igniters. For external igniters the ratio of the effective throat area $A_e$ to nozzle throat area ($A_t$) should be in the range of 1.2 to 1.8, which is used in design.

**4.7 Construction of igniter for particular designed SRM**

Based on SRM design and the selected propellant type by my fellow candidate aerospace engineering graduate, I calculated the above design parameters. All calculated values are applied in the construction of pyrotechnic igniter as shown in the following photograph (See Figure 4.9 and Figure 4.10).

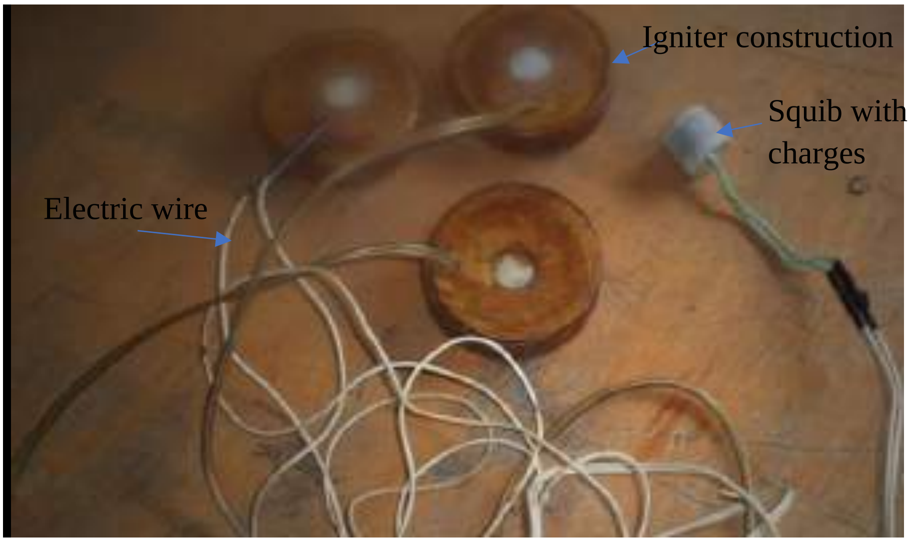



Figure 4.9 Design and construction of pyrotechnic igniter for particular SRM (Photo)

Figure 4.10 Alternative assembly of pyrotechnic igniter in SRM (Photograph)

**4.8 Method of construction of pyrotechnic igniter**

In this thesis work I used my own constructional method and the materials involved are somehow different from the usual constructional material that rocket igniter manufacturers used. In flight version rockets, the rocket igniter manufacturers use different hardware materials such as aluminum, tin, fiber glass and also other related materials. In this thesis I used carton cups as hardware material. The carton caps are made by the HOMICHO ammunition and chemical industry are readily made from hard paper pressed to a cup shape and shellac coated. Since carton cap is easily available and can ignite completely without choking action on the throat of the nozzle during initiation of the igniter. In addition to this it has no environmental effect regarding pollution due to the material that it is made of and the burnable property of carton. Its size is still smaller than the metallic hardware and no smoke generation while burning.

### 4.8.1 Materials used in the construction of igniter

- Cartoon caps, Carton top cover
- Cotton cloth
- Black powder or ignition charge includes grains, pellets, and 9/7 multi perforated rocket ignition charge.
- Copper, Squib, Nichrome (nickel-chromium) wire, gold or platinum wire (optional)
- Needle to stitch the margin of the cheese cloth
- Electronic balance to weigh the quantity of charge to be loaded
- Filter paper and Safety clothes and equipment

I prepared and tested ignition charge (BP) of different sieve size. The sieve sizes made in this experiment work are fine powder of 500 µm, the medium size of 1.00 mm and 2.00 mm course sieves. Preparing the igniter hardware from locally existing material such as carton cup, carton top cover, glue, and shellac.

- Preparing electrical wires such as copper wire, low resistance filament wire that made from nickel chromium material called Nichrome, and high heat producing squibs
- I also prepared cheese cloth made of cotton as a bag for containing ignition charge. The cheese cloth is cut in a circular manner and stitched in two positions as shown in figure below, to accommodate the required amount of ignition charge. The 15gm of medium sized ignition charge is loaded at the center and course pellet of 10gm is introduced at the outer donut shaped stitch of the cotton cloth.

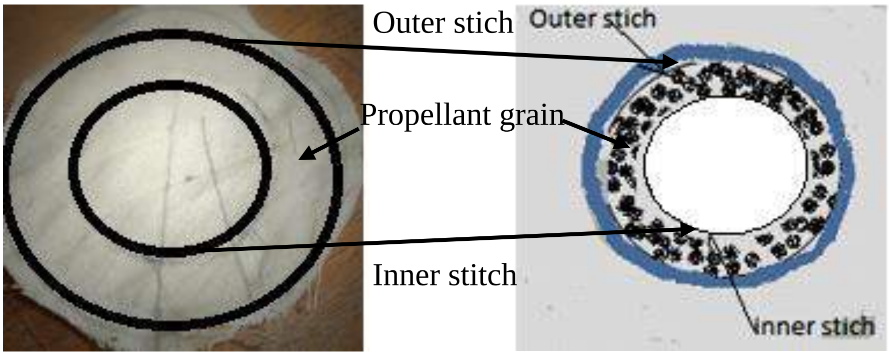
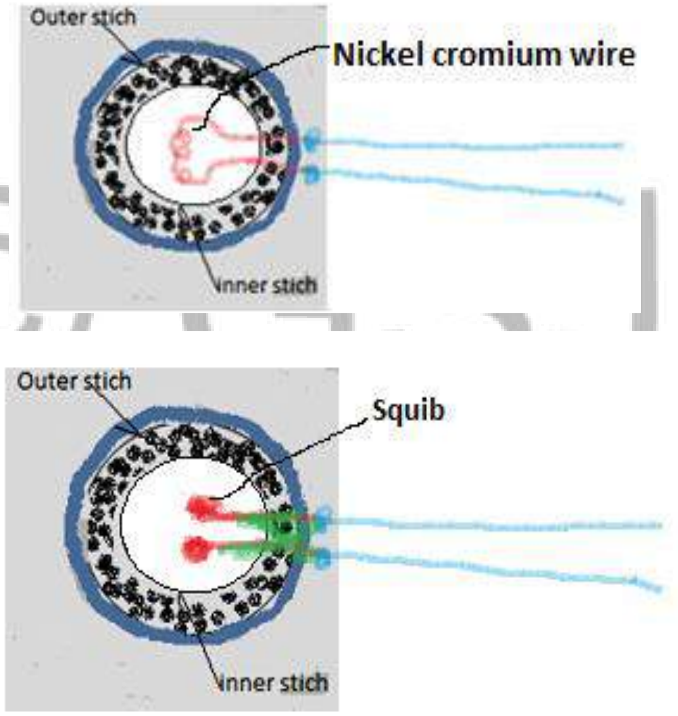



Figure 4.11 Cheese cloth stitched in two positions

- Then an initiation system consisting of a high heat Nichrome wire which is tied with a pair of copper wire is introduced in to small sieve ignition charge at the middle of the cotton bag with its coil positioned center. See the following figure (Figure 4.11).




a) Nichrome wire ignition system b) Squib ignition system

Figure 4.12 Ignition system construction

Actually, I prepared four different igniters as shown in Fig. 4.10 by varying the type of charge and ignition system.

i. For the first one I used an experimentally synthesized black powder charge and pellet with nichrome wire ignition system.

ii. The second one is also made using experimental ignition charge and the squib ignition system.

iii. The third on is made from 9/7 type multi perforated ignition charge of high energy material as the main charge at the outer stitch and commercially manufactured ignition charge as initiation charge at the center of the bag.

Figure 4.13 Multi perforated ignition charge of high energy material

The last igniter is prepared to ignite the rocket motor propellant designed by my fellow candidate graduate, and is constructed from medium sieve ignition charge obtained from this research and using squib as an ignition system.

# CHAPTER FIVE

# EXPERIMENTAL STUDY OF PYROTECHNIC COMPOSITION, ITS SAFETY PRECAUTIONS AND TESTING

## 5.1. Introduction

Black powder is an explosive that has been used for centuries as pyrotechnics. Black powder (BP) usually called as gun powder which is characterized by the process of burning known as deflagration rather than detonation. Deflagration differs from detonation in that BP produces subsonic shock waves, rather the supersonic shock waves produced by well-known explosives, that are Dynamite, C-4 or TNT. Therefore, BP is a suitable as a propellant ion the case of fireworks, bullets and SRM ignitors than the detonating or blasting explosives[52].

## 5.2 Ingredients used in the preparation of black powder

BP traditionally made from three basic ingredients: The ingredients include potassium Nitrate ($KNO_3$), Sulfur (S) and Charcoal. In its composition the Sulfur and charcoal provide fuel for the chemical reaction, while $KNO_3$ provides Oxygen ($O_2$) and is act as oxidizer. Even though, Sulfur and Charcoal can burn themselves, an addition of oxidizer ($KNO_3$) greatly facilitates the burn rate of the fuel, that resulting in an explosive reaction. I used the following ingredients in our experimental work and while preparing BP for particularly selected igniter type [30].

a) 75 % of potacium nitrate b) 10 % sulfur c) 15 % charcol

Figure 5.1 Basic ingredients in the preparation of black powder

The chemical equation of BP containing potassium nitrate, sulfur and charcoal becomes:

$$4KN0_3 + C_7H_4O + 2S \rightarrow 2K_2S + 4CO_2 + 3CO + 2H_2O + 2N_2 \quad (5.1)$$

And the chemical equation of BP with no sulfur in its composition is:

$$6KN0_3 + C_7H_4O \rightarrow 3K_2CO_3 + CO_2 + 6CO + 2H_2O + 2N_2 \quad (5.2)$$

Where $KN0_3$ potassium nitrate, $C_7H_4O$ charcoal, S sulfur, $K_2S$ potassium sulfide, $K_2CO_3$ potash, $CO$ carbon monoxide, $CO_2$ carbon dioxide, $N_2$ nitrogen.

The ingredients are formulated in a proportion of 15:3:2 of $KNO_3$, $C_7H_4O$ and S respectively by weight but not by volume.

### 5.3 Pyrotechnic safeties

It is not possible to provide a set of rules that assures your safety in during using pyrotechnics. Some of important safety aspects of handling the pyrotechnic chemical are as given below. The rules are applied to a wide variety of compositions. Some pyrotechnic compositions be rammed or may be pressed to work properly. Other composition may explode when rammed or pressed. Some pyros must be in wet condition with water; others may spontaneously ignite when wet.

### 5.4 General Safety Precautions

A safety precautions in to be followed during preparation of pyrotechnic composition are as listed below, (no particular order is presented, just for general use):

1. Never smoke when handling Pyrotechnic compositions.
2. Keep away the pyrotechnics chemicals from the reach of children and pets.
3. You have to be familiar with the properties of the composition in your work. Thoroughly test new compositions for sensitivity, stability, compatibility with other mixtures etc., until you are absolutely sure that the mixture is ok to use in your application and method of construction.
4. Chemicals that need to be finely powdered before use should be ground separately in a clean mortar with pestle or a clean ball mill or tumbler.
5. Keep separate equipment for oxidizers and fuels.
6. For cleaning equipment used for fuels, a solvent or sand may be useful.
7. Never grind explosive compounds or mixtures!!
8. Use only non-sparking tools. Make your tools from wood, paper, aluminum, lead or brass. Other metals and materials may cause spark (especially steel will).
9. Paper bags or wooden containers are good to use for storing mixed compositions.
10. Store compositions dry and cool.
11. Avoid plastics, glass and metal.
12. Avoid storing compositions in general.
13. Make as much as you will need in the near future and keep no more in stock than necessary.

14. Finished items should also be brought to a safe place immediately.
15. Prevent contamination of chemicals and mixtures.
16. Have separate tools for every type of mixture
17. Use different sets of clothing for working with different mixtures. Wash them every time after use (dust collects in the clothing).
18. Have a separate rooms or separate buildings for working with different types of chemicals.
19. Keep a clean working place.
20. Keep chemicals in closed cabinets or in a separate building.
21. Chemicals or mixtures should not be kept in the working place anyway.
22. Provide adequate ventilation. This is especially important when working with volatile solvents or (poisonous, flammable) powdered chemicals.
23. Be aware of static electric charge buildup and follow the following rules.
    - Ground your working table.
    - Monitor humidity and keep it above 60% as a rule of thumb.
    - Touch a grounded surface before you place things on it.
    - Touch other people before handing over compositions or finished items.
24. Wear cotton clothing, avoid synthetics
25. Simple things such as unscrewing a (plastic) bottle, unwinding some tape or even moving your arm may accumulate enough charge on your body to ignite a sensitive composition.
26. Wear proper protective clothing. A face shield, dust mask, heavy gloves and a leather apron are minimal. Wear cotton clothing. Hearing protection can be good but it also makes it harder to hear other people's warnings.
27. Provide safety screens between you and compositions, especially when pressing, ramming, and sieving or in other ways causing frictions/shocks/pressure etc.
28. Be prepared for the worst. Have a plan for when something should go wrong. Have a fire extinguisher and plenty of water ready (excepting for mixtures for which water would create a greater hazard than ignition). Think beforehand of what might happen and how you could minimize the damage. Know how to treat burns. Inform someone else so he/she can help in case of an accident. Have a fast escape route from your working place.
29. Work location: The work location for compounding of low sensitivity propellant should be a minimum of 25 meters from any inhabited building, with distance to increase appropriately depending on the amount and type of material being used. All materials must

be locked in proper storage facilities when not actually being used. Finished propellant/motors will be stored in a proper magazine.

30. Neatness: Keep the area where propellant compounding is being carried out, clean and neat at all times. Oxidizers, powdered metals, and other ignition hazards will be treated with appropriate care to minimize the danger of accidental ignition, with special care taken to avoid "dusting" of fine material. Never have more than one open container of chemical within this area at any time.
31. Chemicals: Become familiar with each chemical used. Don't use "makeshift" chemicals, but instead will obtain technical grade or appropriate/equivalent purity for propellant compounding. Learn about chemical incompatibilities and avoid them (examples: ammonium compounds with chlorate compounds; aluminum and any nitrate). Never make substitutions simply to see "if this works", but instead will engineer mixtures to meet the preselected criteria.
32. Training: You have to study regularly to learn more about the nature of your propellant and motor work.
33. Amounts: Work with small amounts of materials. For well characterized minimal hazard mixtures make no more than can be used within a reasonable length of time. Uncharacterized experimental mixtures will be made initially in quantity not to exceed one gram, until the mixture has been properly characterized as to sensitivity and other hazard.
34. Legal: Work in compliance with federal, state, and local laws. The local authorities having jurisdiction will be aware of your activities.
35. Testing: Test the sensitivity of mixtures using the smallest practical amounts of the mixture. Carefully note and avoid any mixtures that are unduly sensitive. Test any motor design at least three times, by proper static test, before committing that motor to flight.
36. Waste: Dispose of scrap material and flammable waste from your operations properly, by remote ignition, on a daily basis or more often. Scrap and waste will not be allowed to accumulate.
37. Carry out any other procedures needed to minimize properly the hazard to myself, to others, and to your surroundings.

**5.5 Preparing the pyrotechnic ingredients**

The quality of the resulting gun powder depends on various factors. These includes the binding, that is to how firmly $KNO_3$ is mixed with the other compositions like charcoal and Sulfur mixture. A loose binding (i.e. dry mix) produces a very low-grade gunpowder. The quality of the BP is defined by its burn rate. The normal burning rate is expressed in mm/sec or in/sec while the bulk burn rate at any instant, the area that is burning times the normal burn rate and is expressed in $mm^3$/s or $cm^3$/sec in metric unit and $in^3$/sec in inch system. In bulk burn rate [8], a burn rate of about 14 $cm^3$/s or greater is required to use the BP as a propellant for ignition of SRM.

In this thesis we followed two methods of preparing BP ignition charge for SRM ignition. The first method produces powder with a slightly lower burn rate, but is very safe to prepare. The second can produce very high-quality powder, but contains an element of accident or danger. Commercial BP manufacturers use a machine called ball mills to crush the charcoal and sulfur. A ball mill is large rotating drum filled with pyrotechnic compositions such as charcoal, sulfur and a crushing lead balls or heavy stones. The mill is rotated at high speed for up to more than 48 hours. Finally, we obtain very finely powder of charcoal/sulfur mixture. Alternatively, simply buy the charcoal in a powdered form directly from supplier companies that will provide powdered charcoal. The other alternative approach is to prepare your own a ball mill or else buying a cheap gem polishing toy mill from local market and use decorative stones as a crushing agent. Another most usually used type includes mortar and pestle to crush the ingredients of BP.



**5.5.1 Materials required in the preparation of black powder**

I obtained the following items from HOMICHO chemical and ammunition industry for the preparation of black powder for the application of SRM igniter charge.

- Powdered potassium nitrate or saltpeter
- Charcoal
- Sulfur
- Water
- Isopropyl alcohol
- Cheese cloth or an old cloth
- Paper, plastic containers
- Sieve, coffee filters
- Plastic stirrer
- Stovetop
- Beakers for boiling water
- Cooling furnace to chill alcohol and to cool hot mixture

- Mortar and pestle

Note: since there is no ball mill machine in the factory, I used mortar and pestle.

### 5.5.2 Methods of preparation or synthesizing BP

#### 5.5.2.1 Boiling method

**Requirements:**

Skillet, stovetops, plastic stirrer, isopropyl Alcohol, household sieves, coffee filters. Before we start, a bottle of rubbing alcohol should be chilled in a freezer for at least 24 hours. We can purchase rubbing alcohol (Isopropyl Alcohol, alternatively 98% pure ethyl alcohol) from any drugstore, pharmacies or supermarket. The following step illustrates the boiling method of preparation of BP.

1. Mix 15% of powdered and crushed charcoal with 10% of powdered sulfur
2. Using a deep skillet, bring about three or four cups of water to boil.
   Stir in 75% of $KNO_3$.
   Keep stirring until $KNO_3$. is completely dissolved.
   Add water as necessary, but try not to over-water the mixture.
3. Slowly sift in the charcoal/sulfur mixture. Keep stirring until it become wet, grayish sludge. Don't let any mixture slop out of the skillet onto the hot stove-top, that will most likely cause a start of fire.
4. Once the sludge is uniformly mixed, remove the skillet from the stove. Pour it in a chilled alcohol and also stir it. Keep pouring and stirring until the sludge is cool enough to touch.
5. Allow the water/alcohol to drain out until the sludge is dry enough to leave an impression when you press into it.
6. Using a fine size sieve, press the sludge through the sieve onto a large piece of cardboard or blotting paper. Take your time, evenly spreading the granules onto the paper or cardboard.
7. Allow the granules to dry in direct sunlight for more than 24 hours. When dry, pour the granules through a fine sieve to remove any fine powder from the granules.

#### 5.5.2.2 Method of agitation

Agitation method uses electrical equipment, and is considered more dangerous than the boiling method described above, but capable of produce high-quality powder.

**Requirements:** Electric kitchen blender, Isopropyl Alcohol, household sieve, coffee filters.

1. Add 3 to 4 cups of boiling water into the blender. Slowly add 75 % of KNO3.
   Cover the blender, and agitate at medium speed for 10 minutes.
   Note: it is advisable to use an extension cord to start the blender from a safe distance. Again, this should be done outdoors!
2. Add and slowly mix 25 % charcoal/sulfur mixture.
   This should be done by turning off the blender, pouring in a small amount of the mixture, restarting the blender and mixing until the charcoal/sulfur is completely wet. Repeat until all the fuel has been added and thoroughly mixed.
3. Allow the blender to run at high speed for 15 minutes.
   Slowly pour in the Isopropyl alcohol while the blender is running.
   You should hear the blender slow down as the mixture solidifies.
   Add more Isopropyl alcohol until the mixture is cool to touch.
4. Follow steps 5 through 7 from method 1 (boiling method).

Note: the percentage ratios are not in volume but in weight of ingredients used.

From the above two methods, I used the boiling method of preparing black powder for my experiment, and the procedures involved during preparation are as follow:

### 5.5.3 Steps involved in preparation of black powder ignition charge for thesis work

#### 5.5.3.1 Administrative procedures

1. Receiving a letter from Defense University College of Engineering to the stack holder industry particularly, Ambo chemicals and Ammunition industry (HOMICHO).
2. Getting permission letter from vice manager and operation leader of the industry to different sections of factories.
3. Dispatching letter to the authorized sections of HOMICHO industry according to the requirement of the thesis work.
4. Getting permission from store administration of HOMICHO industry.
5. Receiving the required chemicals for the preparation of BP ignition charge such as potassium nitrate, sulfur and charcoal from the store and ethyl alcohol from chemical laboratory instead of Isopropyl alcohol.
6. Receiving safety closes and equipments to the laboratory where I am preparing the chemical composition, that is chemical laboratory.

### 5.5.3.2 Technical procedures in the synthesis of black powder

The following are the technical procedures that I followed while preparing ignition charge for pyrotechnic igniter in collaboration with Ambo chemicals and ammunition industry.

1. Cleaning the working area and equipments used for ingredient formulation.
2. Wearing safety closes such as over coat, plastic gloves, and respiratory mask and discharging static electricity by grounding.
3. Placing all required chemicals, tools and equipments which are as shown below, on well cleaned table using separate filter paper and other plastic containers. The following figure illustrates the tools, equipments and the chemicals used in the process.

Figure 5.2 A set of mortar and pestle for grinding the chemical compositions

Figure 5.3 A set of Sieves and filters used in the preparation

a) Gloves b) Respirator Safety Mask c) eye goggle d) filter paper

Figure 5.4 Some the safety equipments and tools involved in the experimental work

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Figure 5. 5 Beakers, flasks and ethanol alcohol

  

A) lab electronic balance B) Electronic Balance C) Electric stove

Figure 5.6 Different types of electronic balances

4. Grinding potassium nitrate, sulfur and charcoal separately with the help of mortar and pestle until they become fine powder. It is good practice to grind each chemical individually than grinding it together for safety aspect.

   Place crushed charcoal and sulfur in a ball mill, then run the ball mill for several hours. Once the ingredients are grinded to fine powder, then remove it from the ball mill. In this thesis work ball mill is employed for grinding the ingredients.



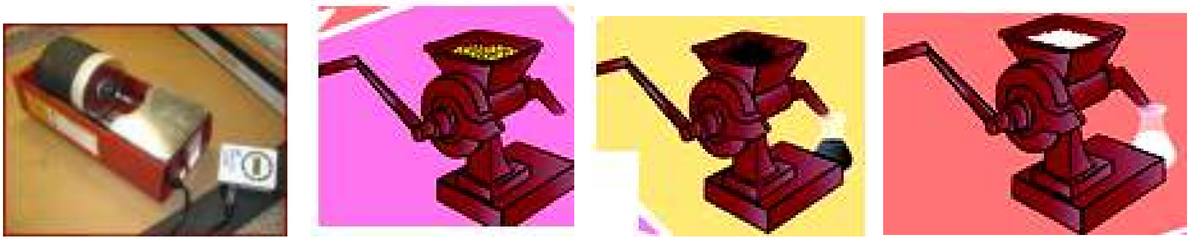

Figure 5.7 Grinding ingredients of black powder using ball mill.

5. Measuring the required quantity of the ingredient with the help of an electronic balance having 200gm maximum capacity and the alcohol with flask with milliliter graduation.
   I measured the ingredients for experiment according to the following:

- Potassium nitrate = 150 gm; Powdered charcoal = 30gm; Powdered sulfur = 20gm; Ethyl alcohol = 750ml, since there is no isopropyl alcohol in the factory

6. Preparing charcoal/sulfur mixture:

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It is good practice to Chill 300ml Isopropyl alcohol for every 50gms of charcoal/sulfur mixtures. Once it cooled in a refrigerator, mix the alcohol with charcoal/sulfur mixture.

Figure 5.8 Mixing charcoal/sulfur mixture with isopropyl alcohol.

7. Preparing potassium nitrate: Measure 60 ml of water for every 150 grams potassium nitrate in an old pan or beaker. I added potassium nitrate and brought to boil thereby stirring continuously. I added little bits of water at intervals until the potassium nitrate is completely dissolved in water.

Figure 5.9 Preparation of potassium nitrate

8. Preparation of black powder slurry:

   We added the charcoal/sulfur mixture to a hot pot of boiling $KNO_3$ and stir it until all ingredients are completely mixed or combined.

Figure 5.10 Adding the charcoal/sulfur sullary to a hot pot of boiling $KNO_3$

9. By taking a chilled or highly cooled alcohol and a hot mixture (sullary) outside, and add the mixture to alcohol. Stirring them together thoroughly.

Figure 5.11 Adding the hot mixture to an isopropyl alcohol

10. Chilling this new mixture: this can be achieved by introducing the hot slurry in the refrigerator. The more quickly it can chill to $0^0$c, the better quality of ignition powder obtained.
11. Removing liquid from mixture: We filtered the mixture using cheesecloth. This helps to remove all the liquid content from the solution.

Figure 5.12 Filtering the mixture through cheesecloth/or old cloth

12. Drying the mixture in direct sun light:
    Expose the mix of chemical out on a piece of paper to dry in direct sun light for about 24 hours. For this I prepared a neat and clean wooden table near the working area and placing a clean paper on the top surface of the table and then the mixture be over the paper as shown below

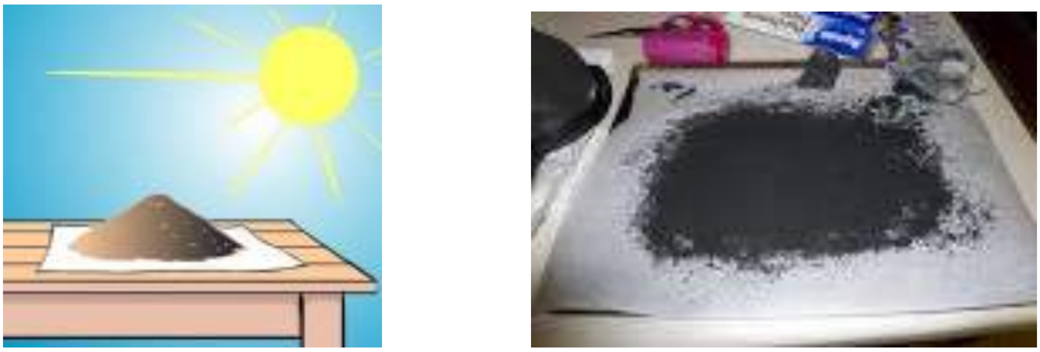

Figure 5.13 Drying the mixture by sun light

13. Press a mixture using a sieve while it is still slightly damp. Spread it out on paper again and allow it to dry some more. The maximum amount of water content expected in ignition powder is 0.7% to 1%. If above this amount, it directly affects the performance of the powder.

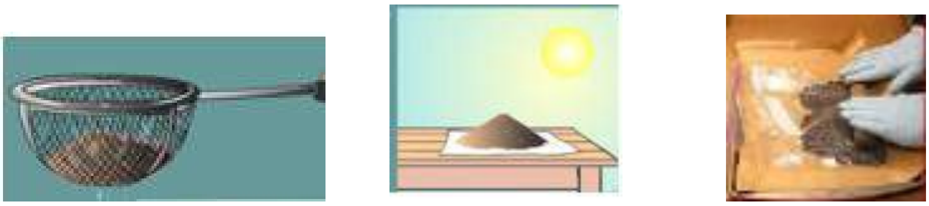

Figure 5.14 Pressing a mixture using a sieve

14. shake the powder using a sieve with different mesh size to get it completely broken down. The size of sieve is based on the demand of grain size required. For this experimental work I prepared three different sieve sizes. These are 500µm, 1mm and 2mm sieve sizes. All the sieves are spherical in shape.

Figure 5.15 Crushing and sieving the powder to required grain size

15. Storing the obtained powder BP in a safe place and safe stores like cans and plastic containers. We have to be sure for choosing a place that is out of the reach of children and pets.

Figure 5.16 Storing the prepared powder in safe place with appropriate containers

In my experimental preparation of BP, we employed the above steps as much as possible outdoors and away from any flame or spark. We also packed the mixture in appropriate containers and stored in the storage of safe place in factory until the legal permission given for the product to take it to our university college. The prepared black powder charge has been tested for its ballistic performance using bulk burning rate method. The method will be illustrated in the next section:

### 5.6 Testing experimental black powder

The most extensively used experimental test method to determine energetic properties of various propellants is burning a specific propellant in a closed vessel and is called a closed vessel tests (CVT). The CVT of solid propellants are aimed mainly on the formulation of their ballistic and energetic characteristics which is considered as individual material constant.

The procedure of determining material constants needs knowledge of experimental conditions; these are initial volume of a closed vessel chamber, the mass and type of propellant involved in combustion process, grain geometry and size as well as its mass. It also includes the quality of material that initializing the ignition process.

#### 5.6.1 Bulk burning rate test for experimentally synthesized black powder

The bulk burning rate is the rate at which the amount of propellant consumed per unit time, or the rate at which gas is formed, is the function of surface area that is burning times the distance in to the propellant burn per unit time. The distance burned per unit time is the normal burning rate. Therefore, the bulk burning rate at any instant is the area that is burning times the normal burning rate [8]. Mathematically it is modeled as:

$$B = AR \tag{5.3}$$

Where: B is the bulk burn rate,

$R = ap_c{}^n$ , That is the normal burning rate illustrated in previous chapter and

$A = \text{burning surface area}$

To perform the test, we measured the height (h) and diameter (d) of the can in cm and filled the can to the rim with ignition powder and inhibit the can in all its sides except the top surface. Then we inserted a strand of candle at the top of the filled volume of can and with the match or other safety fuse. Light the match, wait for the powder to start burning, and time the burn with the stopwatch. We divided the volume of powder by the time it takes to burn completely, and calculated the burn rate. In order to test the burn rate of igniter charge, we need a stopwatch and a milliliter graduated soda can, that 1.0 ml = 1cm$^3$. A soda can is marked with the volume in mm; the average can is 340 ml. simply cut a full sized can using a pair of metal shears, and calculating the volume of the can using the formula:

$$V = h * \pi * r^2 \tag{5.4}$$

Where: V is the volume, r is the radius and h are the height of the can.

### 5.6.2 Materials involved in bulk burning method


a) Safety match b) stop watch c) ruled carton tubes d) soda can

Figure 5.17 Materials and equipments used in bulk burning method of ignition charge

I used containers made of cardboard or soft plastic and also soda can during testing. If we use "metal pipes" or "glass bottles" it easily causes great disaster. We understand that when a metal/glass container bursts due to internal pressure, the air inside will suddenly be filled with very tiny pieces of glass/metal, which traveling at speeds of several hundred meters within a second in all directions. This is called shrapnel, and our aim is to avoid such shrapnel.

### 5.6.3 Validation of recent experimentally obtained pyrotechnic ignition charge with the commercially manufactured Gun powder

From this experimental testing the ignition charges prepared and under test in this research was burned at the rate of 10 to 12 $cm^3$/sec. But the expected burn rate of black powder ignition charge is 14$cm^3$/sec according to the US law of black powder manufacturers.

The variation in burning rate is resulted from different factors. Among the factors, the propellant formulation is the most critical one. Another factor is the tools and equipments that we used are not appropriate for getting the required degree of quality of the charge. In Ambo industry there is no cooling furnace to bring the hot solution of ingredients to immediately to zero degrees centigrade and that also affects the quality of charge. The burn rate of BP is directly proportional to the surrounding pressure. The more the pressure increases, the faster the powder will burn. If the powder burns in a confined space, it will release large quantities of gas, which in turn increase the internal pressure, thus increases the burn rate.

### 5.6.4 BP burning performance test in closed vessel

The CVT also known as ballistic bomb test is used for determining BP burning law[53]. Selected weight of BP charge is ignited in constant volume without the presence of gas exhaust. The pressure developed inside the closed vessel course is properly measured and recorded. The values are needed for the determination of BP burning rate directly from the pressure course recorded. The BP charge has not all grains in the same shape and dimensions; for example, sphere or cylinder. Its sizes are used as average ones for all grains of the selected BP charges. The BP is sifted through the system of sieves and the distribution of grains dimensions along the selected dimensions range is assumed uniform.

Figure 5.18 illustrates the ballistic test fixture (CVT) setup for testing BP. The ballistic test fixture is a thread together device intended for multiple uses, rapid assembly, and multiple initiators that is pyrotechnic or optical configurations. It is constructed of 17-4 PH stainless steel and features an internal spherical volume of 100cm$^3$. To prevent galling, a course thread and the treads are fully nitride to increase surface hardness. The fixtures have proven insensitivity to seizing at routine operating pressures of 241MPa or 35000Psi and are capable of withstanding pressure in excess of 689MPa or 100,000Psi. Pressures are monitored using piezoelectric transducers and gases may withdraw through valves for analysis by FTIR OR GTMS.

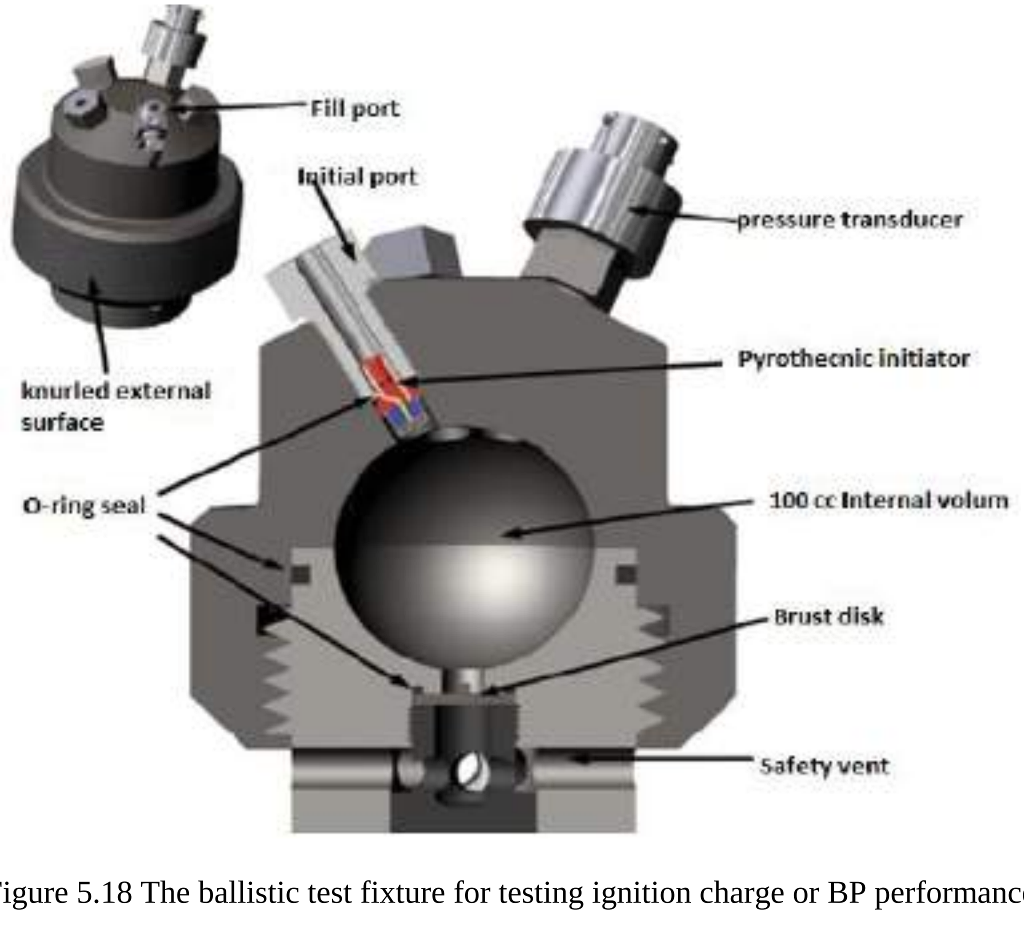


Figure 5.18 The ballistic test fixture for testing ignition charge or BP performance

5.10 CONCLUSION

The ignition of a particular propellant grain is determined by its external surface temperature at time $t_{ign}$ from the starting of its heating. In the conditions of CVT, an ignition of propellant in a closed chamber is understood by a small mass of BP. The transfer of energy to the ignited surface (already ignition initiated) of the propellant being analyzed from the ignition gasses takes place with the help of:

- Free convection as well as forced convection,
- Radiation of ignition gasses particles of the igniter material
- Collisions of particles of the igniter material with an ignited surface of the propellants,
- Thermal conduction in between solid particles of igniter material and an ignited grain of propellants

# CHAPTER SIX

# NUMERICAL SIMULATION OF INTERNAL BALLISTIC PARAMETER AND BOUNDARY LAYER MODELLING OF SOLID ROCKET MOTOR PYROTECHNIC IGNITION CHARGE

## 6.1 Solid propellant internal ballistics simulation

In design and development of SRM, the use of numerical tools to simulate and predict the behavior of a given motor in all its operative conditions is particularly very important in order to decrease planning times and overall costs. This chapter is intended to present an approach to the numerical simulation of SRM internal ballistic performance during combustion of ignition charge in a combustion chamber (i.e. ignition transient, quasi steady state and tail-off) by using BurnSim ballistic numerical simulation modelling tool.

## 6.2 BurnSim Internal Ballistics Simulation software

BurnSim is a software package used for the simulation of solid rocket steady state ballistic performance in a combustion chamber. In SRM, we place propellant characteristics and nozzle parameters for the simulation using BurnSim, then the software will calculate the burn area ratio (Kn) and predicts the motor performance and the quantities of chamber pressure. The most important inputs during simulation using BurnSim includes nozzle diameter (grain core diameter), chamber pressure, motor thrust. The main advantage of BurnSim software is to optimize the design of nozzle. Once we input nozzle diameter (grain core diameter) in BurnSim it immediately calculates the Kn value. The use of this software allows the users to make notes about propellants properties and rocket motor design parameters, all saved in one convenient location [10].

## 6.3 Characteristic features of BurnSim internal ballistics simulation software

BurnSim software supports various grain configurations. Some of the most common grain configurations and its combination are: BATES, End burning, Moon (Offset Core), D- type, C-Slot, Finocyl, Star-type, X-Core grain configurations

- As we provide an input to the software, it immediately graphs the burn area ratio ($K_n$), combustion chamber pressure (Pc), thrust (F), and displays how it changes with the change in motor attributes.
- It also graphs the mass flux over the burn to monitor erosive burning of propellant

- BurnSim can import the test data and plot a graph during simulations
- We can save our motor designs and propellant characteristics, as well as notes and imported test data
- The propellant characterization data can be varying with the range of pressure. The following figure illustrates a simulation for Finocyl- grain of fast burning viper type propellant using BurnSim software.

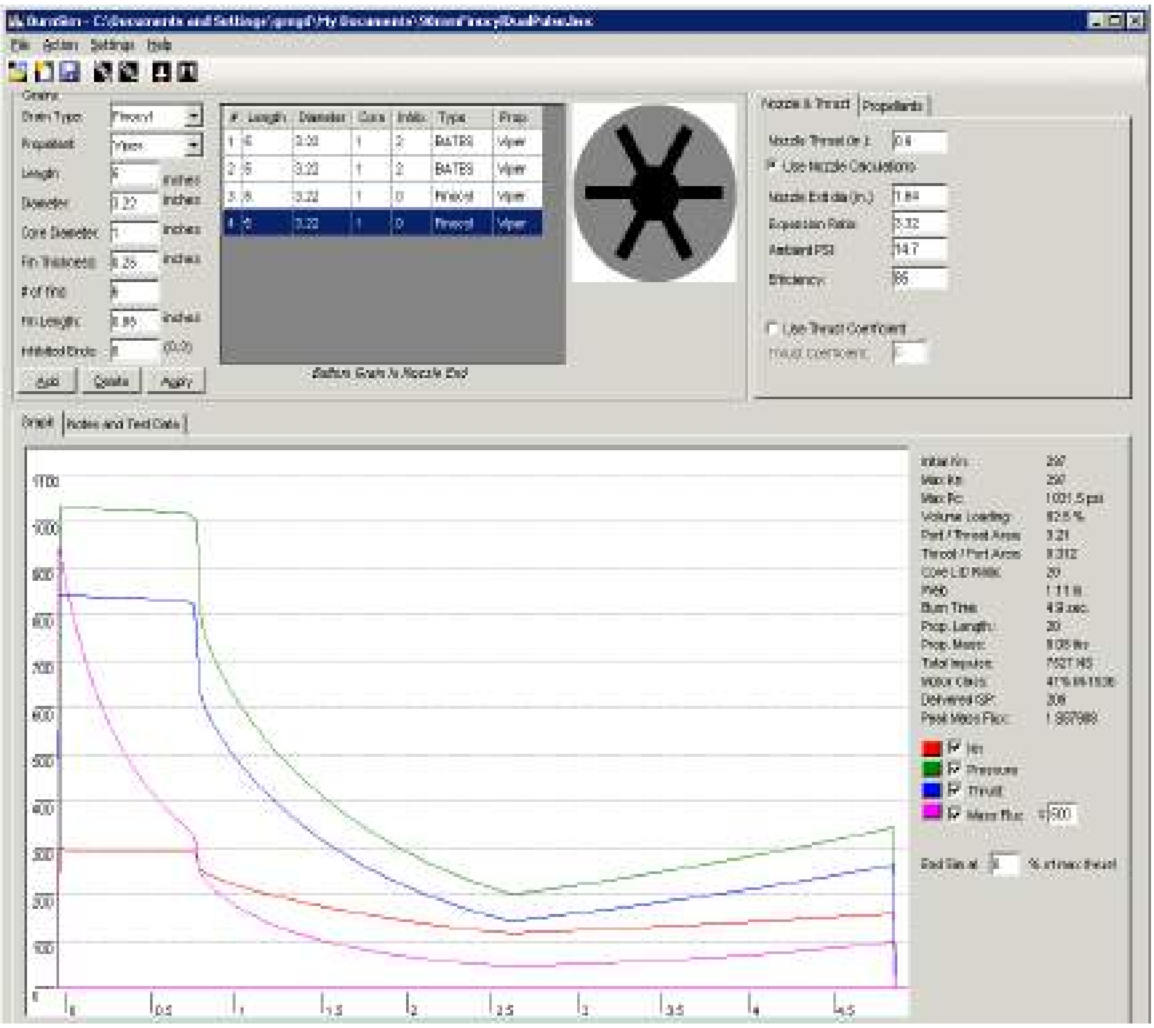


Figure 6. 1 Rocket performance simulation using BurnSim for 6point star Finocyl grain of past burning propellant type

We can observe the plot of quantities like $K_n$, pressure, thrust and mass flux from the above figure. The following inputs are given as an input in BurnSim simulation software:

Grain type: Finocyl

Propellant: Viper

Length: 5.00 in

Diameter: 3.22 in

Core diameter: 1.00 in

Fin thickness: 0.25 in

Fin length: 0.80 in

Number of Fin: 6.00

Geometry of propellants

Nozzle throat: 0.90 in

Nozzle exit diameter: 1.64 in

Ambient PSt: 14.70

Expansion ratio: 3.32

Efficiency: 85

The following diagrams represent a performance simulation for solid rocket motor ignition propellant of different type and different grain using BurnSim simulation software.

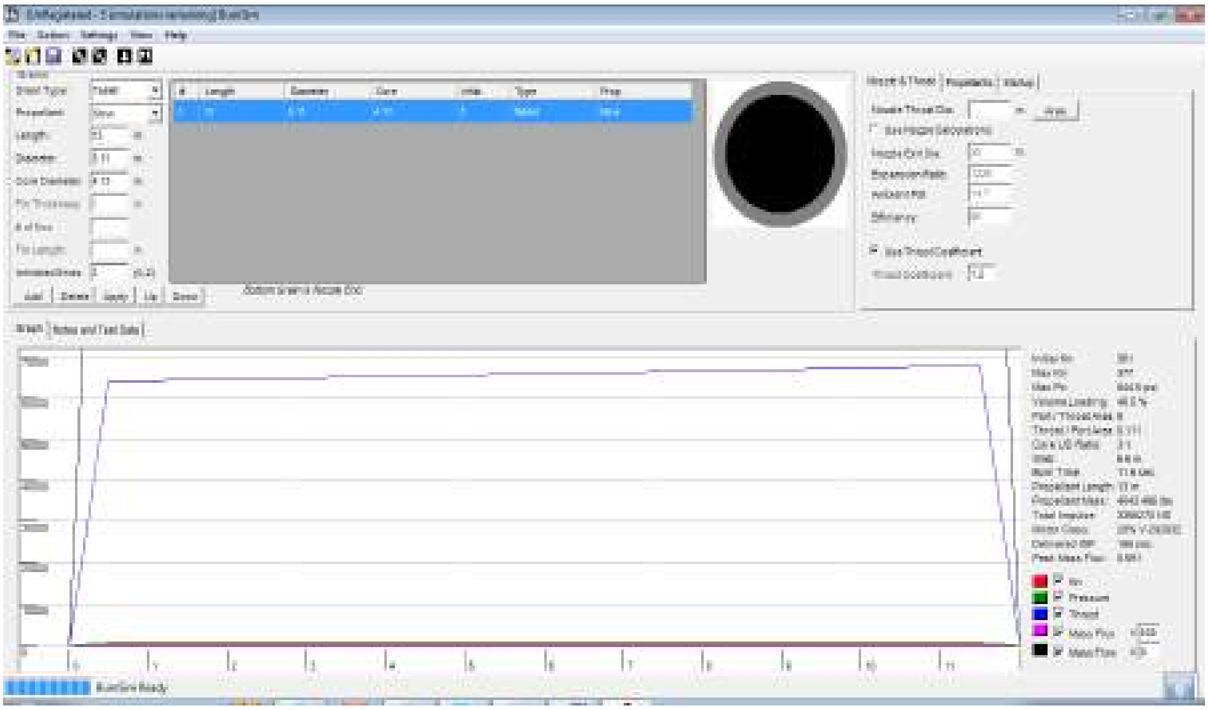

Figure 6. 2 SRM thrust simulation using BurnSim rocket internal ballistic performance simulation software for Tablet grain of slow burning propellant

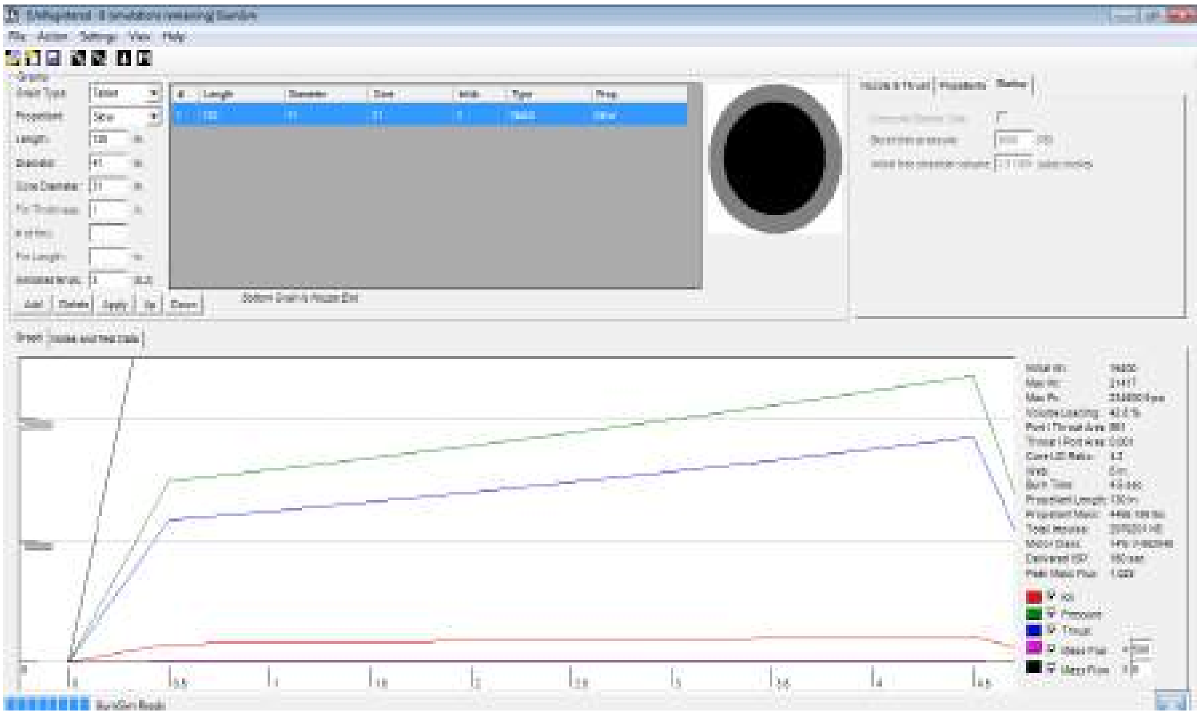

Figure 6. 3 SRM Kn, thrust, pressure, mass flux and mass flow simulation using BurnSim rocket internal ballistic performance simulation software for Tablet grain of slow burning propellant

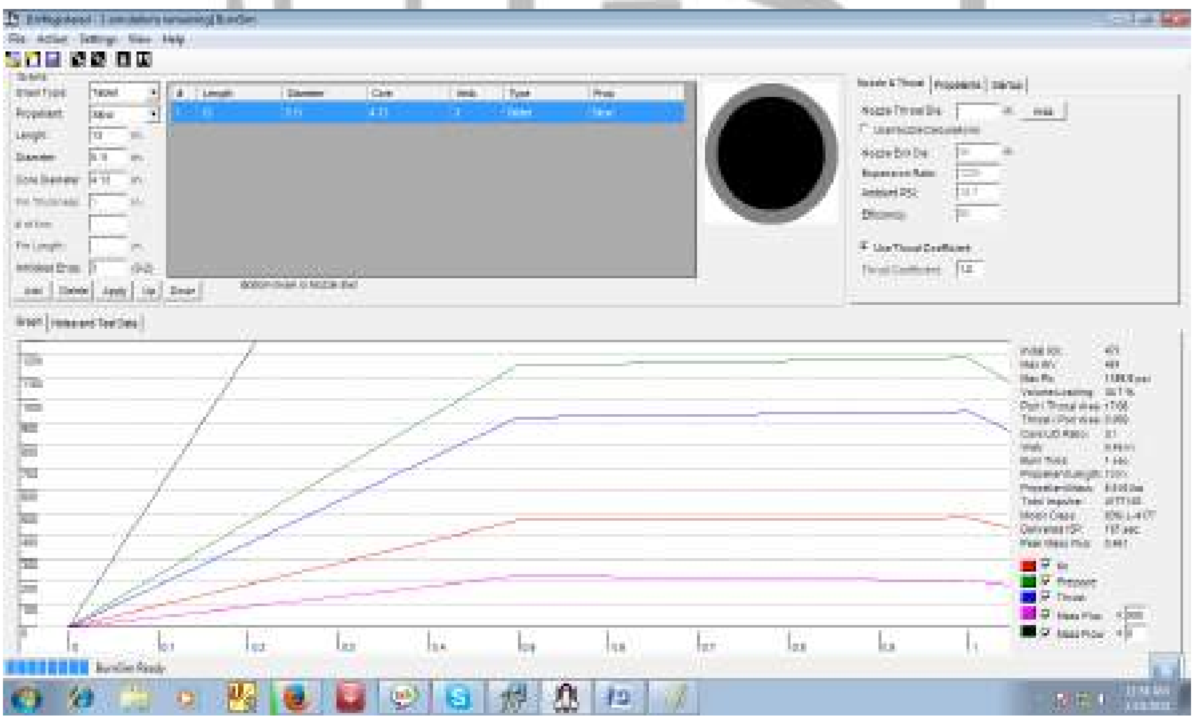

Figure 6. 4 SRM Kn, thrust, pressure, mass flux and mass flow simulation using BurnSim rocket internal ballistic performance simulation software for Tablet grain of slow burning propellant

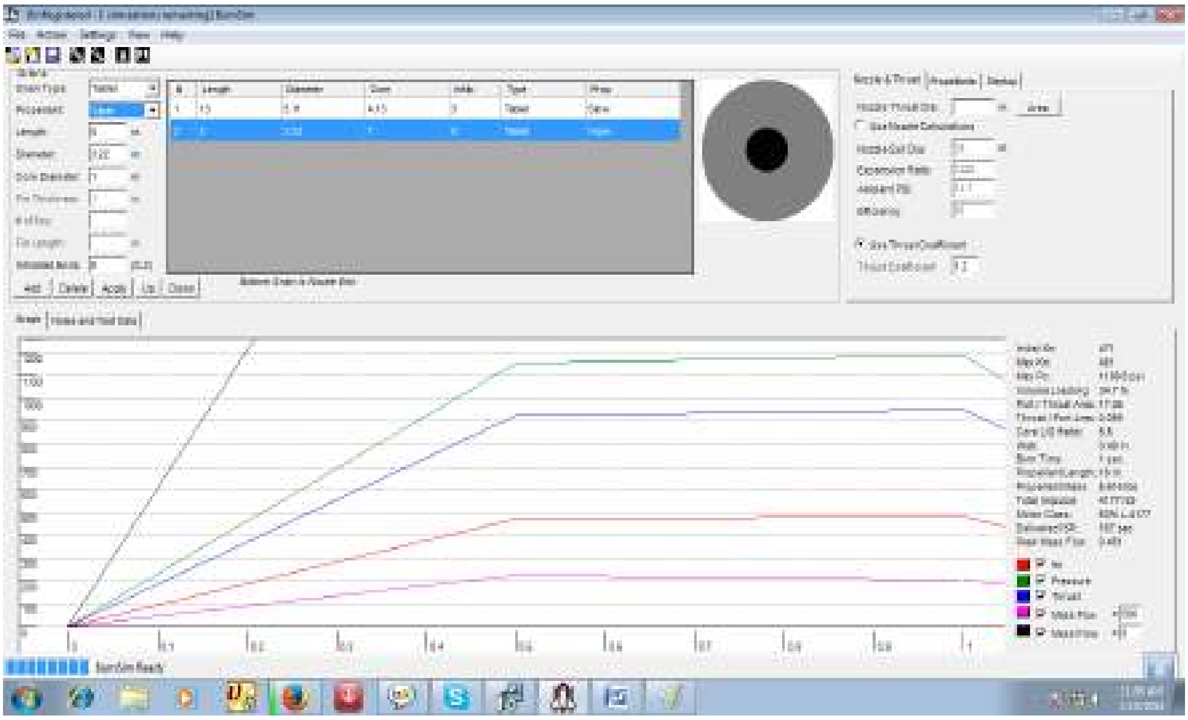

Figure 6. 5 SRM $K_n$, thrust, pressure, mass flux and mass flow simulation using BurnSim rocket internal ballistic performance simulation software for Tablet grain of slow burning propellant with change in dimension of the propellant

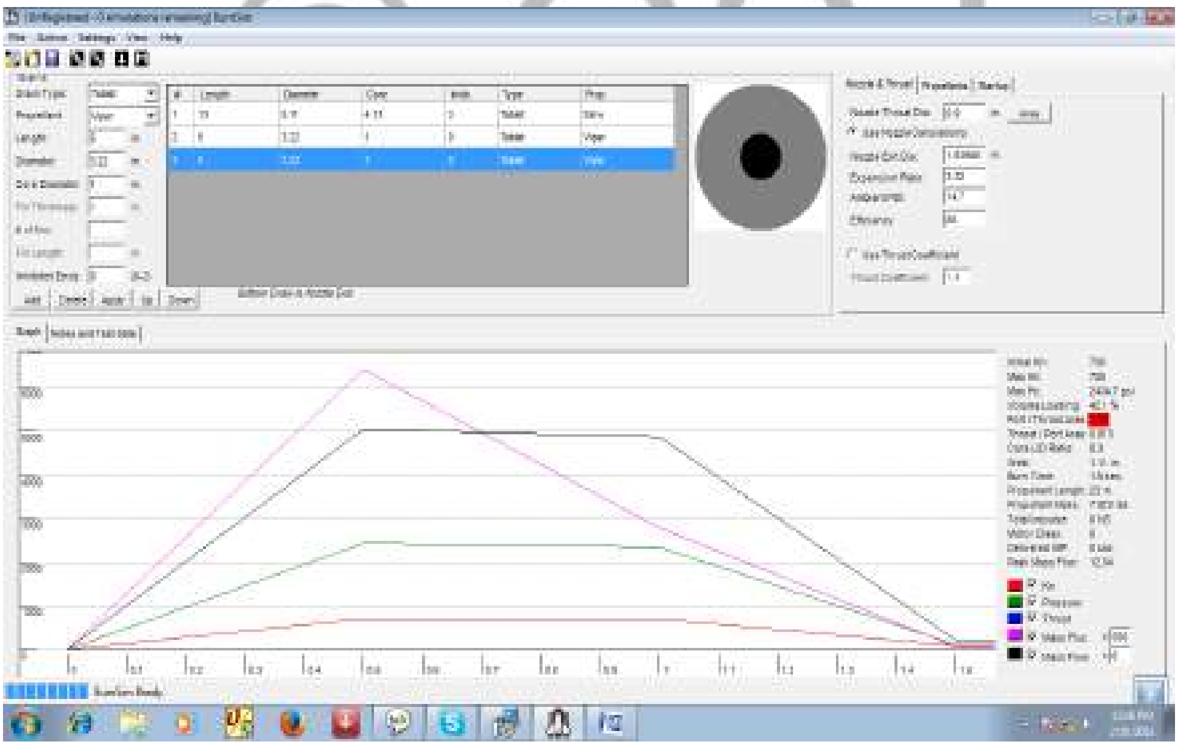

Figure 6. 6 SRM $K_n$, thrust, pressure, mass flux and mass flow simulation using BurnSim rocket internal ballistic performance simulation software for Tablet grain of fast burning propellant

## 6.4 Heat transfer processes modeling using Boundary layer approach

There exist a boundary layers between hot particle of igniter material and the surface energetic propellant materials which is known as thermal boundary layers (TBL). It has been recommended that the igniter material within thermal boundary layers dominates the energy transfer mechanisms for ignition of SRM propellant. The advantage of this work is it allows the design of optimal pyrotechnic igniters for less sensitive SRM propellant charges.

Here we use the most common numerical platform ANSYS software suitable for reaction design in a chemical engineering called CHEMKIN[54],[55] to model a TBL at the interface of solid propellant igniter gases and energetic material of solid rocket propellant.

Basically, here we required to conduct initial modelling of homemade BP ignition charge and applying these charges to SRM propellant ignition. There are two modeling approaches: equilibrium modelling and non-equilibrium modelling modeling approaches. An equilibrium modelling approach unnoticed the chemical reactions in core flow and permits a limited set of reactions at the propellant surfaces, while non-equilibrium modeling approach permits the chemical reactions to take place everywhere.

## 6.5 Modeling software CHEMKIN for heat transfer phenomenon

The boundary layer model is general be used in any channel-flow in which the gas phases and surface kinetic mechanisms are well identified [54], [55],[56].

**Flow conditions:**

The inputs used in CHEMKIN simulation at inlet of the nozzle includes: inlet pressure, inlet temperature, inlet velocity and the propellant mass fractions. In the case of large caliber guns many grains are in-contact to each other, there exists small channels or holes through which the ignitor hot gasses will flow or propagate[54], [55],[56].

For current simulations, we considered a gas flow through cylindrical shaped channel was used as given in figure below (Figure 6.7). The cylindrical shaped channel with diameter of 10mm, and semi-infinite length (let us take 1000 mm) was considered for analysis. Igniter gas enters in to the channel for recent simulation process with a set of initial conditions.

The following flow conditions are considered in recent simulation using CHEMKIN:

- The gas temperature of BP is taken 2, 000 $^0$K for both cases;
- The gas velocity taken as 200 m/s, 300 m/s and 400 m/s;
- Operating Pressure is considered 0.10 N/mm$^2$ and 5.00 N/mm$^2$.

Figure 6.7 The energy flow from igniter to a cylindrical channel of propellant in SRM

### 6.5.1 An equilibrium modelling approach

The simulation software for a thermal code using CHEMKIN CEA2 was used to predict the temperatures and pressures which are equilibrium products during analysis. For every set of equilibrium conditions, to produce species and the mass fraction [57], [58]. For the equilibrium condition of modeling, these compositions were fixed in appropriate ratio throughout the simulation process. The only difference to this composition would be the surface reactions and the diffusion of species.

The figure (Figure 6.7) shows an equilibrium combustion product as a function of pressure and temperature for BP charge at a pressure range of 0.10 N/mm$^2$ to.00 N/mm$^2$ respectively. The composition of BP in current simulation contains a proportion by weight as 75% :15% : 10% potassium nitrate, carbon and Sulphur respectively [59].

### 6.5.2 CHEMKIN MODELLING RESULTS

#### 6.5.2.1 Black powder - Equilibrium modeling

The temperature 2000 $^0$K, axial velocity 3000 m/s and pressure varies from 0.1 MPa to 5.00 MPa are considered in both equilibrium and non-equilibrium simulations. Figure 6.8 to Figure 6.11 illustrates the temperature and velocity distribution in axial direction for inlet flow of BP in equilibrium conditions that showing Axial coordinate vs temperature distribution, Axial coordinate vs velocity distribution for 0.10 MPa and 5.00MPa pressures.

Similarly, Figure 6.12 to Figure 6.15 illustrates the temperature and velocity distribution in axial direction for inlet flow of BP in non-equilibrium conditions that showing Axial coordinate vs temperature distribution, Axial coordinate vs velocity distribution for 0.10 MPa and 5.00MPa pressures.

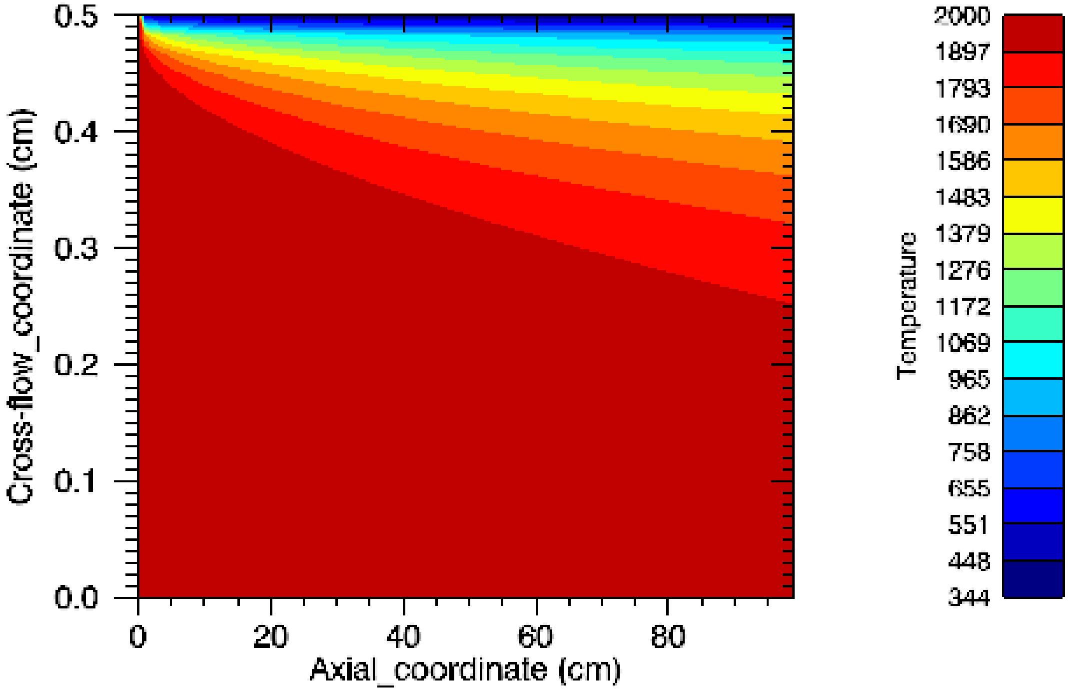


Figure 6. 8 Temperature and velocity distribution in axial direction for inlet flow of BP in equilibrium conditions (Axial coordinate vs temperature distribution for 0.10 MPa)

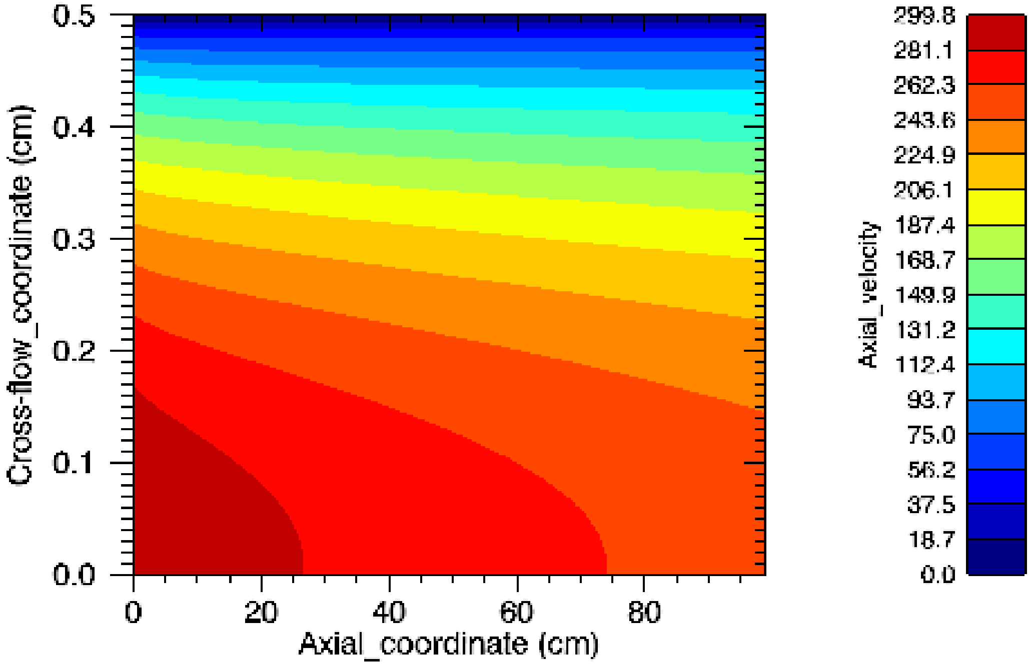


Figure 6. 9 Temperature and velocity distribution in axial direction for inlet flow of BP in equilibrium conditions (Axial coordinate vs Velocity distribution for 0.10 MPa)

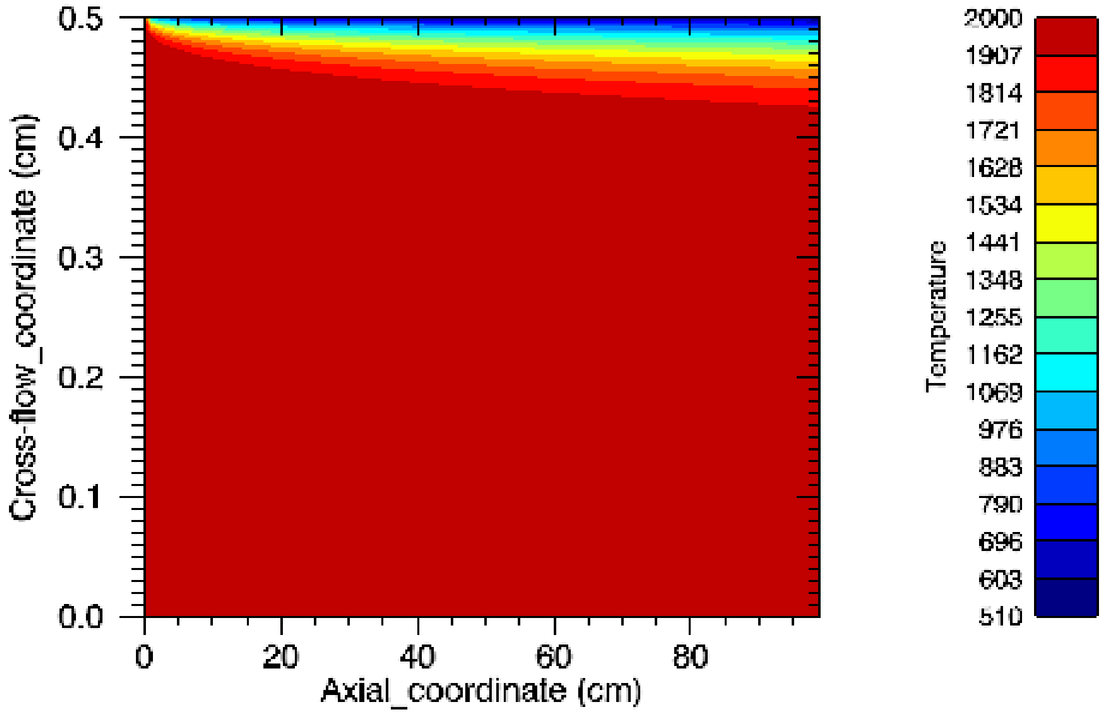


Figure 6. 10 Temperature and velocity distribution in axial direction for inlet flow of BP in equilibrium conditions (Axial coordinate vs temperature distribution for 5.00 MPa)

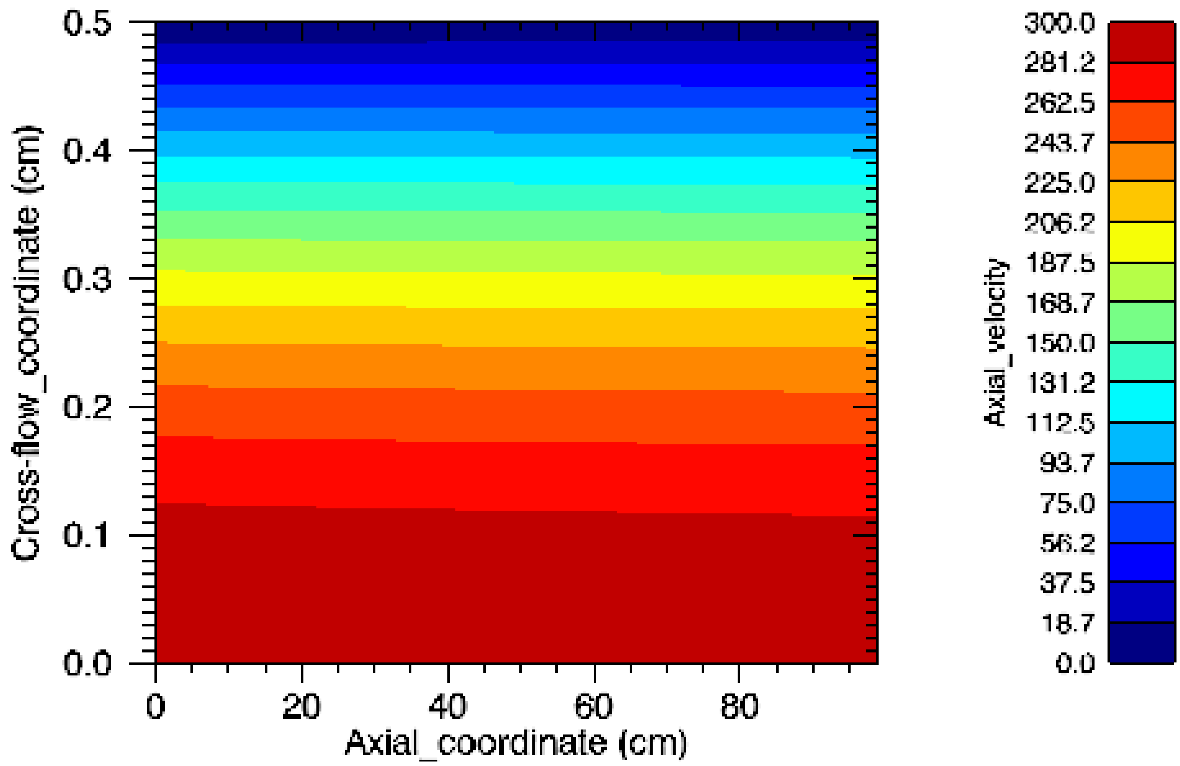


Figure 6.11 Temperature and velocity distribution in axial direction for inlet flow of BP in equilibrium conditions (Axial coordinate vs Velocity distribution for 5.00 MPa)

### 6.5.2.2 Black powder – Non-equilibrium Modeling

In non-equilibrium condition, the properties of inlet pressure are also higher as that for the equilibrium condition, that it would narrowed the boundary layer. The only difference is the temperature is slightly higher in the case of non-equilibrium condition

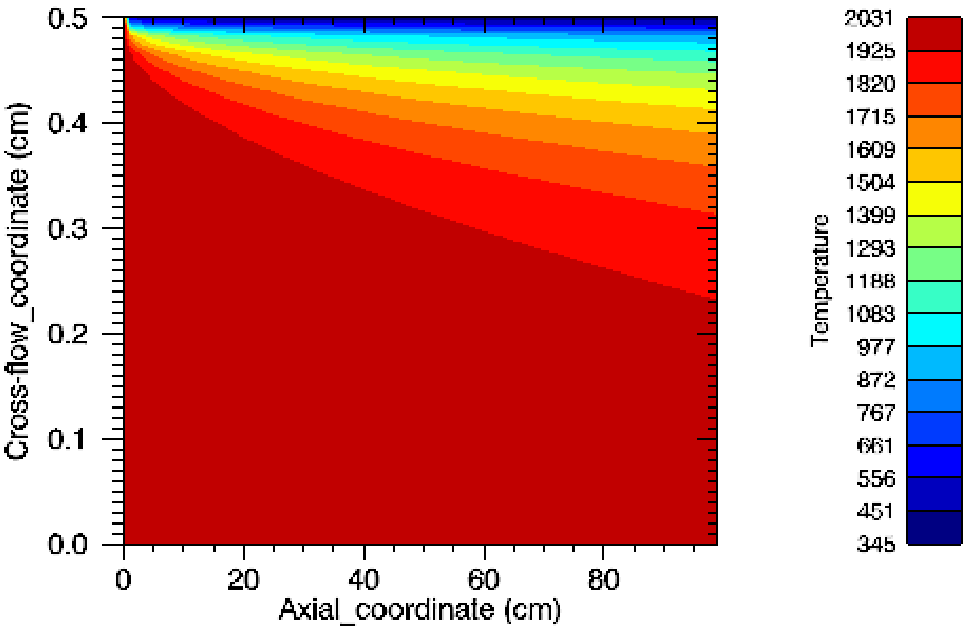


Figure 6. 12 Temperature and velocity distribution in axial direction for inlet flow of BP in non-equilibrium conditions (Axial coordinate vs temperature distribution for 0.10 MPa)

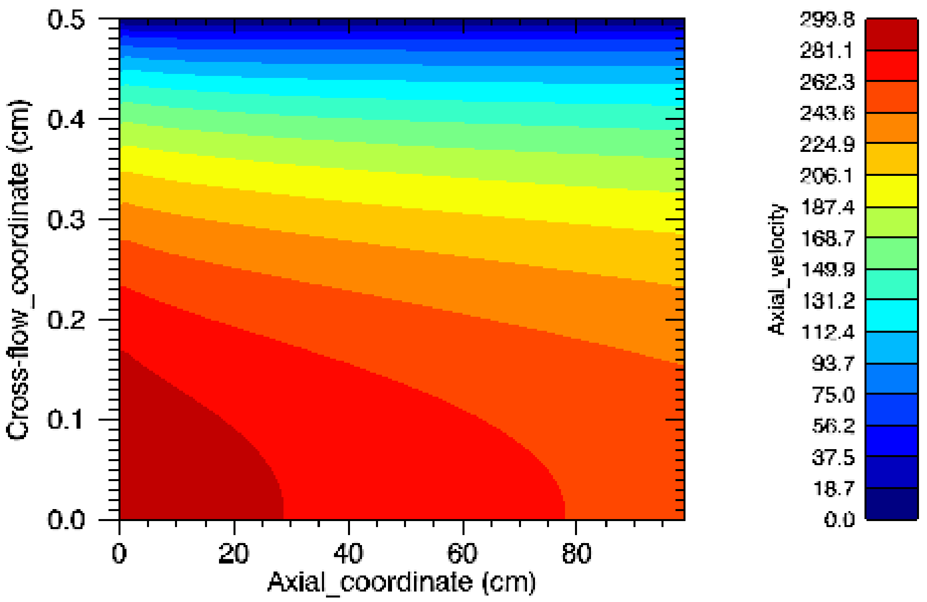


Figure 6. 13 Temperature and velocity distribution in axial direction for inlet flow of BP in non-equilibrium conditions (Axial coordinate vs Axial velocity distribution for 0.10 MPa)

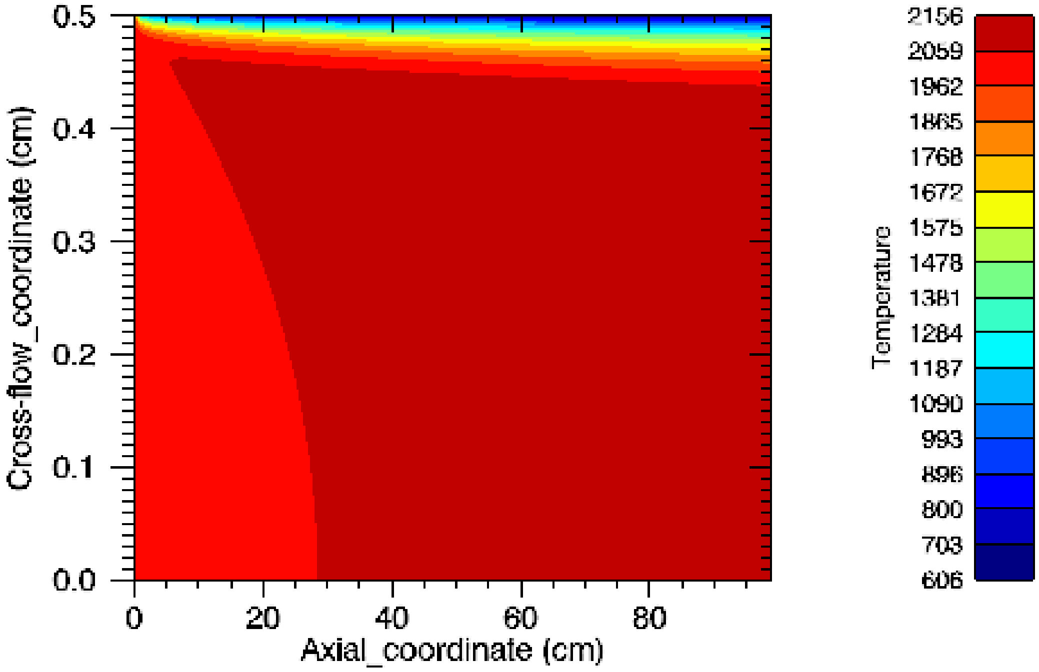


Figure 6. 14 Temperature and velocity distribution in axial direction for inlet flow of BP in non-equilibrium conditions (Axial coordinate vs temperature distribution for 5.00 MPa)

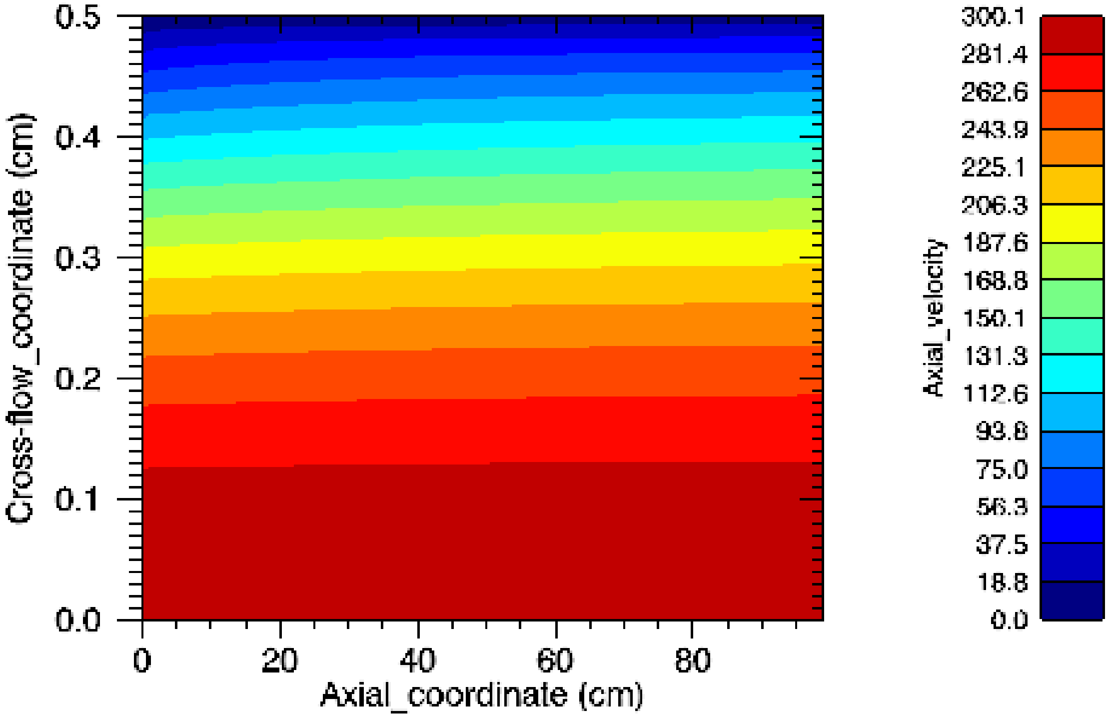


Figure 6.15 Temperature and velocity distribution in axial direction for inlet flow of BP in non-equilibrium conditions (Axial coordinate vs Axial velocity distribution for 5.00 MPa)

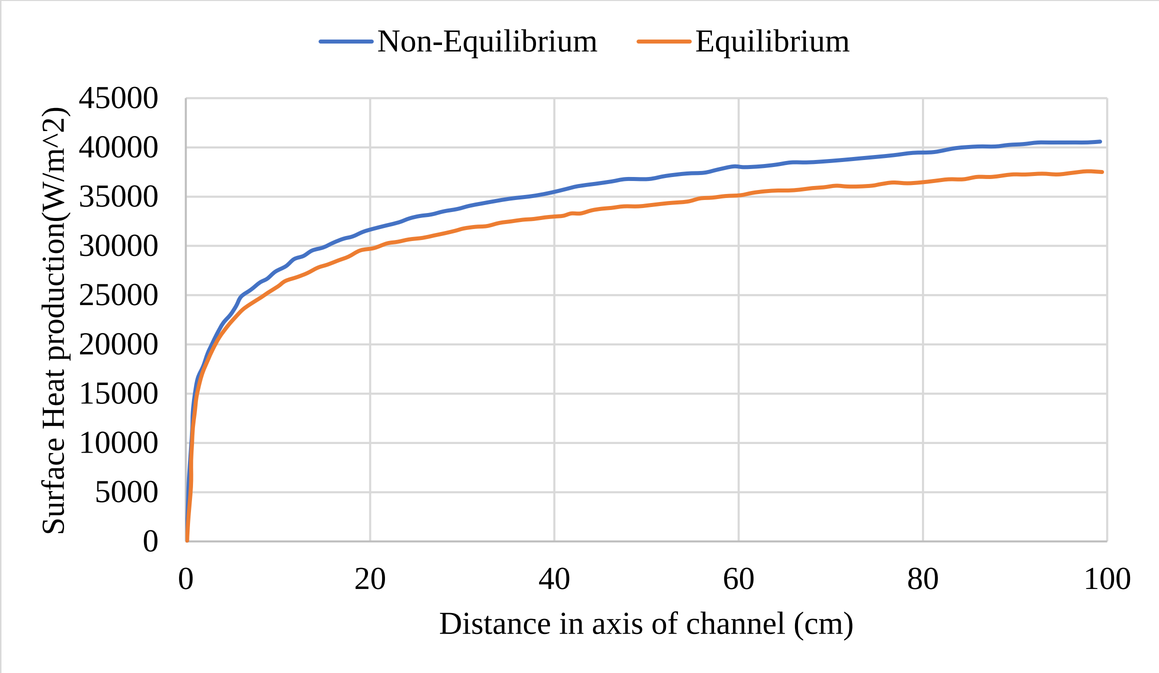


Figure 6.16 Estimated rates of surface heating for inlet flow for an inlet temperature of 2,000 $^0$K, and inlet pressure 0.10 MPa

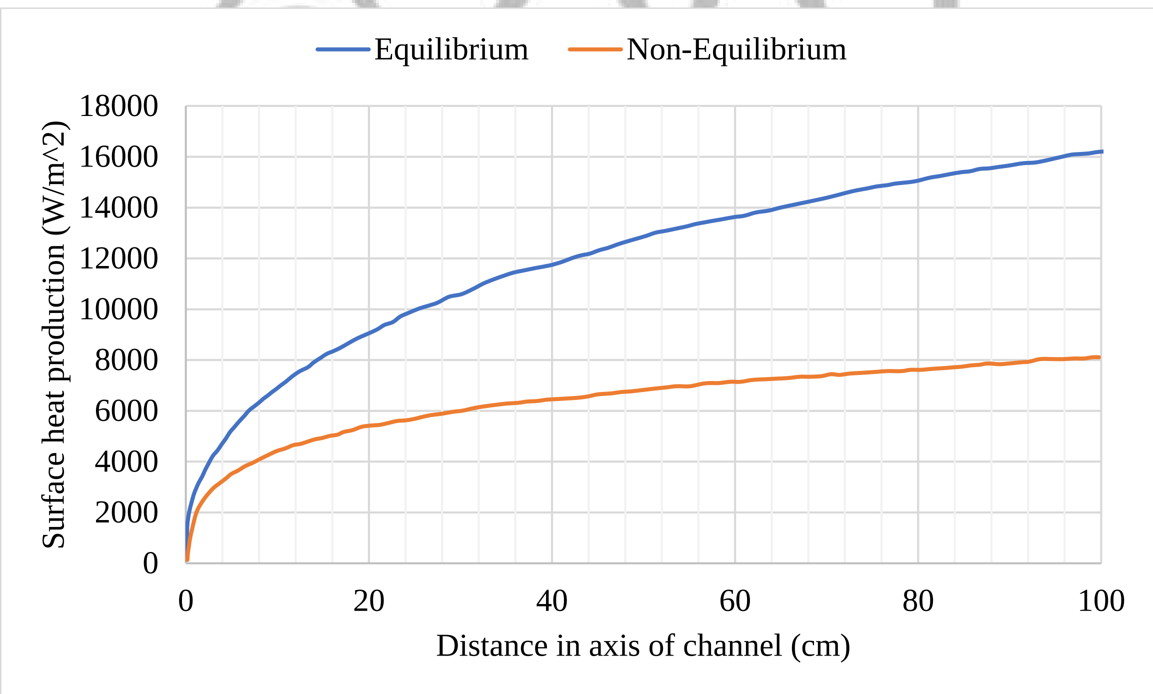


Figure 6.17 Estimated rates of surface heating for inlet flow for an inlet temperature of 2,000 $^0$K, and inlet pressure 5.00 MPa

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Table 6.1 Ignition delay for constant surface heat flux to a semi-infinite solid

| Igniter material and condition | Surface heat flux ($MW/m^2$) | Ignition time (ms) | Convective heat flux ($MW/m^2$) |
|---|---|---|---|
| BP at 0.1 MPa (EQ) | 0.034 | 13,200 | 0.510 |
| BP at 5 MPa (EQ) | 1.300 | 9.300 | 2.750 |
| BP at 0.1 MPa (NEQ) | 0.037 | 11,500 | NA |
| BP at 5 MPa (NEQ) | 0.700 | 34.600 | NA |

Where: EQ = Equilibrium and NEQ = Non-equilibrium, NA=Value is not assigned

The difference in ignition delay between equilibrium and non-equilibrium condition are very small and not significant for BP ignition charge. But the increase of pressure from 0.1 to 5 MPa results a significant reduction in ignition time by order of 1000 for BP ignition charge.

# CHAPTER SEVEN

# CONCLUSION AND RECOMMENDATIONS

## 7.1 Introduction

This chapter summarizes, concludes and proposes the future work to be continued on the theoretical and experimental study of pyrotechnic igniter for solid rocket motor application.

## 7.2 Brief summary on current thesis

This paper work is dedicated to contain an over view of pyrotechnic igniter for solid rocket motor application. The thesis work includes the theoretical study of pyrotechnic igniters, igniter composition and its ballistic performance, igniter energy release and heat transfer phenomenon, and the factors that affect the design and development of pyrotechnic igniter. It also includes the experimental study of igniter composition and testing of an experimentally obtained ignition charge for its ballistic performance and comparing the result with commercially available product specifications. This thesis also presents the work to meet basic technological requirements of the rocket motor ignition using electro-explosive device called electrically initiated pyrotechnic igniter.

The paper contains two main sections. The first section emphasizes on the basic theoretical background of pyrotechnic igniter, igniter chemical composition and its constructional feature. This section provides a brief introduction about solid rocket motor ignition, ignition phenomenon, and ignition charge composition. The topics covered are background of pyrotechnic igniter and its requirement, the history and literature survey in bath national and international level, solid rocket motor basics and its igniters, classification of SRM igniters, ignition system, theoretical determination, and identification of main ignition charge composition, ignition energy release analysis and design parameters.

The second section of the paper includes design and construction of pyrotechnic igniter for solid rocket motor, experimental study of pyrotechnic igniter charge and its preparation in laboratory scale, safety precaution and handling the pyrotechnic mixtures, and its test for ballistic performance using different testing methods. It also included the numerical simulation methods to evaluate the performance of energetic material and energy release phenomenon.

### 7.3 Conclusion

The use of pyrotechnics for SRM ignition is the most important aspect for the development of rocket technology. The design, development and construction of appropriate ignition system for SRM is one of the most innovative activities and also is the most critical step for the development of rocket technology.

Since in Solid rocket motor, once the propellant start burning it will not terminate and is not used further application. Therefore, it is obvious to study the ignition system and its performance parameters before the failure occur in actual rockets.

In this thesis I have synthesized an appropriate igniter charge, designed initiator system and its hardware for the selected type of rocket propellant based on the design data and parameters. The igniter compositions have been experimentally tested for its ballistic performance using bulk burning rate test method. The test results of an experimental ignition charge were compared to commercially manufactured one for its ballistic performance, and have obtained appreciable values that were in the range required.

In addition to this, the numerical simulation of internal ballistic parameter and boundary layer modelling of solid rocket motor ignition charge has been studied theoretically. The numerical simulation of internal ballistic parameter of the selected propellant (BP) has been studied using BurnSim simulation software. And the boundary layer modelling of the heat transfer processes from igniters to propellant uninhibited surface have been analyzed using CHEMKIN for different pressure and temperature condition.

There are many alternative ways of testing the ignition powder in the absence closed vessel tests set up. Some of them are Bulk burning rate test method, baseball firing test method and others. For this paper work I used the bulk burning method of testing, because of unavailability

The thesis also briefly discusses the safety aspect that should be followed while synthesizing the ignition charge in laboratory

### 7.4 Recommendation

The performance improvement of ignition or initiation system for SRM propellant that had been studied in this thesis should be continued to further to enhance the optimum design and development. In other words, to establish rocket technology in the country, we have to optimize the performance parameters that affect its ignition in order to achieve the intended. In current work I have faced challenges or constraints in both the theoretical as well as the experimental study of this thesis. Some of the constraints considered in this thesis work as follow:

1. Unavailability of rocket ignition related technology in the country.
2. Lack of prior educated professionals of the nation.
3. Lack of clear information and data, because of the secured nature of technology.
4. Data obtained from internet are also sometimes ambiguous to use.
5. The failure of existing ballistic evaluation test equipment and laboratory setups in Ambo chemicals and armament industry.
6. Lack access of visit to related companies outside of the country, and unavailability of aerospace laboratory within the college

In order to design and develop rocket motor and its ignition system in the industries the following recommendations are very vital and should be considered for future research work:

**1.** Giving emphasize for the design and development of rocket and rocket ignition system within the national level in collaboration with the stack holder companies.

**2.** Establishing the aerospace laboratory in both industries and academic sectors.

**3.** Purchasing the ballistic performance measuring instruments like strand burners, closed vessel test set ups or ballistic bomb with capacity of at least 6.89MPa or 1000PSi up to 68.9MPa or 10,000PSi in both colleges and industries.

**4.** Performing reengineering work of the existing rockets and rocket ignition systems

**5.** The use of NASA software and other licensed software such as BurnSim, CHEMKIN and SPINBALL numerical simulation software are further recommended in order to get theoretical values of performance related parameters.

I presented mathematical modeling of the energy transfer using different theories. I propose that the research in the area of these theories would have been continued further for the better-quality product of the ignition and its related phenomenon. I also propose to provide more theoretical and analytical models that are not indicated in this work for future research work of SRM ignition system in advance. Another important topic to be studied further is the evaluation of igniter energy release and transmission, and the response of motor propellant to a given externally applied energy in advance than presented in this work.

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## GLOSSARY

**1. Rocket Propulsion:** is a means of locomotion whereby thrust is produced by ejecting matter, which is stored in the vehicle being propelled.

2. **Chemical Rocket Propulsion:** refers to those systems where the energy comes from a chemical reaction or combustion of a Fuel with an Oxidizer.

3. **The Chamber Pressure:** is the pressure in the combustion chamber of an operating rocket propulsion system.

4. **Propellant**: is the stored matter that is energized and ejected. It can be a Liquid Propellant (stored in vehicle or missile tanks) or a Solid Propellant (stored inside its combustion chamber).

5. Specific Impulse: is a parameter indicating propulsion system performance. It can be defined as the thrust of an equivalent rocket propulsion system (same chamber pressure, same propellant, same nozzle throat to exit area ratio) that has a propellant mass flow of unity. Higher values of specific impulse indicate a better system.

6. **Total Impulse:** is the integral of thrust over the propulsion operating time. It is a measure of the total kinetic energy of the nozzle exhaust gas as released by the combustion of all the available propellant in the propulsion system.

7. A **Rocket Motor:** uses solid propellants and a simple motor usually has these key components: the propellant Grain (the shaped mass of solid propellant), the motor Case, which is a pressure vessel containing the grain, Insulation for preventing the case from becoming too hot, a supersonic Nozzle to accelerate the gasified, reacted propellant, and a mounting provision to hold the motor to the vehicle or missile. Cases are really pressure vessels constructed from heat treated alloy metal (steel, titanium) or from filament reinforced plastic (usually an epoxy plastic) with fibers made of glass, Kevlar, or carbon.

8. **Solid Rocket Propellant:** typically consists of an oxidizer (usually a crystalline solid like ammonium perchlorate), an organic Fuel (such as a rubbery polymer like polybutadiene, which also acts as the glue to hold the grain together), and various additives to improve performance, storage, thrust-time profile, manufacture, aging, etc. Additives include liquid Plasticizers, Explosives, Burning Rate Catalysts, etc.

9. **The Burning Rate**: is the rate of regression of the burning grain surfaces as propellant is consumed or burnt in a direction normal to the surface. Surfaces that are bonded to the case walls or to insulators, will not burn. The burning rate varies with chamber pressure and the initial ambient temperature of the grain.

**11. Inhibitors:** are layers of non-burning materials that are glued to exposed grain surfaces so that they will not burn.

12. **The propellant Grain:** has Perforations, Slots, Grooves, holes, or Port Areas so as to predetermine the amount of initial burning surface. Most grains are cast into and bonded to the case; some grains are bonded to a separate cartridge, and then loaded or placed into the case.

13**. The Binder**: is a thin layer of sticky rubbery material that promotes the adhesion of the grain to the case.

**14. Igniters:** burn igniter propellants, which then form hot gas at an elevated pressure and they in turn initiate the combustion of the main propellant, either a solid propellant or a non-hypergolic liquid bipropellant. The igniter is started by a small amount of electrical energy, (e.g., hot wire) or laser energy.

15. The **Nozzle Area Ratio:** is the nozzle exit area divided by the nozzle throat area. For optimum gas expansion in a nozzle the gas pressure at the nozzle exit is equal to the local ambient atmosphere pressure. Typical values of this nozzle area ratio are between 4 and 20 for expansion to sea-level pressure and between 40 and 200 for operation at very high altitude (space vacuum).

**16. Pyrotechnic igniters** are device containing a pyrotechnic composition used primarily to ignite other materials which are more difficult to ignite, like thermites, gas generators, and solid rocket propellants

17**. Pyrogen igniters** are small rocket motors, designed in accordance with the same principles as a rocket motor and consist of a cast propellant grain of the fast-burning type as the main charge.

**18. Burn Area Ratio** (Kn) is the ratio of the burn area $A_b$ to the throat area $A_t$

**19. Thrust** is a reaction force described quantitatively by Newton's second and third laws. When a system expels or accelerates mass in one direction, the accelerated mass will cause a force of equal magnitude but opposite direction on that system