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NOMENCLATURE

C	Capacitance [F]
E	Total Discharge Energy [J]
I_{bit}	Impulse bit [N-s/shot]
Isp	Specific Impulse [s]
η	Thrust Efficiency [%]
m	Mass [gms]
m_{bit}	mass bit [gms/shot]
l	length of cavity [mm]
d	Diameter of cavity [mm]
ε_d	dielectric constant
ε_o	permittivity of free space [F/m]
Δv	velocity increment [m/s]
γ	specific heat ratio
μ	viscosity [Pa s]
μ_o	permeability of free space [N/A^2]
κ	electrical conductivity [Si/m]
ρ	Density [kg/m3]
σ	plasma conductivity [Si/m]
R	gas constant [J/kg/oK]

q Charge [C]

Q volumetric flow rate [m^3/s]

r radius [m]

M Mach number

K thermal conductivity [W/m/^oK]

K Boltzmann's constant [J/^oK]

dL length increment [m]

M_{fuel} Mass of fuel

M_{sat} Mass of Satellite

S Distance

V_{jet} Velocity of exhaust Jet

t_{flight} Time of flight

PREFACE

Over fifty years of dedicated research since the first launch of the Russian satellite Zond-2 flown with the electric propulsion system to the space has improved the capabilities of the Pulsed Plasma Thrusters. Due to its microsecond operation time the Plasma Thrusters are suitable for interplanetary space travel, but the internal dynamics and nature of operation is still unclear. The Pulsed Plasma Thruster is very economical to fabricate and to operate, which makes it a most popular system for research worldwide.

Not only economical but the Pulsed Plasma Thruster has very unique capabilities when compared with other propulsion systems. The simple operation but complicated principals make it a very suitable device for research. The Pulsed Plasma Thruster accelerates the plasma generated, at the nozzle in short intervals to produce impulse. This thrust which is generated at intervals of time gives time for storing energy in the capacitors, hence ready for next discharge. The storing of energy improves the power drawing ability of the thruster and makes it dependant on the frequency of the system. This property of the thruster makes is suitable for performing controlled manoeuvres.

The work here covers the design optimization. The experimental tests conducted on the Pulsed Plasma Thruster is the basis of the conclusion of the best design and the second area covered here is the computational analysis of the thruster using Magneto hydro Dynamic simulation.

Chapter 1

Introduction

1.1 Motivation for Research

Satellites require propulsion systems once it is separate from launcher to the de-orbiting operation. At this separation with the third stage, the satellite is injected on a transfer orbit with an apogee at a certain distance from the Earth's surface.

The satellite has to be maintained at this working position throughout the Mission or the life of the satellite. The satellite moves in accordance with Lunar and Solar. The drag effect is negligible in space. The predominant effect is the Lunar-Solar interactions which are greater than the Earths non-homogeneity and the Sun radiation effects. Consequently, thrusters are required to move the satellite back to its initial working place and to perform daily North-South and East-West corrections.

Moreover, it becomes necessary to move the satellite during the mission in order to avoid a collision with a moving object or debris in space. Because of human activities, there are as many as 13000 objects larger than 10 cm are in space, and more than 200000 from 1 to 10 cm . When a risk arises, a thruster is started to move the satellite and avoid a collision.

Finally, in order to de-orbit the satellites to make way for the new satellite the thruster is used. Hence the thrusters are required from initial stage to the end of the satellites life.

The thruster which is also known as electromagnetic accelerators are devices where the use intense bursts of electrical current to create high speed jets of plasma. They find application as plasma sources in many basic plasma science experiments as well as in a specific genre of electric space. Due to the increased interest in micro-satellite technologies, the bulky cold gas propellant thrusters and conventional reaction-wheel attitude control systems are being replaced for lighter and more capable electric thrusters serving all kinds of purposes from attitude-control, drag make-up, to primary propulsion depending on the application.

Pulsed Plasma Thrusters (PPT), the first EP technology to ever fly in space currently enjoys the heritage of over ten successful spaceflights. The Pulsed Plasma Thruster being a popular device among researchers, it is often underestimated due to its simplicity and low manufacturing cost. Providing an efficiency of not more 20% the Pulsed Plasma Thrusters are not much popular within the industry. Even though simple and cost effective, the Pulsed Plasma Thruster has complex underlying physical principles which make the research groups to fall into the trap of building these devices.

The operation is by the discharge of the stored energy form the capacitor into propellant between the electrodes. The propellant is ionized when the initial energy is given allowing the capacitor to discharge and charge again. High currents induced by low resistance create strong magnetic fields in the electrodes. The cross product between the energy density and magnetic field creates a force that accelerates the plasma along the axis of thrust.

The project focuses on the best design optimization which is carried out on purely experimental tests. More than fifty experiments were conducted in the vaccum chamber in order to determine the best configuration. The aim of this study is to increase the energy efficiency of the system, by configuration studies of electrodes, propellant and the energy density. From the experimental studies optimization of the system design was arrived.

1.2 Outline of chapters

1.2.1 Literature Review

The available literature has been reviewed in this chapter. This chapter covers the history of the Pulsed Plasma Thrusters from the first flight to the recent thrusters used in the satellites. The chapter consists of the successful flights and those that have failed. There are also elements that describe the current level of understanding of the process that takes place in the PPTs

1.2.2 Working Principle

In order to understand the working of PPTs experiments were conducted. After a number of iterations the thruster was developed and the test were conducted for different propellant geometries. .In this chapter the working principle of a Pulsed Plasma Thruster is explained.

1.2.3 Modelling

2D modelling of the PPT was carried out using AutoCAD. The 3D model was developed in Catia. The modelling was done with respect to several aspects including the nozzle design.

1.2.4 Results and Discussion

The results and observations are discussed in this chapter. All the results are tabulated for experimental tests conducted.

1.2.5 Conclusion

Conclusion is discussed here, which outlines the best configuration of the thruster.

1.2.6 Future Scope of Work

This chapter explains the scope for future work regarding this project. What more can be done in this project.

Chapter 2

Literature Review

2.1 Introduction

Due to its vast operational principals the PPT has an unusual affinity towards research. Since, the first flight of the Pulsed Plasma Thrusters as an electric propulsion device it has been on top as a research project. Being of the simplest and economical propulsion devices the Pulsed Plasma Thrusters have seen a very less improvement since five decades. This fact shows that even though being a simple and economical there lies a very complex procedure in understanding the mechanism of the thruster.

The thruster is basically known as an electric propulsion device which uses electric current to ionizes the propellant. Traditionally the Pulsed Plasma Thruster is defined as a device consisting of few parts which includes the electrodes and propellant basically. A PPT has an energy storing device ie a capacitor which discharges at a certain frequency, the discharge is initiated by the sparkplug.

Fig 2.1 shows a PPT consisting of an anode, a cathode, a solid propellant or Teflon, spark plug, and a spring. This is how the Pulsed Plasma Thruster is visualized but it would be an inaccurate representation. For example the propellant may change as per the requirement or an inductor could be used instead of a capacitor.

So, what is the correcting understanding of a Pulsed Plasma Thruster ? It is an energy source which continuously discharges creating a magnetic field around the flow of the current, where the current flows through the plasma generated. Here the thrust is majorly created from the Lorentz force produced due to the interaction of the current flowing through the plasma and the magnetic field.

This definition not only gives you an understanding of the principal mechanism but also says how the thruster must be designed.

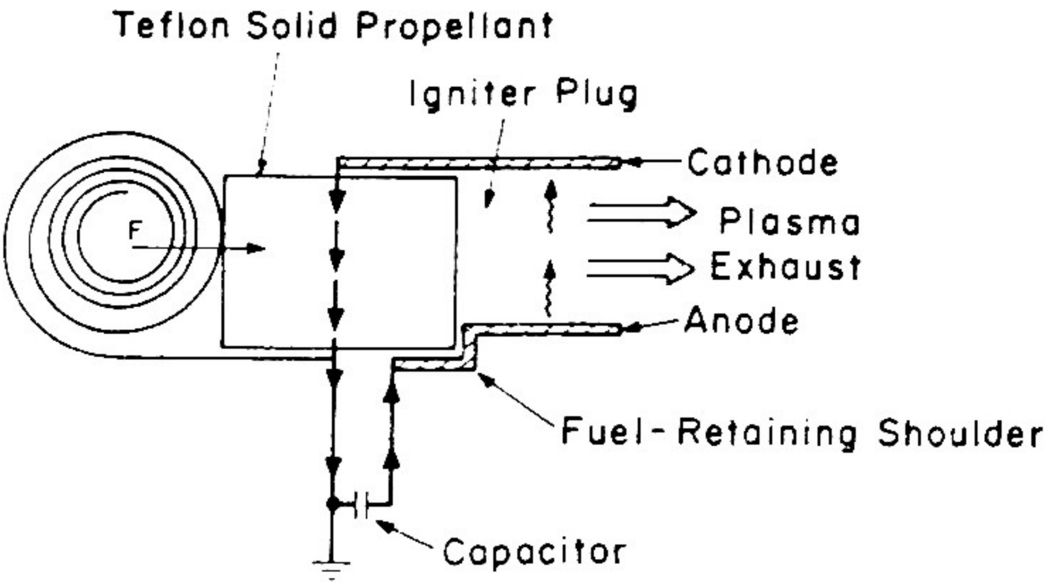

Figure 2. 1 Pulsed Plasma Thruster

Roger M. Myers and Steven R. Oleson et.al [1] Examined a Two orbit maintenance missions. In the first mission a 100kg satellite had to be maintained with a cross section of 0.38m2 for sun synchronous orbit over a period of five years, hence the total change in velocity for the mission was about 122m/s. If the same mission was to be performed by a monopropellant system it would have given a total dry mass of 19.3Kgs and the propellant to weigh about 7kgs, consuming a volume of $0.022m^3$. instead of which a PPT system was used carrying two thrusters weighing around 8.4kgs and carried propellant of 1.36kgs, requiring a volume of 0.012 m3. Another positive point of the PPT is that it would consume very less electrical power ie, only about 5W for the mission. This reduction of mass of about 18kgs increased the use of more payloads and also resulted in increase in the delivery altitude. Which could be over an altitude of 300 km if eight spacecraft were launched on a Pegasus XL

Junji, Yukiya, Takashi et.al [2] Concluded through experiments that the higher impulse bit with low specific impulse generated at small cavity diameter and longer length.

M. DUDECK [3] said that Electric thrusters present a great interest for space applications in orbit maintenance by the large number of satellites using this propulsivedevice and in future for orbit transfers and interplanetary missions which is already demonstrated by the success of the European Smart 1 mission.

Michael Keidar and Iain D. Boyd et.al [4] described how the discharge of the current can be non uniform due to several physical aspects. For example, cathode and anode spot formation and current constriction. These effects increase the discharge current. For instance, if there is an increase in current in the range of several kilo ampere can cause significant current constriction depending on the distribution of the plasma density. The effects related to the cathode and anode spot generation also depend on the current constriction. Hence, one can expect that an increase in current or the discharge energy can cause a high probability of current constriction which generates azimuthally no uniformity of the discharge.

Abdolrahim Rezaeiha, Tony Schönherr et.al [5] said in order to reduce the contamination and erosion of the satellite from the plasma plume generated it was necessary to provide a shield or a hood to the PPT. this hood also resulted in an effective thrust performance up to an angle of 40 degrees. Kumagai et al. (2003) at TMIT studied the effect and reported that the distribution of contamination did not change with an angle up to 40 degree. Also that the narrower the opening of the hood became, up to 40degree, the narrower was the contamination Distribution.

R.J. Vondra et.al [6] showed that the thruster even though being a reliable one had problems with the electrical discharge circuit. When the power processing unit was established in the vaccum chamber the thruster encountered problems during firing. This led to a robust design of the electrical circuit for proper working.

2.2 History

Antropov and Khrabrov had designed the first thruster that made successful flight in the year 1964.Though experiments had started as early as 1934 it to three decades for the thruster to practically make a flight. The satellite named Zond-2 carried this thruster which was had to attempt a flyby of Mars but unfortunately, the satellite lost its communication after several months. Much work was also done by the Massachusetts Institute of Technology and the Fair Child Republic Company and finally on September 26th US developed a Pulsed Plasma Thruster that was used for attitude control on LES-6 for over 10 years. Transit Improvement Program (TIP) which had a history of 10 years of successful flying was initiated to provide a radiation hardened satellite hence, was supported by a PPT for drag compensation. Just about a Kilogram of the Thruster provided 10 years of fuel for the satellite. Success of the TIP expanded the usage of PPT and was used in the NOVA program. Both this programs contributed over 50 million pulses and up to two decades of successful operation providing highly reliable impulse bit hence corrected the disturbance down to 10^{-11g}

Though giving many successful flights the PPTs were not much trusted. Hence, there were only two successful missions since the millennium. NASAs Earth Observation Satellite was launched as a millennium program carrying a PPT which was also thought to be highly risky as it could affect other systems of the satellite. But after 26 hous of firing upto 96000 pulses the thruster was considered to be successful project. The PPT successfully showed the ability to provide high performance even though it lacked internal momentum accumulation.

Once the life of the satellite EO-1 is up high risk experiments would be conducted on the PPTs to know the performances.

COMPASS developed by the Electric Propulsion lab at Princeton University with the institute of terrestrial magnetism ionosphere and radio wave propagation of Russia flew with a PPT but that operation soo failed without delivering any important data. Despite this another attempt was made with the COMPASS-2 project in the year 2006 to study physical phenomenon of earthquakes but this project was also considered as dead as the solar panels had failed to deploy.

The Dawgstar one of the three microsatellites that made the ION-formation developed by Primex Aerospace and Washington University carried a PPT. TechSat21 that was developed to show that formation flying was possible with a PPT developed basically by students was to be launched but cancelled after the Columbia Space Shuttle disaster.

The micro satellite developed by the US air force Research Lab with Busek improved the Attitude control System that was flown in 2007 but the mission failed as the satellite started to spin uncontrollably. AFRL are still working to gain control over this satellite.

The table below shows the history of the successful PPT flights.

Name of the Satellite	PPT Developer	Country	Year
Zond-2	Kurchatov/FAKEL	USSR	1964
LES-6	MIT	USA	1968
UAP-1/2	Kurchatov/FAKEL	USSR	1974
L-4SC-3	ISAS/MITI	Japan	1974
SMS	NASA/Fairchild	USA	1974
TIP-II	Johns Hopkins University	USA	1975
TIP-III	Johns Hopkins University	USA	1976
LES-8/9	MIT	USA	1976
ETS- IV	NASADA/MITI	Japan	1981
MDT-2A	SSTC Academia Sinica	PRC	1981
NOVA-1	Johns Hopkins University	USA	1981
NOVA-3	Johns Hopkins University	USA	1984
NOVA-2	Johns Hopkins University	USA	1988
Mighty Sat II.1	USAF	USA	2000
EO-1	NASA	USA	2000
FalconSat-3	Busek	USA	2007

Table 2. 1 Successful PPT flights

2.3 Overview of Electric Propulsion

While Comparing between the chemical and electric thrusters the thrust varies according to the mission requirement . For instance 200-400 N is required for elliptic-circular orbit transfer, thrust from 80-100 mN is required for station keeping of a GEO satellite and a very few micro-Newton's of thrust for positioning of scientific probes. Thrust is not the only parameter that has to be taken into account while selecting the best thruster that is the specific impulse *Isp* which is defined as the ratio of thrust to the mass flow and gravity at the surface of Earth.

High specific impulse leads to reduced propellant mass in turn decreasing the overall mass of satellite, Which allows increase in payloads. On the other hand, in order achieve change of orbit a high thrust is needed.

Moreover in chemical rocket there is no limitation for power that depends on the propellant but the weight increases with the increase in propellant quantity. Electric rockets are power constrained but it is easier to achieve high exhaust velocities at very less cost.

Electric Propulsion is a field which uses a broad variety of techniques in order to achieve propulsion. Electric propulsion has made deep space missions possible with very less limitations. This field of achieving propulsion is classified into Electro thermal, Electrostatic and Electromagnetic. The thrust is produced by gaining an electric field across the system. In Electro thermal propulsion the propellant is heated electrically and the expanded through a nozzle thermodynamically. In Electrostatic propulsion acceleration of the ionized propellant is achieved through electric field. An electromagnetic system is the one which can produce a range of thrust as it interacts with the magnetic field produced in order to provide a stream wise body force.The thrusters designed on these basis are :

Arc jet Thruster: In this the propellant is heated up by passing a very high electrical arc through it after which the propellant expands in the nozzle

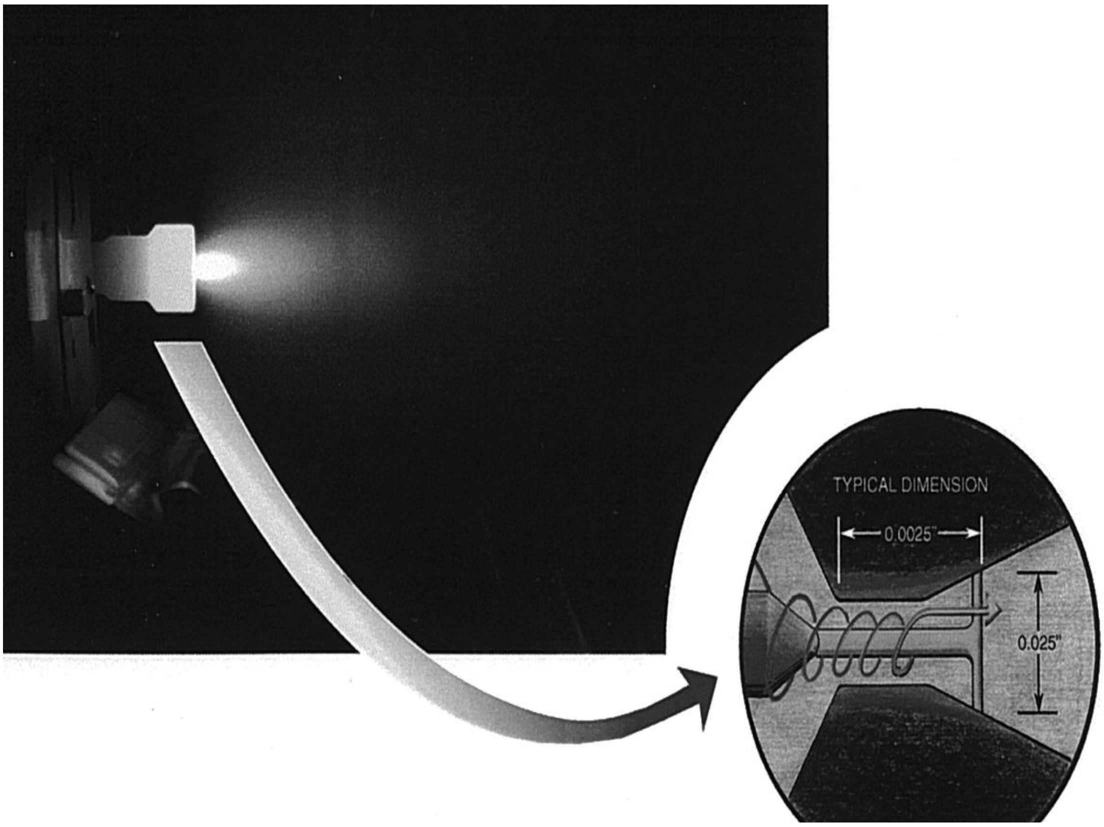

Figure 2. 2 Arc jet Thruster

Hall Effect Thruster: Electric current applied perpendicular to the electric field in presence of a superimposed magnetic field.

Figure 2. 3 Hall Effect Thruster

Inductive thruster: the stream of propellant is heated up through an inductive discharge before the ionized gas is expanded through a nozzle.

Ion thruster: An electrostatic field accelerates the propellant in this type of the thruster.

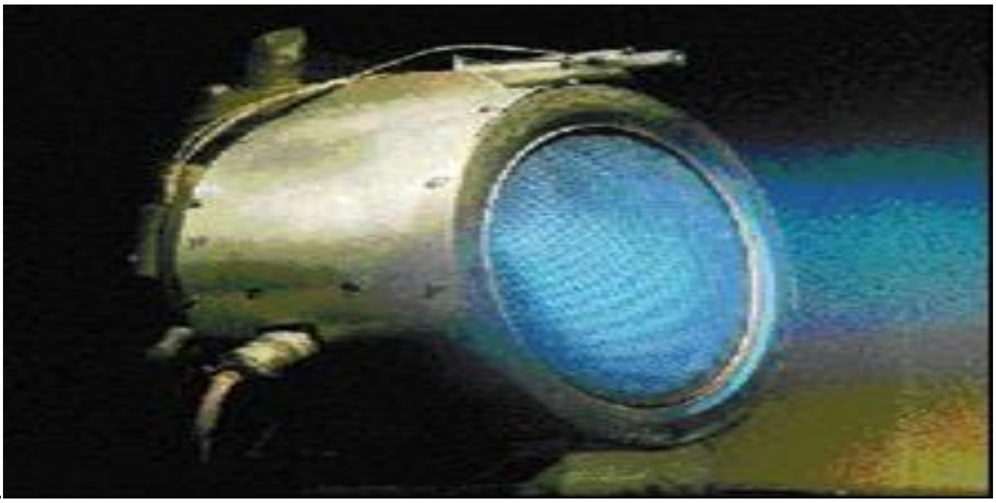
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Figure 2. 4 Ion Thruster

Magneto plasma dynamic thruster: The plasma is accelerated through an external or induced magnetic field.

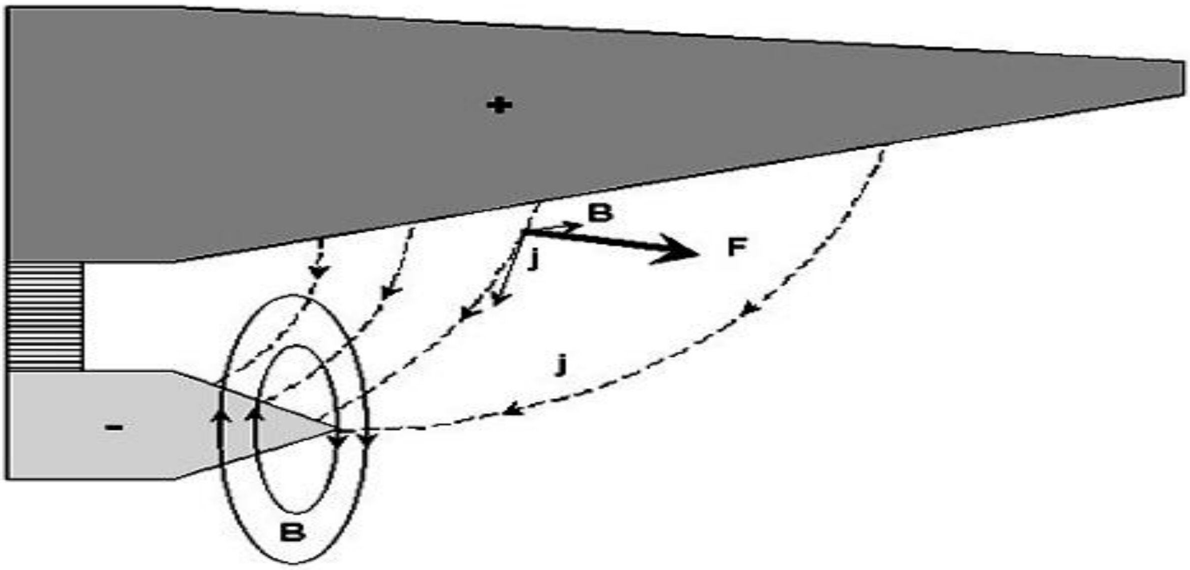


Figure 2. 5 Magneto plasma dynamic thruster

Resistojet: Here the chamber is resistively heated which heats up the propellant and then expanded through the nozzle.

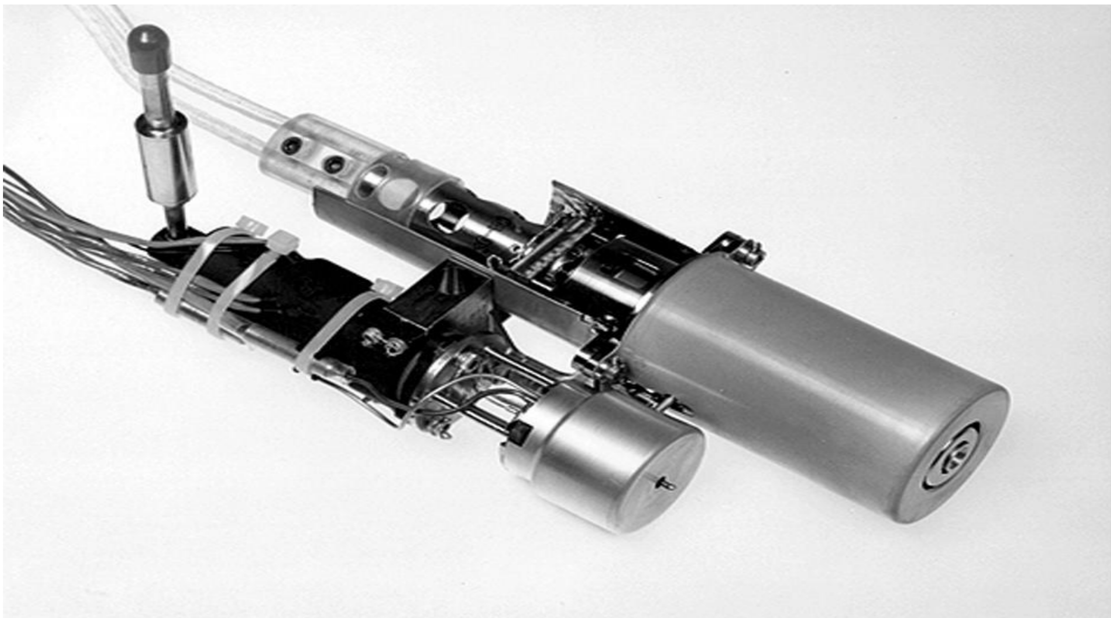


Figure 2. 6 Resistojet Thruster

Pulsed Plasma Thruster: In this thruster the energy is stored in energy storage devices like capacitor, then rapidly delivers energy into the electrodes. This mechanism induces a magnetic field which results into plasma acceleration due to Lorentz force.

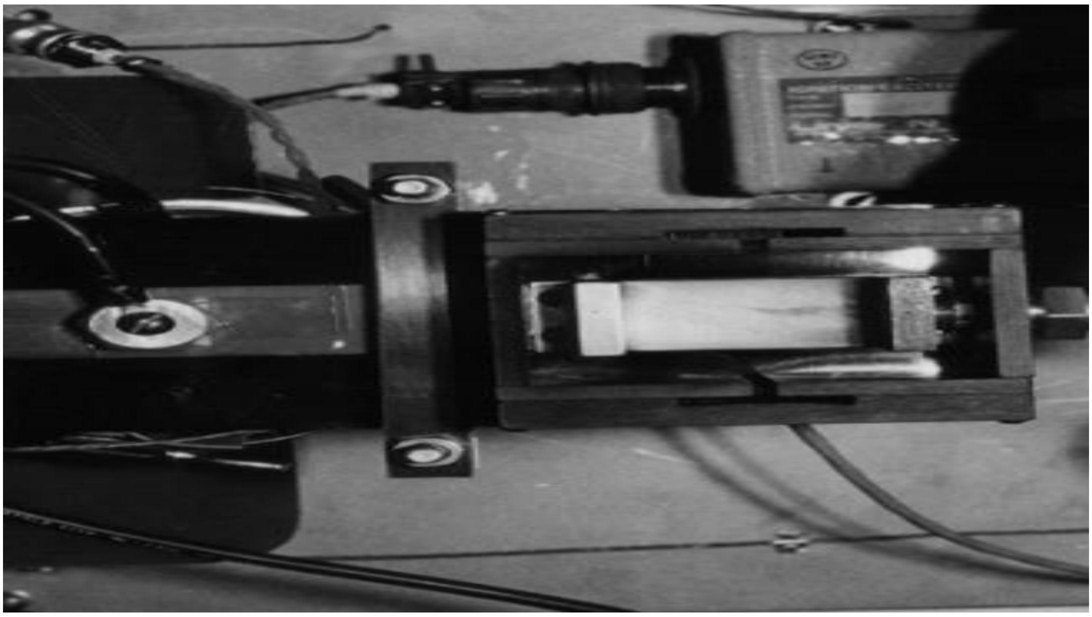


Figure 2. 7 Parallel plate Pulsed Plasma Thruster

2.4 Thruster Development

The thruster development can be categorized into two parts ie hardware and the principal

2.4.1 Hardware

The major requirements of the thruster can be classified as:

- Power Supply Unit
- Energy storage device
- Discharge cavity
- Ignitor
- Propellant

Power Supply Unit

The major function of this unit is to provide a high voltage line. The power is supplied through the spacecraft bus and is converted into high voltage.this is done by the transformer unit in the supply unit.

The satellite generates its own power with the help of the solar panels. This energy is stored in the battery packs. The architecture of a power supply is given below

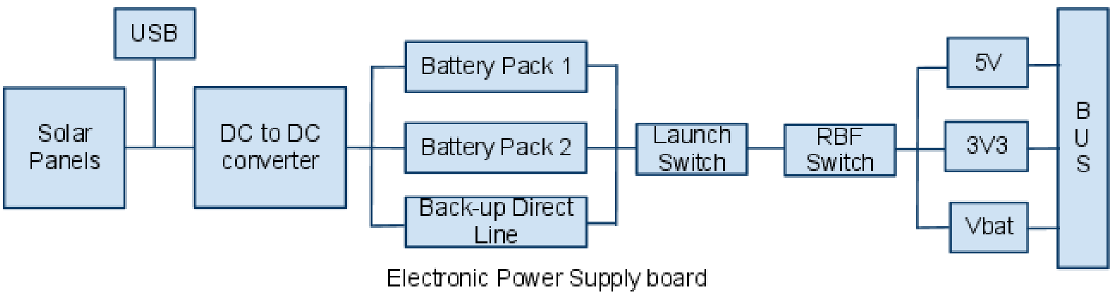


Figure 2. 8 Electronic Power Supply

The power from the solar panels is converted from DC to DC step up using a step-up transformer that increases the voltage. This voltage is used for charging the battery packs and also for emergency

There are two switches in the unit. The launch switch and the Remove Before Flight (RBF) switch that are serially connected to output. No voltage will be supplied at the BUS even if any one of the switch if pressed. In case both switches are in ON position then only the battery packs are supplied with the voltage.

Voltage regulators are used to regulate the voltage supply to the power bus.The figure below shows the Power Processing Unit of the thruster which is connected to the main satellite BUS power. The power processing unit is governed by a onboard telemetry system. This unit is divided into two power supply sections. One to charge the capacitor banks and the other to the Ignitor.

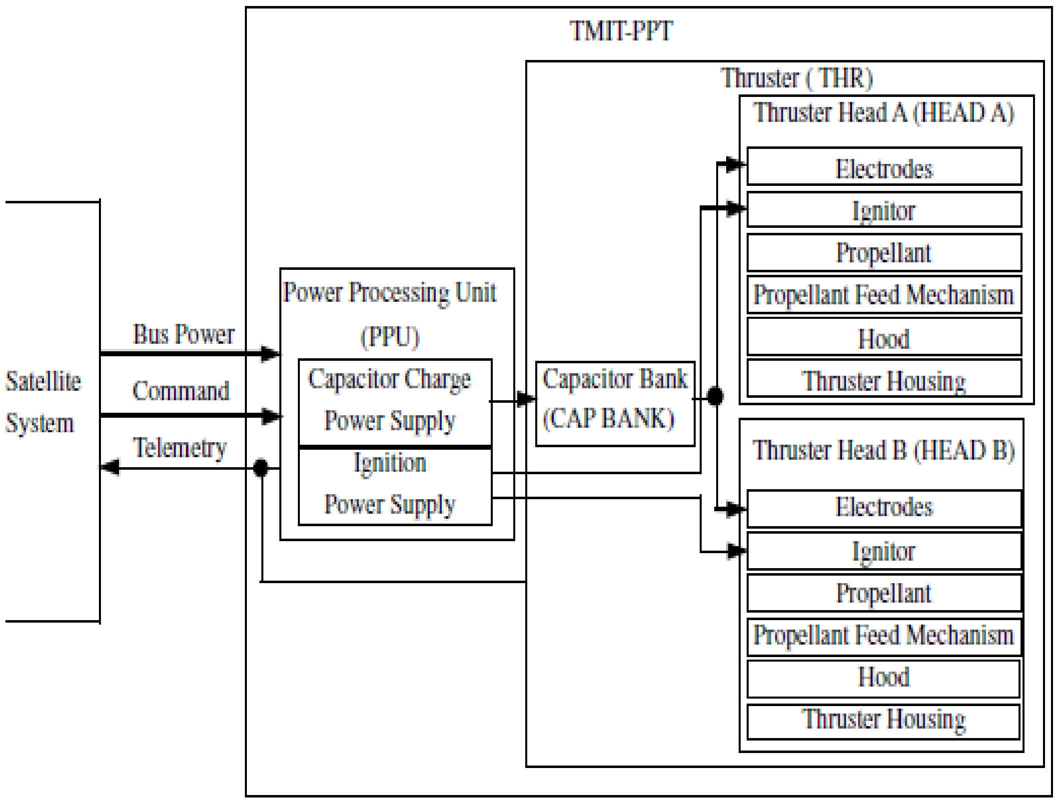


Figure 2. 9 Subsystem of Power unit

The capacitor bank is connected to the Electrodes and the ignitor supply to ignitor or the Spark plug. The basic functioning of the Power Processing Unit is to supply a very high voltage to charge the capacitor. The spark plug ignites and the capacitor is discharged at a determined frequency hence, the capacitor needs to be charged to be ready for next discharge. This whole process is controlled by the telemetry system.

Energy Storage Device

Basically a capacitor is used as an energy storage device. The capacitors used are space qualified capacitor that are able to work under vaccum conditions. Also these capacitors can take voltages up to 2000V.

Principal of working of a capacitor – A capacitor consists of a pair of electrodes separated by a dielectric material. The work is done by moving the charge by an external influence ie current. When the charge is allowed to come back to its equilibrium position discharge takes place. Hence, the energy can be stored up to a certain period of time and can be released in short pulses enabling the PPT with enough energy to create short duration plasmas.

Usually the capacitance of the capacitor is fixed and is defined as the ratio of charge held between the electrodes to the Voltage applied across the electrodes. Theoretically the dielectric is an insulator but practically there is very small amount of current flowing through the dielectric hence, each capacitor is having its own Equivalence Series Resistance (ESR). The capacitance can also be expressed in terms of the geometric dimensions and the permittivity of the dielectric. The figure below shows a regular capacitor where electrodes are separated by the dielectric. The increase in the surface area of the conductors increases the capacitance value, with decrease in the gap between the electrodes.

Capacitor showed in the figure below indicates the physical features.

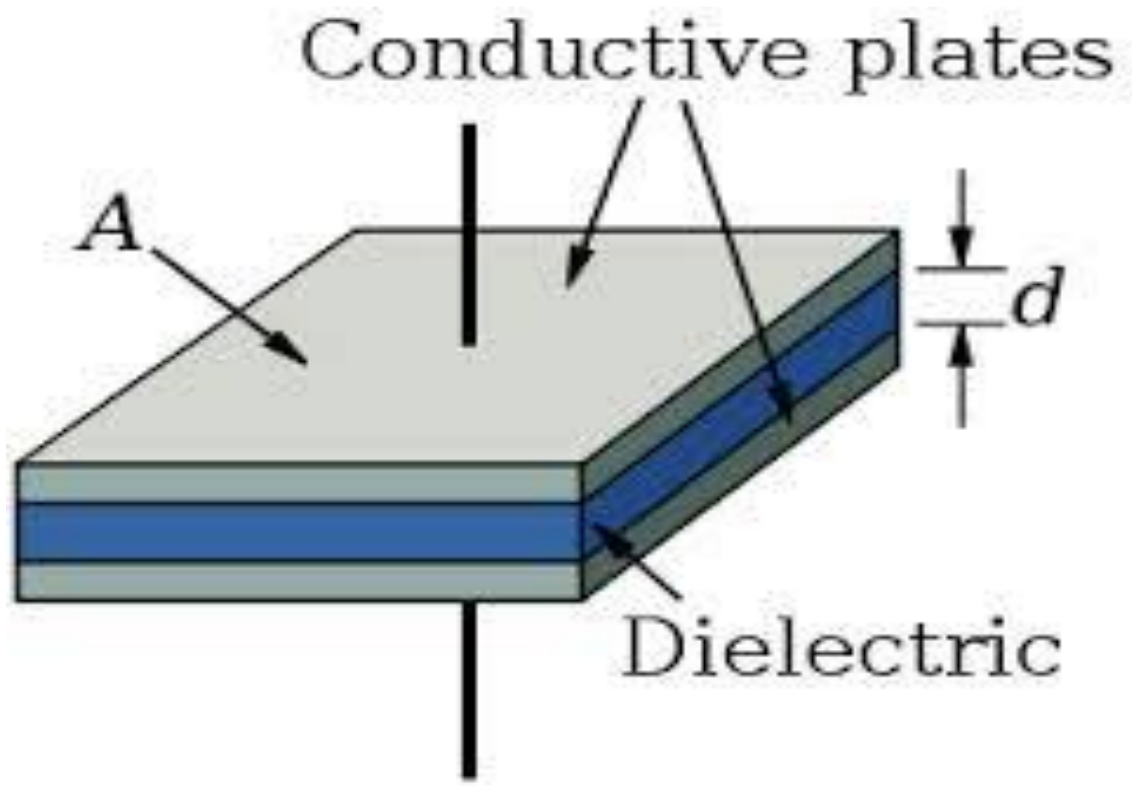


Figure 2. 10 Capacitor

These features play an important role in determining the capacitance. One of the important terms to be understood is the Breakdown Voltage, which we will be using in further chapters. Breakdown voltage is the minimum voltage that makes an insulator partially electrically conductive that means the insulator starts transmitting current after a certain voltage is reached. Hence the capacitance of a capacitor is based on the Breakdown voltage of the dielectric material used. The path of conduction is created through the electrodes by breaking down the electrons in the dielectric in presence of high electric fields.

Capacitance of the capacitor is influential due to factors like Temperature, Humidity, Pressure and frequency of discharge.

Discharge Chamber development

The discharge cavity is where the plasma is accelerated out. It is important to know the material properties from which the discharge chamber is built as the plasma causes erosion of the material. Usually in a co-axial PPT the electrode boundaries create the discharge chamber geometry. Since the past many geometries have been suggested to improve acceleration effects.

Igniters

The spark plug initiates the charged particles to move towards the discharge chamber. There are also other techniques to trigger the discharge by mechanically bringing the highly charged anode towards the cathode. As the PPTs were used in satellites less than 100kgs the conventional method of spark plug was used. Spark Plugs were designed in such a way that they would work efficiently even in the vaccum conditions.

The major problem encountered with the spark plugs was carbon deposition oon the tip of the spark plug which reduced the life of the spark plug. Also the spark plugs had to be designed in such a way that they wouldn't add much to weight of the thruster.

Figure 2. 11 Spark Plug

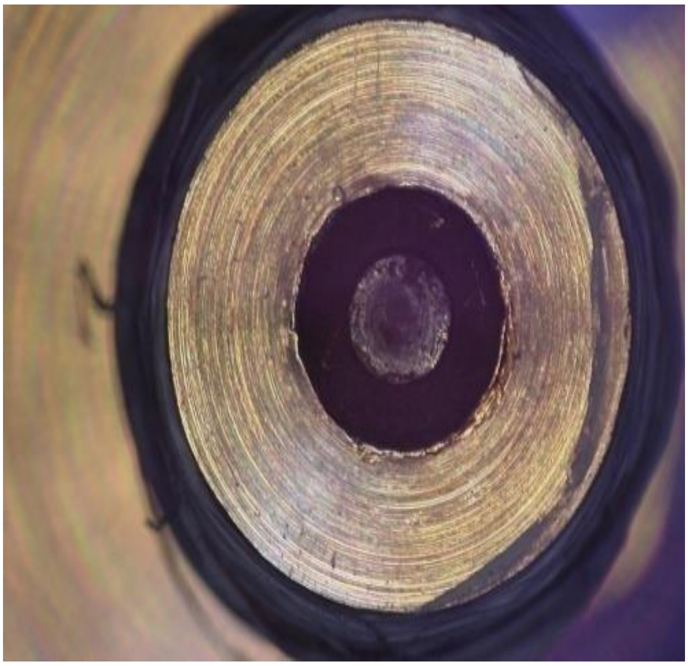


Figure 2. 12 Effect of spark plug after firing (Blackening effect)

Propellant

All PPTs flown used Teflon as a propellant due to its very less out gassing properties in vaccum conditions. The solid propellant is placed between the electrodes and once when the electric field is initiated the propellant is ionized. The characteristics of ionization of the propellant depend on the surface area of contact of the electric current. There are very less residues left out after the ionization of the propellant only when enough energy is available. This is again defined by the Breakdown voltage and Paschens' Curve. The Paschens law says that, the characteristics of breakdown of a gap are the function of the pressure and the gap length.

$$V = f(pd) \qquad \text{\_\_\_(1)}$$

Where p is the pressure

And d is the gap length. This law shows the Townsend breakdown mechanism in gases, the effect of the electrons emitted in the gap. Paschens curve defines the breakdown at very high pressures.

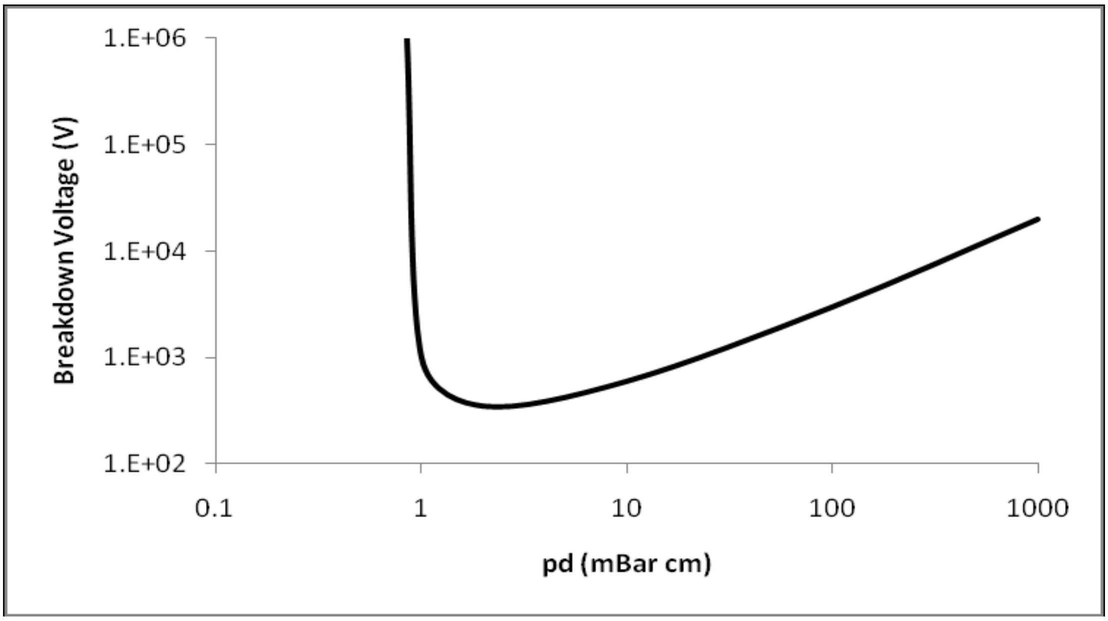


Figure 2. 13 Paschens Curve

The figure above shows that a typical voltage is required to sustain the discharge depending on the type of gas, the pressure and the gap length.

Chapter 3

THEORY

3.1 Working Principle

3.1.1 Assumptions

In order to build a simple analytical system few assumptions were introduced

Assumption 1: The new model is based the global quantities

Assumption 2: The capacitor bank is the device where the balancing of energy starts from as it also determines the discharge time. Also it is the first place from where the energy loses starts from.

Assumption 3: The RLC circuit has active components that are the electrodes, the acceleration chamber, and the plasma with constant parameters. This helps to consider the plasma as conducting agent in presence of resistance and inductance.

Assumption 4: Black body radiation is considered to determine the heat losses.

Assumption 5: It is considered that the specific energy for Teflon ablation is 1.5xl06 [J/kg]. Which helps to determine the energy required for breakdown of the Teflon polymers

Assumption 6: The interaction of the plasma particles is thermodynamic which is homogeneous confined within a volume.

Assumption 7: Plasma blob is in the direction of X-axis

Assumption 8: The mass is expanded as a perfect gas in the subsonic cavity. This cavity is also known as the acceleration chamber

Assumption 9: The process takes place in Vaccum.

3.1.2 Pre-ignition

Once the capacitor is provided with energy from the power unit the process starts. Charging of the capacitor takes place till it reaches a saturation point . charging depends on the supply of energy with respect to time and hence the discharge. The process of discharge can take place only when the potential difference across remains constant of certain period of time. When the capacitor reaches saturation point it will be ready for discharge process.

3.1.3 Ignition

The ignition process is started by the spark plug. The theory behind this process still remains complex. The electrons released by the metal of the sparkplug starts the plasma generation process. It is important for the spark plug to ignite in order to create a discharge process in the capacitor. The spark plug is fired with a frequency required as per the purpose.

3.1.4 Discharge

When a conductive path is created between the electrodes through the discharge cavity, means the discharge is initiated. This is also known as Current loop. The magnetic field is stored in the electrodes once the flow of current begins across the system. When the capacitor is discharged, there is no potential difference between the electrodes. The energy required for the flow of current is taken from the magnetic field created earlier. Hence, the capacitor needs to be charged for next discharge to take place. Once the energy from the magnetic field is extracted the capacitor is then charged and the process continues in a cycle. The discharge process is mainly affected by the electrode geometry and the distance between the electrodes.

3.1.5 Plasma generation and acceleration.

Plasma is generated in the propellant Teflon's cavity when there is a flow of current between the electrodes and the generation of the magnetic field takes place. Plasma is generated and accelerated due to the magnetic field present in the system. As we know the current flows through Anode to cathode, the magnetic field will be allocated with a direction vector according to Amperes law. The vector is same in Anode as that of cathode.

The magnetic field interacts with the strong current density flowing across the electrodes producing Lorentz force. The magnetic field and the current are always perpendicular to the Lorentz force. The Lorentz force accelerates and forces the plasma bulk in the direction of the vector. In order to study the plasma flow high speed cameras required as the plasma is ejected at very high velocities. In these cameras we get the unfiltered images which shows the flow from the nozzle

3.1.6 after Effects

Though the thrust produced is in the level of micros but it is very significant when used in vaccum conditions. Once the process of discharge is finished and the capacitors energy is depleted but only a considerable amount of energy is extracted to accelerate the ions, rest is lost in depolarization of the capacitor causing delay in ablation and some amount in radiation at the time of discharge.

3.2 Fundamental Development

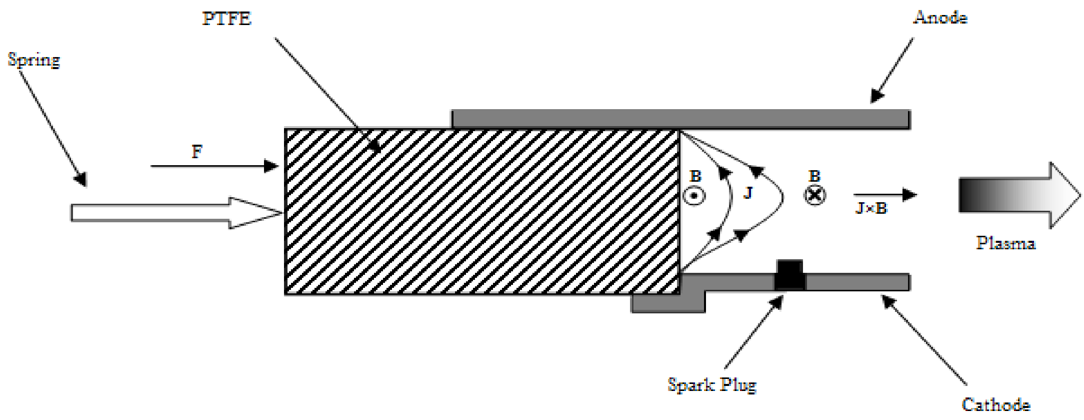


Figure 3. 1 Schematic of Pulsed Plasma Thruster

3.2.1 Thrust measurement

Major set back in PPT modelling is the lack of thorough theoretical understanding of the energy transfer process and the mass ablation process. The process becomes more complicated due to involvement of the electromagnetic phenomenon. Hence, there are no physical model which accurately predicts the thrusters behaviour.

PPT can have different electrode configurations that are parallel-rail electrodes and co-axial PPT. The coaxial PPT provides a closed magnetic and electric field which enhances the exhaust velocities of the thruster.

Kimura 1978, explained the effect of magnetic field on the parallel rail and co-axial PPT which resulted into more symmetric plasma plume and increase in thrust to power ratio upto 50%.

The efficiency is greatly influenced due to electrode geometry ie length, width and the gap between the electrodes. Guman (1968) defined the inductance of parallel plate electrodes as :

$$L = \mu h \frac{l}{d} \tag{1}$$

Where L is inductance, μ_0 permeability, h as gap between electrodes, l length of electrodes, d as cavity dia.

The magnetic field induces a thrust which is given by :

$$Tmag = f\mu h/2d \int i^2 \,\mathrm{dt} \tag{3}$$

Where f is the frequency of pulse, i is the total current.

The thrust due to expansion of gases is given by :

$$Tgas = f\left[\frac{[8(\gamma-1)\dot{m}E]}{(\gamma^2(\gamma+1))}\right]^{\frac{1}{2}} \tag{4}$$

Where m is the mass ablated per pulse, gamma is constant related to the propellant. For Teflon gamma =1.3

Hence total thrust is the sum of thrust produced due to magnetic field and due to gas expansion.

$$T = T_{mag} + T_{gas} \tag{5}$$

The efficient exhaust velocity of the propellant is indicated by the specific impulse. It is defined as ratio of magnitude of thrust to the mass flow rate.

$$Isp = \frac{T/f}{mg} \tag{6}$$

Or

$$Isp = \frac{Ibit}{mg} \tag{7}$$

Impulse bit is the function of mass ablated and the exhaust velocity.

$$I_{bit} = m\,V \tag{8}$$

$$Isp = \frac{Ibit}{mg} \tag{9}$$

Where V is the exhaust velocity.

Thrust efficiency is defined as the ratio of average kinetic energy to energy in the capacitor before discharging.

$$\eta = \frac{\left(T/f\right)^2}{2mE} \tag{10}$$

Electromagnetic principle

The rate at which the external fields do work on the charged particles can be

calculated (per unit volume) as

$$W = \sum qn\,(E + v \times B).v \tag{11}$$

$$W = E \sum qnv \tag{12}$$

Or

$$W = Ej \tag{13}$$

where we used $(vj \times B) \cdot vj \equiv 0$

The total work is not directly in effect with the magnetic field, as the magnetic force is orthogonal to the particle velocity

The total work is divided into two processes ie heating the plasma and rest pushing the plasma. This is noticed from the following

$$W = E \cdot j = (E^{/} - U \text{ X B})j = E^{/} \cdot j + (j\text{X } B)\,.U \tag{14}$$

Using $(U \text{ X } B) \cdot j = -(j \text{ X } B)$

Also, using ohm's law

$$E^{/} \cdot j = \left(\frac{1}{\sigma}\right) j + j\text{X } \beta\,.j = \frac{1}{\sigma} \tag{15}$$

$$(j \text{ X } \beta) \cdot j = 0 \tag{16}$$

Thus,

$$W = \frac{f}{\sigma} + (j \text{ X } \beta) \cdot U \tag{17}$$

The first term denotes the joule heating and The second term is the rate at which the Lorentz force does the mechanical work for moving the plasma at velocity u.

3.2.2 Mechanism

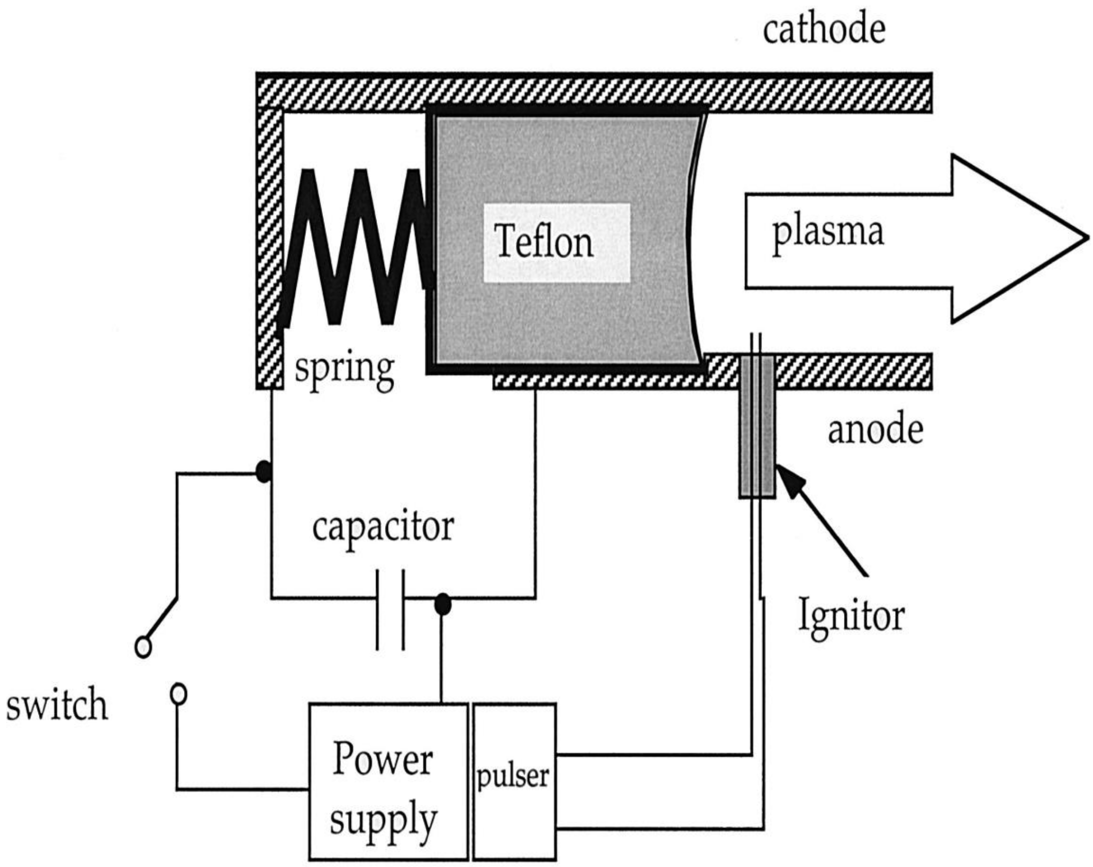


Figure 3. 2 Parallel Plate Pulsed Plasma Thruster setup

The above figure shows a complete setup of the pulsed Plasma Thruster where the electrodes are in parallel rail configuration. The Power Processing Unit supplies power to the capacitor and the ignitor. The potential difference between the electrodes forms a sheet of current due to the ions present in the surrounding. The spring acts as a feeding mechanism that pushes the propellant as it ablates.

The plasma created is pushed out of the chamber which acts as a nozzle. The capacitor helps in providing small bursts ie there is some gap between two consecutive firings. This method helps in saving propellant when there is no requirement of power in the spacecraft. Whereas in chemical propulsion this type of control over the propellant flow is very difficult to achieve.

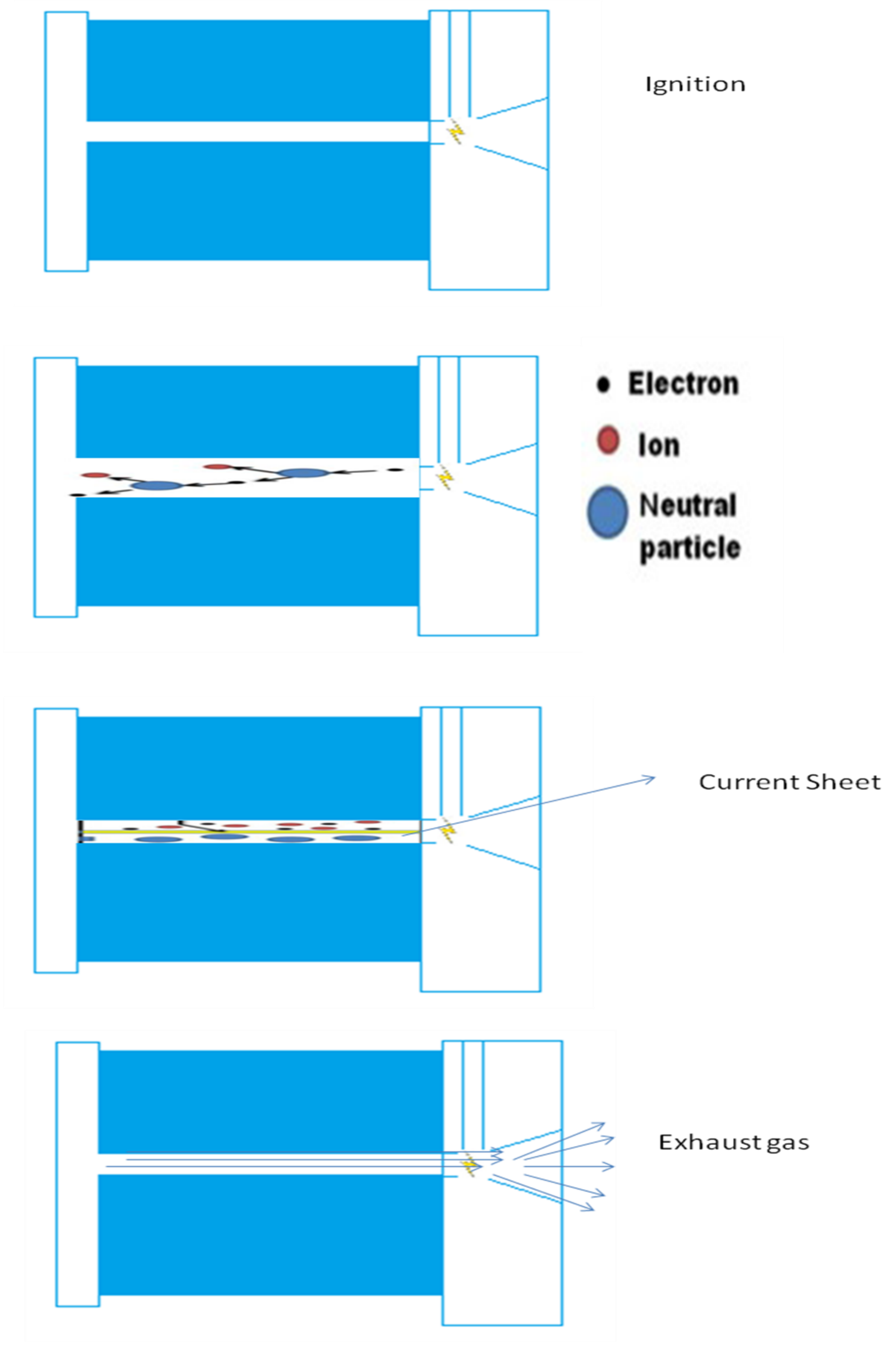


Figure 3. 3 Schematic process of coaxial Pulsed Plasma Thruster

The above figure is a schematic of the process that takes place after the ignitor is started. The first schematic shows that the current is supplied to the ignitor near the cathode. The ions start flowing from the cathode to anode which is depicted in the schematic (b). This flow is due to the flow of neutral ions towards the positive ions in presence of electric field. A sheet of current is created in presence of the ions and the Teflon particles which are ionized due to presence of high voltage. This ionized layer of the propellant is pushed out in presence of a magnetic field which is self generated during the mechanism. The exhaust gas is dependant of the Lorentz force and hence producing a high thrust.

3.2.3 Magnetic field

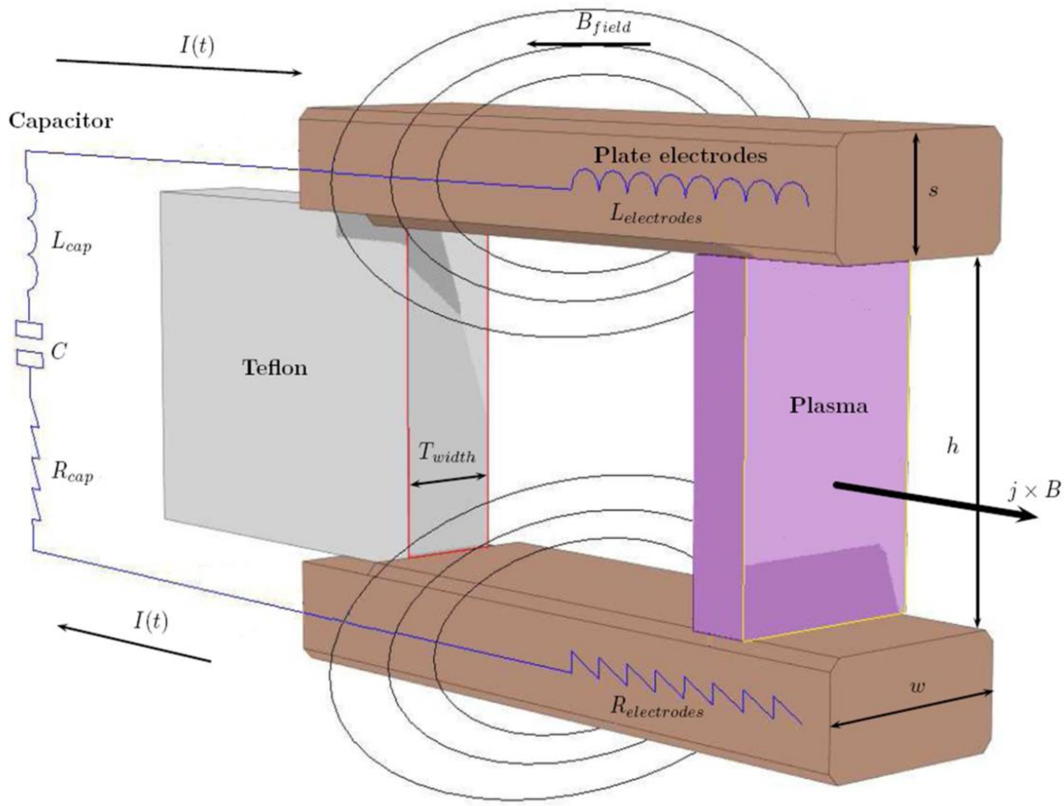


Figure 3. 4 Magnetic Field Schematic

Lorentz force is the force created due to presence of an electromagnetic field. The Lorentz force depends on the electric field, magnetic field, electric charge and instantaneous velocity of the charged particle.

$$F = q(E + v \, X \, B) \tag{18}$$

The variations in the basic formula are explained due to the magnetic field.

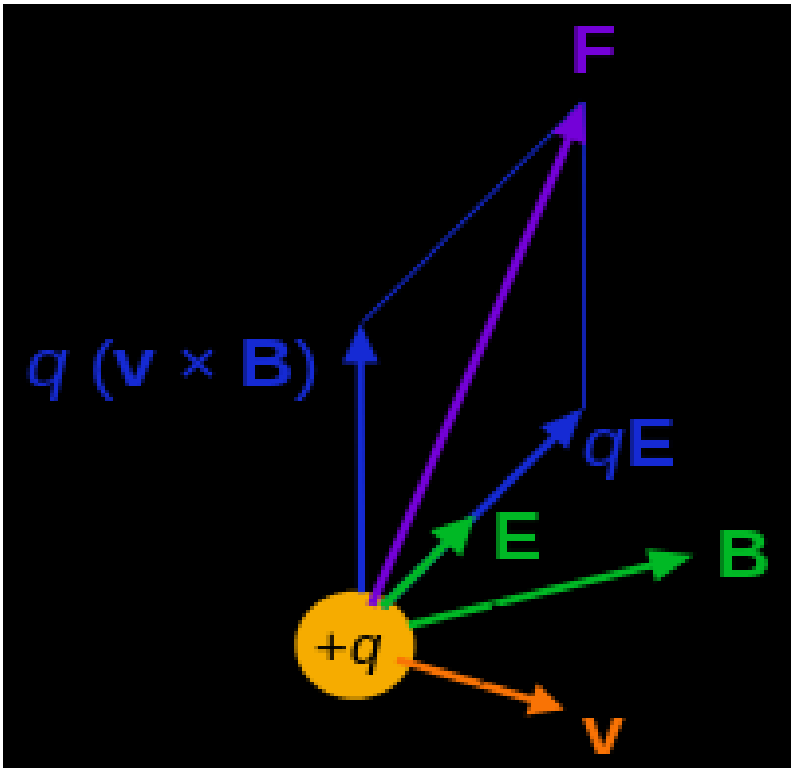


Figure 3. 5 Lorentz force on charged particle

The above figure shows the Lorentz force acting on the charged particle. The force vector is always perpendicular to the direction of current according to right hand rule which says that when you curl the fingers around an element, the thumb pointing towards the direction of electric current, the magnetic field will be in the direction as that of the fingers curled around the element.

There are two basic effects that can help to understand the coupling between the magnetic field and the fluid flow that is the flow of current in a conducting material due to its molecular motion in presence of magnetic field and the effects of Lorentz force due to the electric and magnetic field interaction.

Electromagnetic fields are in general described from Maxwell's equations:

$$\nabla \cdot B = 0 \tag{19}$$

$$\nabla \text{ X } E = -\frac{\partial B}{\partial t} \tag{20}$$

$$\nabla . D = q \tag{21}$$

$$\nabla \text{ X } H = j + \frac{\partial j}{\partial t} \tag{22}$$

Where B is the magnetic field denoted by Tesla and E is the electric field. H and D are induction fields, q is charge density and j is the current density vector

Ohms law defines the current density as

$$J = \sigma E \tag{23}$$

Where is the conductivity of the media.

From ohms law we can form the following equation :

$$J = \sigma(E + U \text{ X } B) \tag{24}$$

Hence we can use the Lorentz force equation in order to determine the force produce due to the induced magnetic field.

3.3 Requirement for an interplanetary mission

Estimation of fuel required for interplanetary missions is a function of Mass of fuel available and time of flight. This calculated as follows:

Mass of fuel is calculated from

$$Mfuel = \sqrt{2\ Msat\ \eta\ P\ \frac{S}{Vjet^3}} \tag{25}$$

Time of flight is given by

$$tflight = \sqrt{2\ Vjet\ M\ sat\ \frac{S}{\eta\ P}} \tag{26}$$

Higher the jet velocity results in lesser fuel consumption in turn giving longer flight time. The velocity of jet of Plasma compared to that of chemical is higher hence increasing the dependence on Plasma Thrusters than chemical rockets for interplanetary missions.

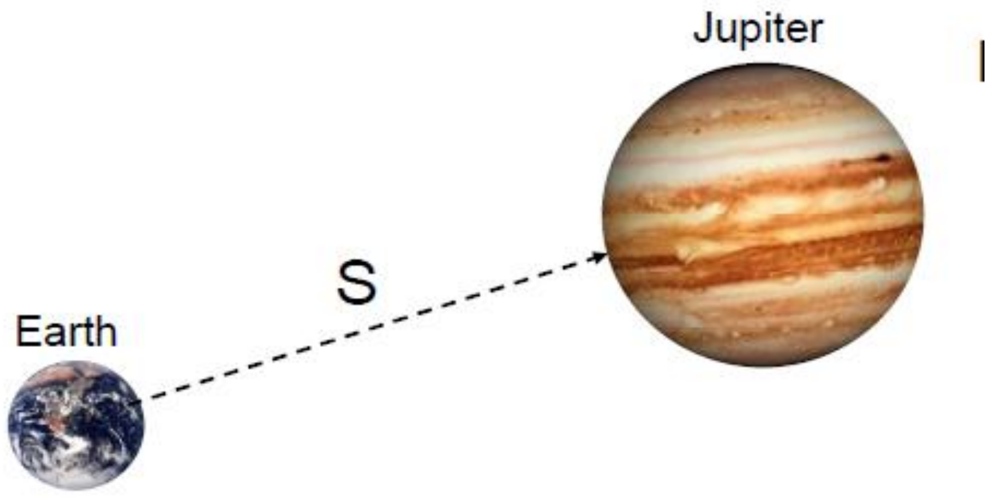


Figure 3. 6 Distance for an inter planetary mission

3.4 Limits on the exhaust jet velocity

The plasma thrusters produce thrust of about micro and mini level hence the limit on the exhaust jet velocity is determined by the requirements of the mission and the time of the mission. The life of the thrusters depends on the number of pulses or number of months/ years of spacecraft life.

For orbit station keeping the plasma thrusters are the perfect devices to provide precise and short duration kicks to the spacecrafts. These kicks are also controllable depending on the power provided and frequency of the kicks.

Change in velocity is given by

$$\Delta V = \frac{T\Delta t}{Msat} \tag{27}$$

Thrust is given by

$$T = 2\eta \frac{P}{Vjet} \tag{28}$$

Chapter 4

METHODOLOGY

4.1 Design and Geometrical modelling

4.1.1Design

The design process begins with the requirements of the mission. The major objective of the project is to design such a thruster that could produce high thrust with low specific impulse. The first step was to select materials for the electrodes. The major criteria for selection of electrode material was that it must have high electrical conductivity and low corrosion properties. Also, the materials must be easily available and economical for manufacturing. The material for anode was selected as Copper, as copper had superior electrical conductivity and being a positive junction in the thruster it had to be a very highly conducting material. Copper is also a non reactive element and hence corrosion free. At very high electrical fields chances of copper getting eroded is very minimal and will not become brittle after the operation. The material selected for cathode is stainless steel (SS304) which is austenitic. It consists of a minimum of 18% chromium and 8% nickel, combined in presence of not more than 0.08% carbon. It is also known as a Chromium-Nickel austenitic alloy. Few characteristics of SS304 are :

- Forming and welding properties- it can be easily welded and economical.

- Corrosion/ oxidation resistance due to presence of chromium content

- Deep drawing quality

- Excellent toughness, even at cryogenic temperatures i.e. at very low temperatures it exhibits very good toughness property.

- Low temperature properties.

- Ease of cleaning, ease of fabrication.

- Electrical resistivity of this material is 0.000116 ohm-cm up to the temperature of 659 °C.

Due to highly reliable properties these materials were selected in order to extract maximum outcome within limited costs and negligible failures.

After going through a number of previous designs and few iterations it was studied that a proper path was necessary in order to direct the current flow hence the anode was designed in a T-shape the vertical tip of the anode was exposed to the propellant cavity through which the flow of current takes place. To avoid any current or gas leakages there had to be negligible gap between the electrodes and the propellant.

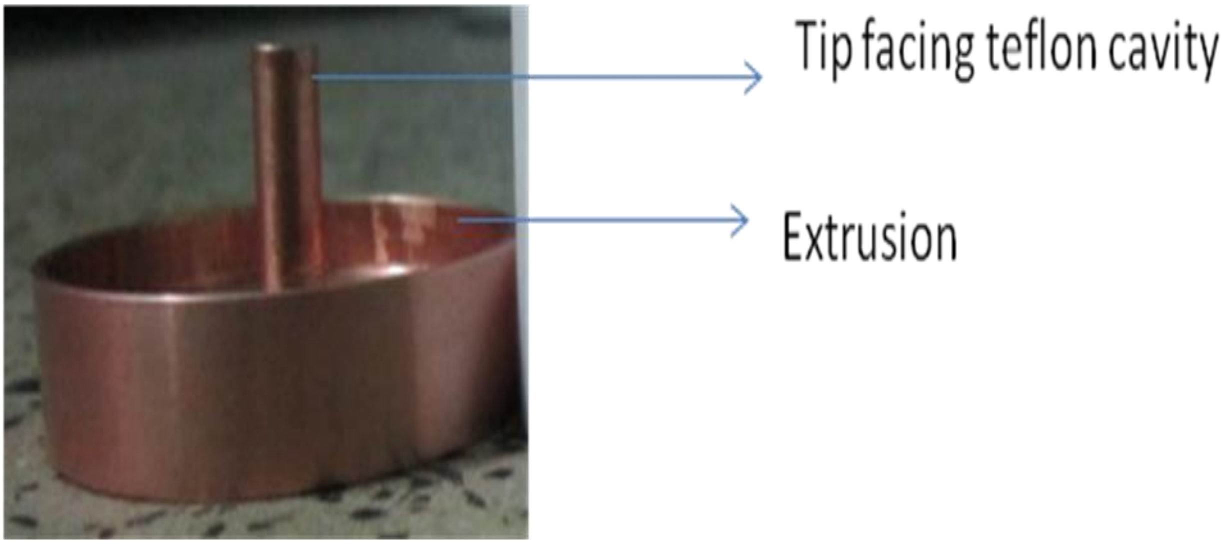


Figure 4. 1Anode

An extrusion is provided in the anode so that it is properly clamped in to reduce leakages. In the same way cathode was also given extrusion to avoid leakages.

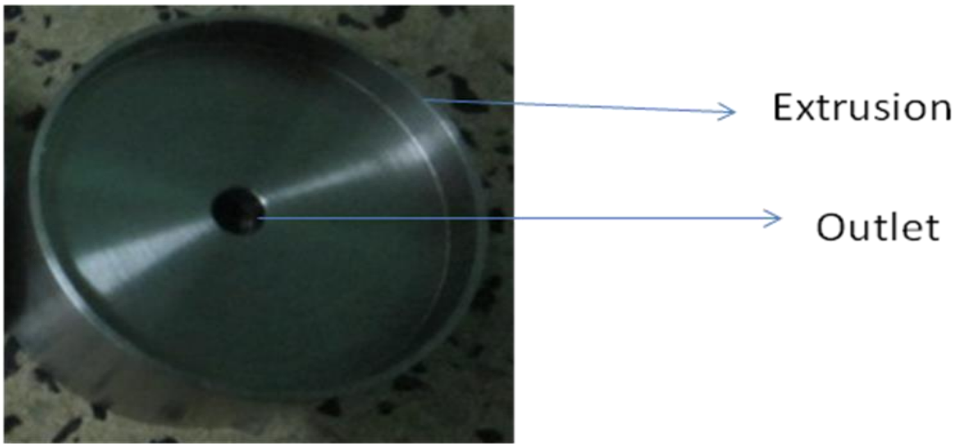


Figure 4. 2 Cathode

The factors dictating the plate area is the development of electric field flux due to the amount of the electric force that is the amount of voltage applied between the two electrodes. Cathode is provided with a nozzle angle also known as hood angle. This angle is fixed to 23^{o}. The angle was provided on the basis of old iterations conducted in order to accelerate the gas flow. The nozzle angle works on the methodology of a conventional divergent nozzle

The propellant used is a conventional propellant made of Teflon. Teflon is provided with a cavity in order for the flow of current. This cavity dimensions are varied to calculate the amount of thrust produced.

The objective of this thesis is to optimize a design configuration which would provide high thrust. The propellant dimensions were varied in order to check the feasibility of the thruster.

4.2 Modelling

Modelling the thruster was divided into two different parts i.e. 2D modelling and 3D modelling.. Conducted in Catia V5.

4.2.1 CATIA

CATIA (Computer Aided Three-dimensional Interactive Application). is a multi-platform CAD/CAM/CAE commercial package which is developed by a French company Dassault Systemes. The package is Written in the C++ programming language, it is the cornerstone of the Dassault Systemes product lifecycle management suite.

Also referred as a 3D Product Lifecycle Management package suite, CATIA supports multistage of product development , from conceptualization, design (CAD), manufacturing (CAM), and engineering (CAE). CATIA facilitates collaborative engineering across disciplines, including surfacing & shape design, mechanical engineering, equipment and systems engineering.

CATIA provides a suite for surfacing, reverse engineering, and visualization solutions for creation, modification, and validation of complex innovative shapes. From subdivision, styling, and Class A surfaces to mechanical functional surfaces

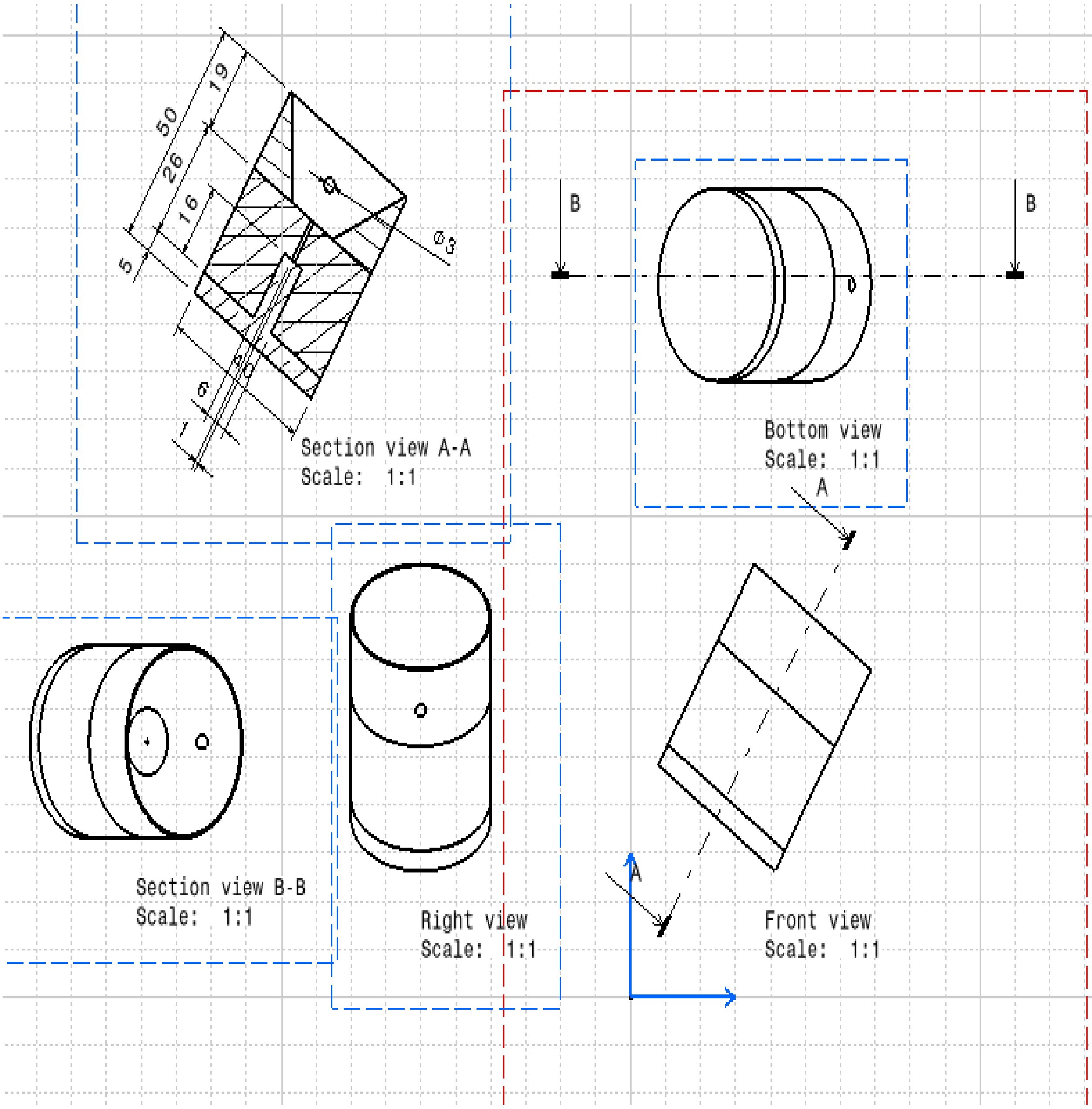


Figure 4. 2-D assembled diagram of PPT

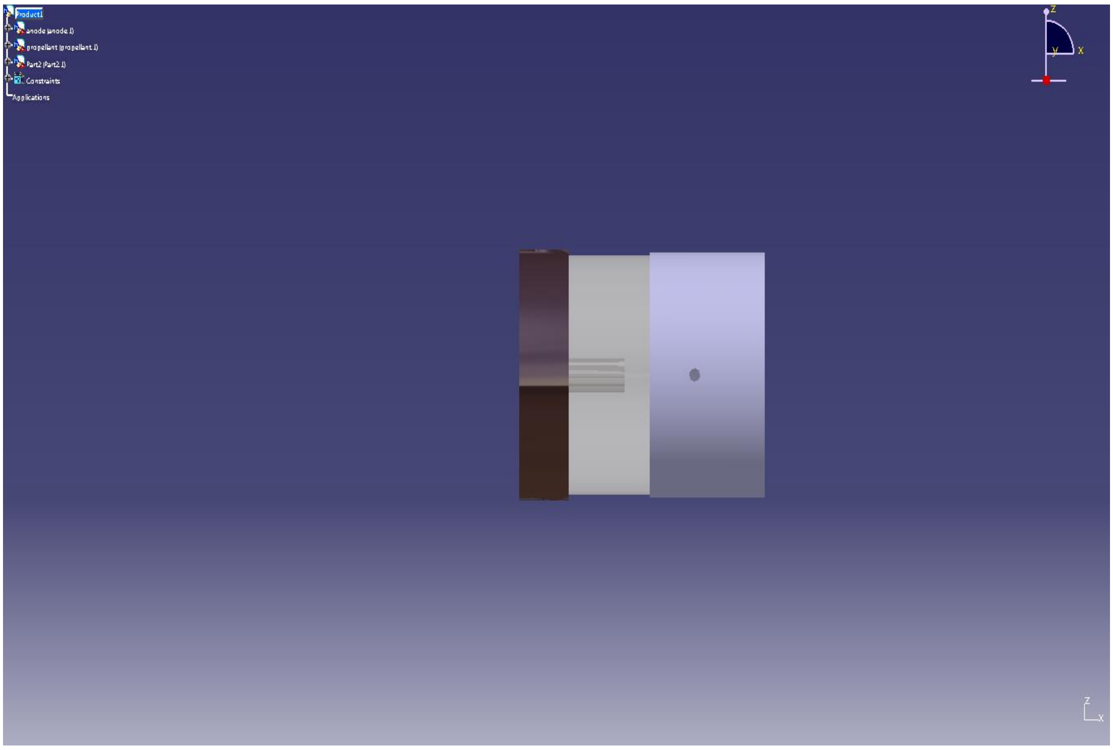


Figure 4. 3 3-D model of PPT front view

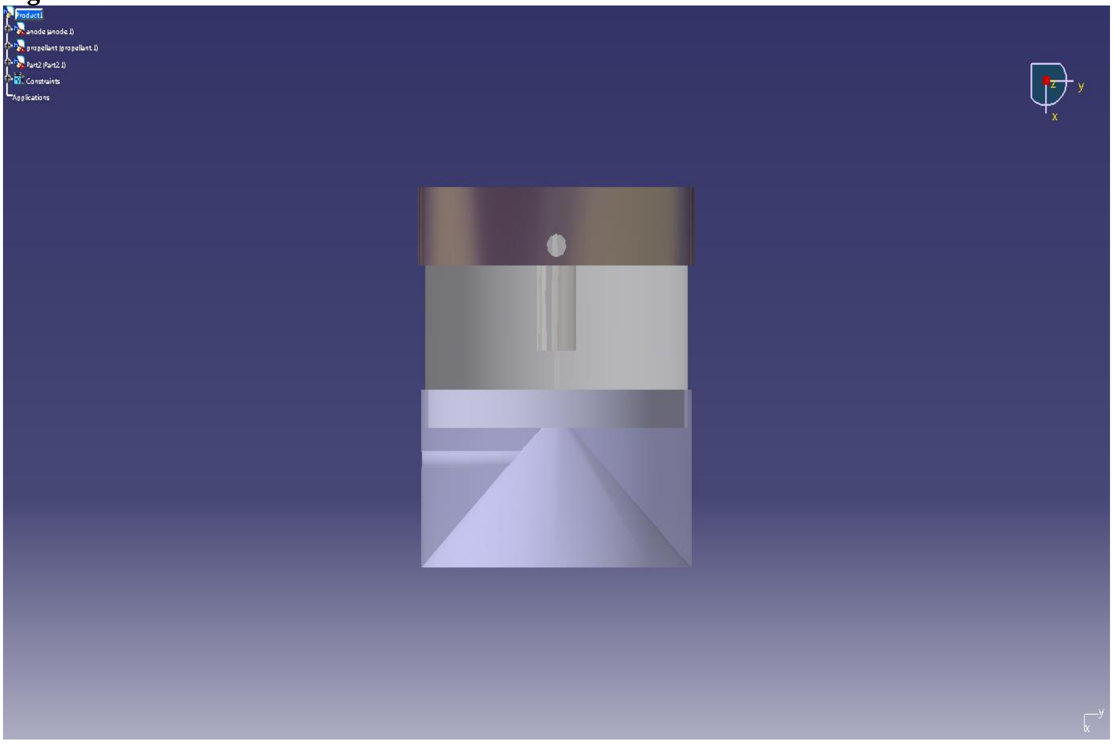


Figure 4. 4 3-D model of PPT side view

Chapter 5

Results and Discussions

5.1 Results

Experiments were carried out with varying the dimensions of the propellant and at different energy levels.

The table below shows different experiments conducted.

Test Plan

CPACITANCE(μF)	1.5	1.5	1.5
VOLTAGE(V)	1500	1800	2000
ENERGY(J)	1.68	2.43	3
CATHODE HOOD ANGLE (Degrees)	23	23	23

Table 5. 1Test Plan

Propellant geometry

Cavity length (mm)	10	20	30	40
CAVITY DIA (mm)				
	1	1	1	1
	3	3	3	3
	5	5	5	5
	10	10	10	10

Table 5. 2 List of propellant dimensions

Experiments were conducted with the above mentioned cavity dimensions and varying the energy in order to find the thrust obtained in each of these dimensions.

The thrust measurement was done by integrating the area under the curve that is obtained from the oscilloscope

The measurement of current is done with the help of a Rogoswki coil. The specifications of the Rogoswki coil is given below

Current range	: 0.015 – 12 kA
Sensitivity	: 0.5 mV/A
Peak di/dt	: 25 kA/µs
Noise max	: 3.5 mV (pk-pk)
Band width	: 17 mHz
Accuracy	: ± 0.2 %
Coil voltage isolation	: 5 kV
Temperature	: - 20 - 100 °C

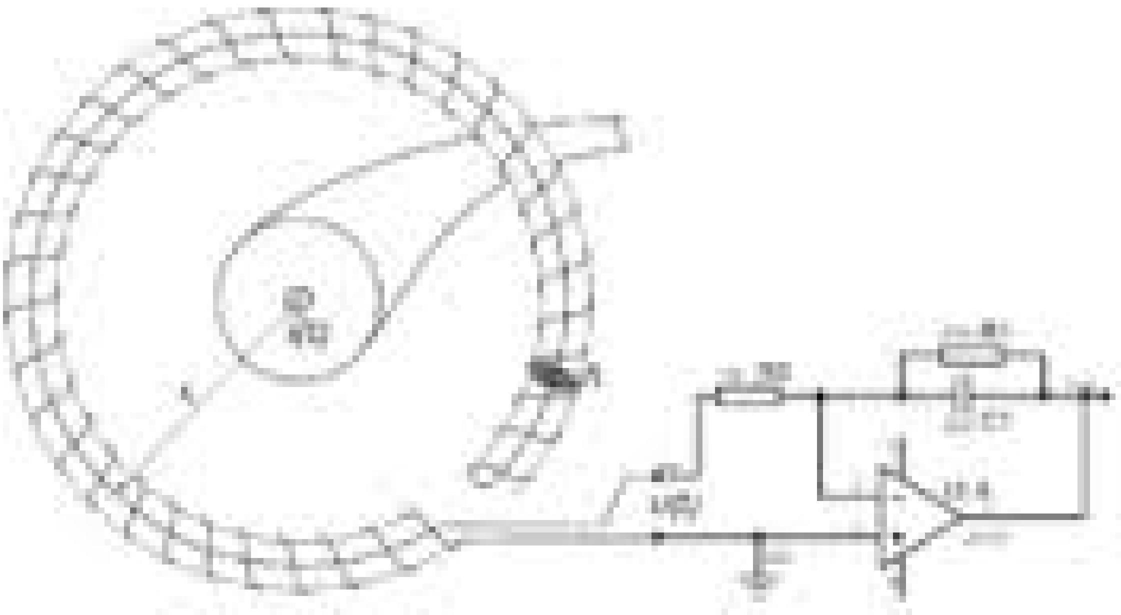


Figure 5. 1 Rogoswki coil line diagram

The picture below shows a recording of current from an oscilloscope.

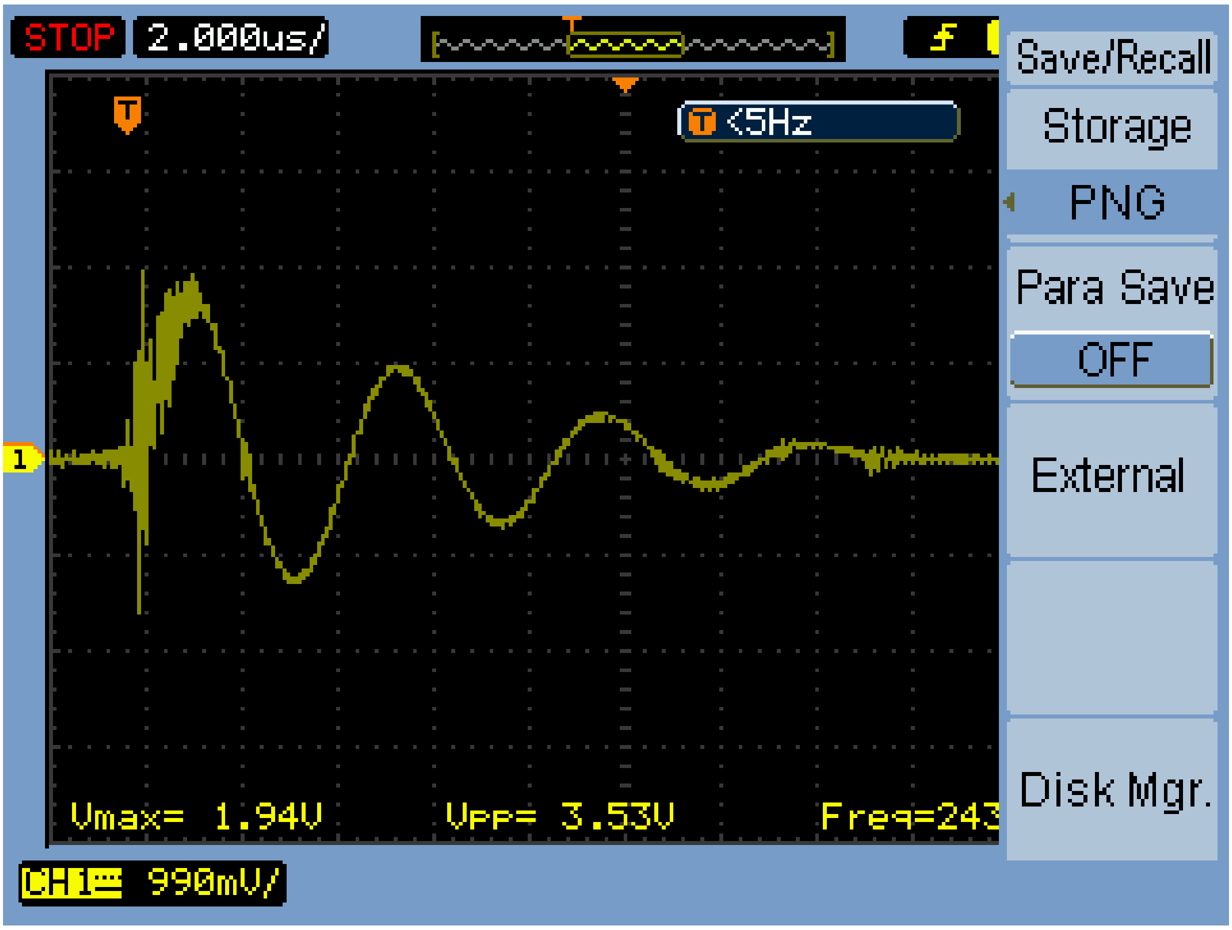


Figure 5. 2 Current graph from Oscilloscope

In the process of integrating the area under the curve it becomes necessary to eliminate the noise recorded in the process. The extra peak which is seen in the picture is eliminated considering as a bad data point.

Calculation

For understanding the method of determining the thrust one of the calculations is shown below :

Input :

Length of cavity l (mm) = 10

Diameter of cavity d (mm) = 1

Frequency (Hz) = 1

Magnetic permeability μ_o (H/m) = 4π X 10^{-7}

Energy (J) = 1.68

Mass ablated m (gms) per 900 pulse = 0.09134

Thrust produced due to Magnetic field

$$Tmag = f \ \frac{\mu}{2} \ X \ \frac{l}{d} \ X \ \int i^2 \ dt$$

$$Tmag = 1 \ X \ \frac{4\pi \ x \ 10^{-7}}{2} \ X \ \frac{20}{1} \ X \ 2.89946$$

$$Tmag = 1.8214 \ X \ 10^{-5} \ N$$

Thrust due to gas dynamic

$$Tgas = f \left[\frac{8(\gamma - 1)}{\gamma^2(\gamma + 1)} \ mE \right]^{1/2}$$

$$Tgas = 1 \left[\frac{8(1.3 - 1)}{1.3^2(1.3 + 1)} \ \frac{0.09134}{900} X \ 1.68 \right]^{1/2}$$

$Tgas =$ 0.000325126 N

Total Thrust

$$Thrust = Tmag + Tgas$$

$$\therefore Total\ Thrust = 343.4\ \mu\ N$$

Specific Impulse

$$Isp = \frac{T/_f}{mg}$$

$$Isp = \frac{\frac{343.4}{1}}{\frac{0.09134}{900}\ X\ 9.81}$$

$$Isp = 338\ Sec$$

Impulse bit

$$Isp = \frac{Ibit}{mg}$$

$$Ibit = Isp\ X\ m\ X\ g$$

$$Ibit = 338\ X\ \frac{.09134}{900}\ X\ 9.81$$

$$Ibit = 343\mu Ns$$

Exhaust velocity.

I_{bit} = mv

$$v = \frac{Ibit}{m}$$

$$v = \frac{0.000343}{\frac{0.09134}{900}}$$

$$v = 3383\ m/s$$

Thrust efficiency

$$\eta = \frac{\left(T/_f\right)^2}{2mE}$$

$$\eta = \frac{\left(\frac{343.4\ X\ 10^{-6}}{1}\right)^2}{2\ X\ \frac{0.09134}{900}\ X\ 1.68}$$

$$\eta = 34.43\ \%$$

1500 volts	capacitor=1.5µF	Energy=1.68J			
Propellant Series		CAVITY DIA (mm)	LENGTH (mm)	ΔM (gms)	AREA(mm^2)
1A1MM		1	10	0.09134	2.89946
1A3MM		3	10	0.01899	12.41651
1A5MM		5	10	0.01872	27.88512
1A10MM		10	10	0.00746	36.68608
1B1MM		1	20	0.0332	4.18611
1B3MM		3	20	0.0056	7.37017
1B5MM		5	20	0.0111	13.21285
1B10MM		10	20	0.0018	17.05151
1C1MM		1	30	0.0307	0.92265
1C3MM		3	30	0.0205	3.76098
1C5MM		5	30	0.027	6.9221
1C10MM		10	30	0.0084	2.29042

T_{mag} (N)	T_{gas} (N)	THRUST (N)	I_{sp} (Sec)	I_{bit}(μNs)	Velocity (m/s)	Efficiency
1.82144E-05	0.000325136	343.4E-6	338.3133593	343.4E-6	3383.133593	34.43%
2.60002E-05	0.000148251	174.3E-6	825.8341098	174.3E-6	8258.341098	42.65%
3.50349E-05	0.000147193	182.2E-6	876.0961594	182.2E-6	8760.961594	47.32%
2.30462E-05	9.29189E-05	116.0E-6	1399.042683	116.0E-6	13990.42683	48.09%
5.25943E-05	0.000196021	248.6E-6	673.9584204	248.6E-6	6739.584204	49.66%
3.08663E-05	8.05061E-05	111.4E-6	1789.91271	111.4E-6	17899.1271	59.08%
3.32012E-05	0.000113343	146.5E-6	1188.199629	146.5E-6	11881.99629	51.61%
2.14235E-05	4.56427E-05	67.1E-6	3353.308559	67.1E-6	33533.08559	66.65%
1.73883E-05	0.000188497	205.9E-6	603.571643	205.9E-6	6035.71643	36.83%
2.36265E-05	0.000154032	177.7E-6	779.9649973	177.7E-6	7799.649973	41.07%
2.60908E-05	0.000176773	202.9E-6	676.2133939	202.9E-6	6762.133939	40.66%
4.31653E-06	9.85994E-05	102.9E-6	1102.67065	102.9E-6	11026.7065	33.63%

1800 volts	capacitor=1.5µF	Energy=2.43J			
Propellant Series		CAVITY DIA (mm)	LENGTH (mm)	ΔM (gms)	AREA(mm^2)
2A1MM		1	10	0.06155	4.394
2A3MM		3	10	0.02302	33.4074
2A5MM		5	10	0.01872	34.8608
2A10MM		10	10	0.00646	35.87712
2B1MM		1	20	0.0611	3.0167
2B3MM		3	20	0.0288	10.49454
2B5MM		5	20	0.0264	12.95005
2B10MM		10	20	0.0055	22.19046
2C1MM		1	30	0.0964	2.61153
2C3MM		3	30	0.03	4.2634
2C5MM		5	30	0.034	11.08064
2510MM		10	30	0.0024	20.57784

T_{mag} (N)	T_{gas} (N)	THRUST (N)	I_{sp} (Sec)	I_{bit}(μNs)	Velocity (m/s)	Efficiency
2.76031E-05	0.0002669	294.5E-6	430.630135	294.5E-6	4306.30135	37.59%
6.99551E-05	0.000163225	233.2E-6	911.6520225	233.2E-6	9116.520225	63.01%
4.37991E-05	0.000147193	191.0E-6	918.2319495	191.0E-6	9182.319495	51.98%
2.2538E-05	8.64671E-05	109.0E-6	1518.647006	109.0E-6	15186.47006	49.06%
3.79018E-05	0.000265923	303.8E-6	447.5318716	303.8E-6	4475.318716	40.30%
4.39511E-05	0.000182571	226.5E-6	707.8804674	226.5E-6	7078.804674	47.53%
3.25409E-05	0.000174798	207.3E-6	706.837304	207.3E-6	7068.37304	43.44%
2.78801E-05	7.9784E-05	107.7E-6	1761.776611	107.7E-6	17617.76611	56.22%
4.92169E-05	0.000334021	383.2E-6	357.794271	383.2E-6	3577.94271	40.64%
2.67827E-05	0.000186335	213.1E-6	639.3541006	213.1E-6	6393.541006	40.38%
4.17651E-05	0.000198369	240.1E-6	635.6495687	240.1E-6	6356.495687	45.24%
3.8781E-05	5.27036E-05	91.5E-6	3430.672291	91.5E-6	34306.72291	93.02%

2000 volts	capacitor=1.5µF	Energy=3J			
Propellant Series		CAVITY DIA (mm)	LENGTH (mm)	ΔM (gms)	AREA(mm^2)
3A1MM		1	10	0.04599	10.2016
3A3MM		3	10	0.02613	18.40356
3A5MM		5	10	0.01776	29.02144
3A10MM		10	10	0.03742	33.36192
3B1MM		1	20	0.0602	3.88641
3B3MM		3	20	0.0392	13.22032
3B5MM		5	20	0.0114	15.44897
3B10MM		10	20	0.0087	21.85583
3C1MM		1	30	0.0838	3.7571
3C3MM		3	30	0.043	8.93352
3C5MM		5	30	0.047	13.97252
3C10MM		10	30	0.0043	27.03605

T_{mag} (N)	T_{gas} (N)	THRUST (N)	I_{sp} (Sec)	I_{bit}(μNs)	Velocity (m/s)	Efficiency
6.40865E-05	0.00023071	294.8E-6	576.9009983	294.8E-6	5769.009983	50.41%
3.85371E-05	0.000173902	212.4E-6	731.7070975	212.4E-6	7317.070975	46.07%
3.64625E-05	0.000143369	179.8E-6	911.3099073	179.8E-6	9113.099073	48.57%
2.0958E-05	0.000208107	229.1E-6	550.9310352	229.1E-6	5509.310352	37.40%
4.88289E-05	0.000263957	312.8E-6	467.6197759	312.8E-6	4676.197759	43.35%
5.53667E-05	0.000212999	268.4E-6	616.1458597	268.4E-6	6161.458597	49.01%
3.88202E-05	0.000114865	153.7E-6	1213.302622	153.7E-6	12133.02622	55.27%
2.74597E-05	0.000100345	127.8E-6	1322.113699	127.8E-6	13221.13699	50.08%
7.08063E-05	0.000311427	382.2E-6	410.5133937	382.2E-6	4105.133937	46.51%
5.61204E-05	0.000223084	279.2E-6	584.3817202	279.2E-6	5843.817202	48.36%
5.26652E-05	0.00023323	285.9E-6	547.4580663	285.9E-6	5474.580663	46.39%
5.09521E-05	7.05454E-05	121.5E-6	2542.972323	121.5E-6	25429.72323	91.57%

Test-1

CAVITY DIA	CAVITY LENGTH	L/D	ENERGY	SURFACE AREA	ENERGY DENSITY	MASS ABLATED
mm	mm		J	mm^2	J/mm^2	gms
1	10	10	1.68	31.4	0.053503185	0.09134
3	10	3.33333333	1.68	94.2	0.017834395	0.01899
5	10	2	1.68	157	0.010700637	0.01872
10	10	1	1.68	314	0.005350318	0.00746

MASS ABLATED PER PULSE	CURRENT	TMAG	TGAS	TOTAL Thrust	ISP	Ibit	EFFICIENCY
Kgs	AREA (mm^2)	N	N	N	Sec	Ns	
0.00009134	2.89946	1.82144E-05	0.000325136	343.4E-6	338.3133593	294.8E-6	34.43%
0.0000211	12.41651	2.60002E-05	0.000148251	174.3E-6	825.8341098	212.4E-6	42.65%
0.0000208	27.88512	3.50349E-05	0.000147193	182.2E-6	876.0961594	179.8E-6	47.32%
8.28889E-06	36.68608	2.30462E-05	9.29189E-05	116.0E-6	1399.042683	229.1E-6	48.09%

Test-2

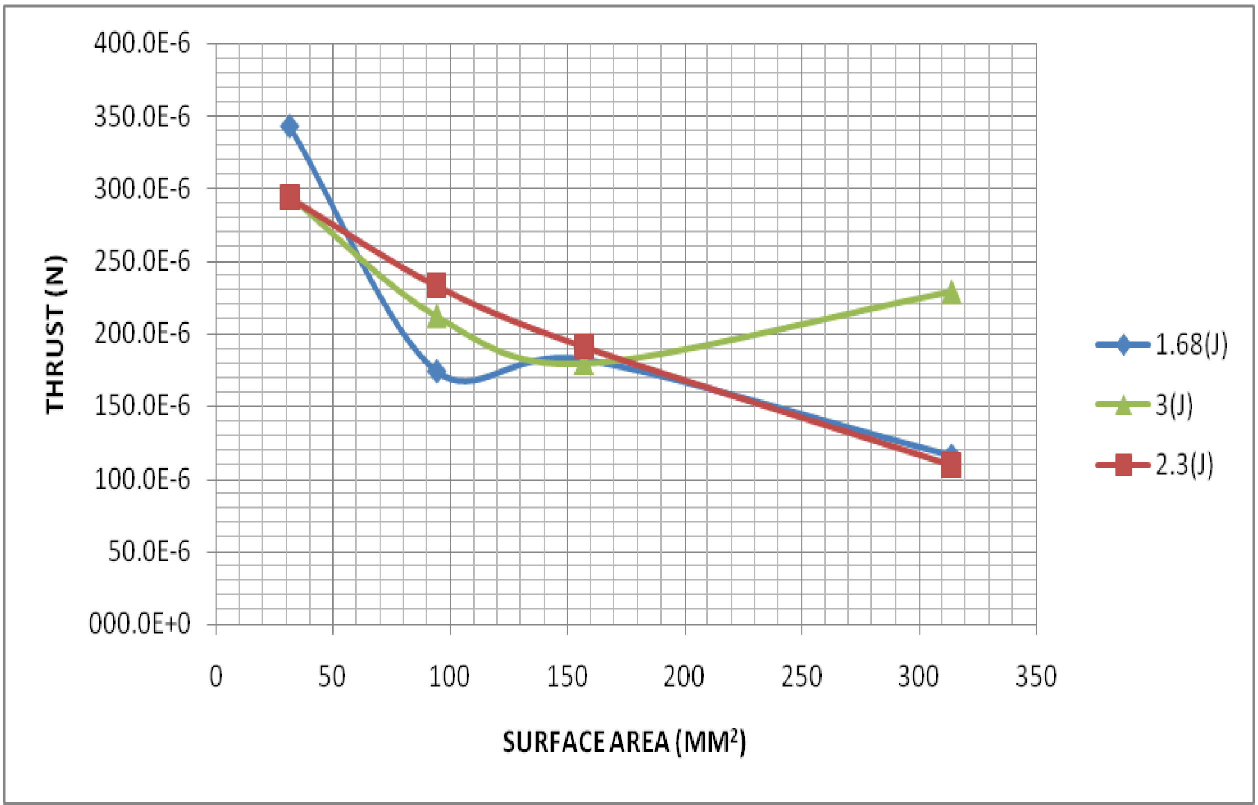
CAVITY DIA	CAVITY LENGTH	L/D	ENERGY	SURFACE AREA	ENERGY DENSITY	MASS ABLATED
mm	mm		J	mm^2	J/mm^2	gms
1	10	10	2.43	31.4	0.077388535	0.06155
3	10	3.333333333	2.43	94.2	0.025796178	0.02302
5	10	2	2.43	157	0.015477707	0.01872
10	10	1	2.43	314	0.007738854	0.00646

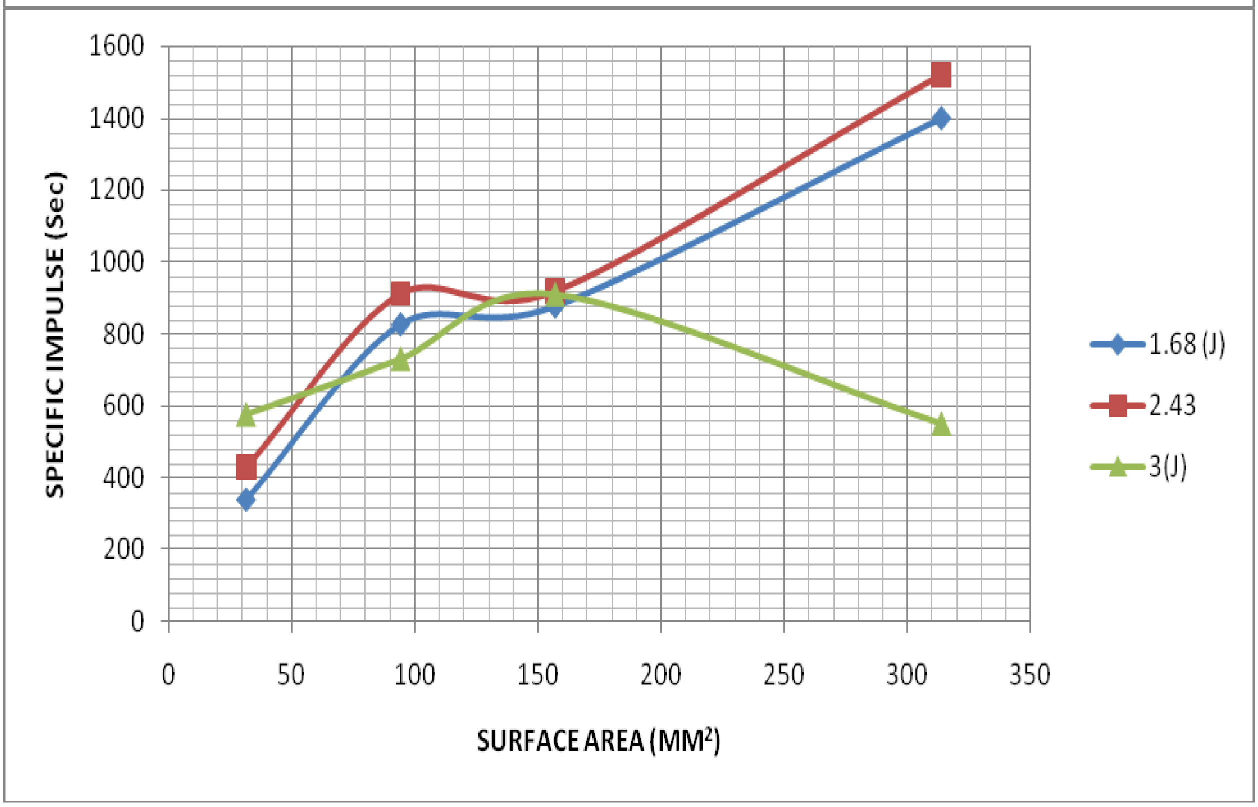
MASS ABLATED PER PULSE	CURRENT	TMAG	TGAS	TOTAL Thrust	ISP	Ibit	EFFICIENCY
Kgs	AREA (mm^2)	N	N	N	Sec	Ns	
6.83889E-05	4.394	2.76031E-05	0.0002669	294.5E-6	430.630135	294.5E-6	37.59%
2.55778E-05	33.4074	6.99551E-05	0.000163225	233.2E-6	911.6520225	233.2E-6	63.01%
0.0000208	34.8608	4.37991E-05	0.000147193	191.0E-6	918.2319495	191.0E-6	51.98%
7.17778E-06	35.87712	2.2538E-05	8.64671E-05	109.0E-6	1518.647006	109.0E-6	49.06%

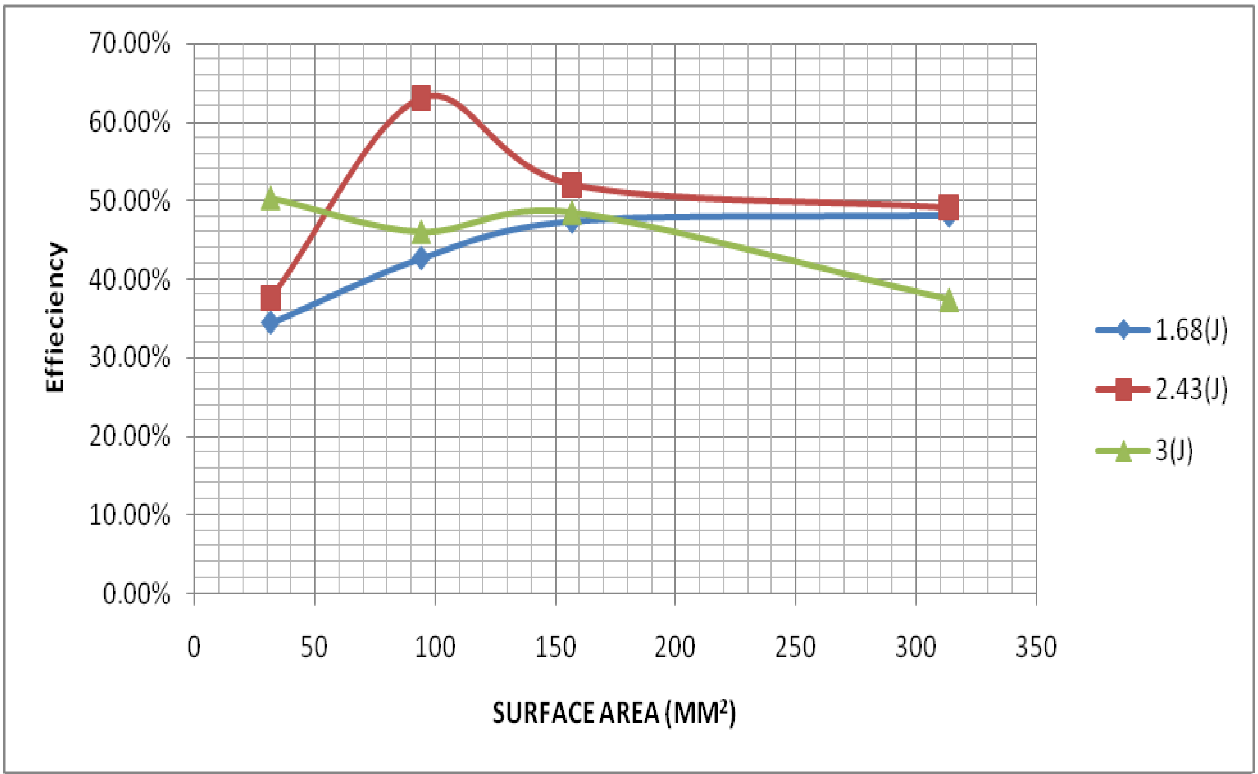
Test- 3

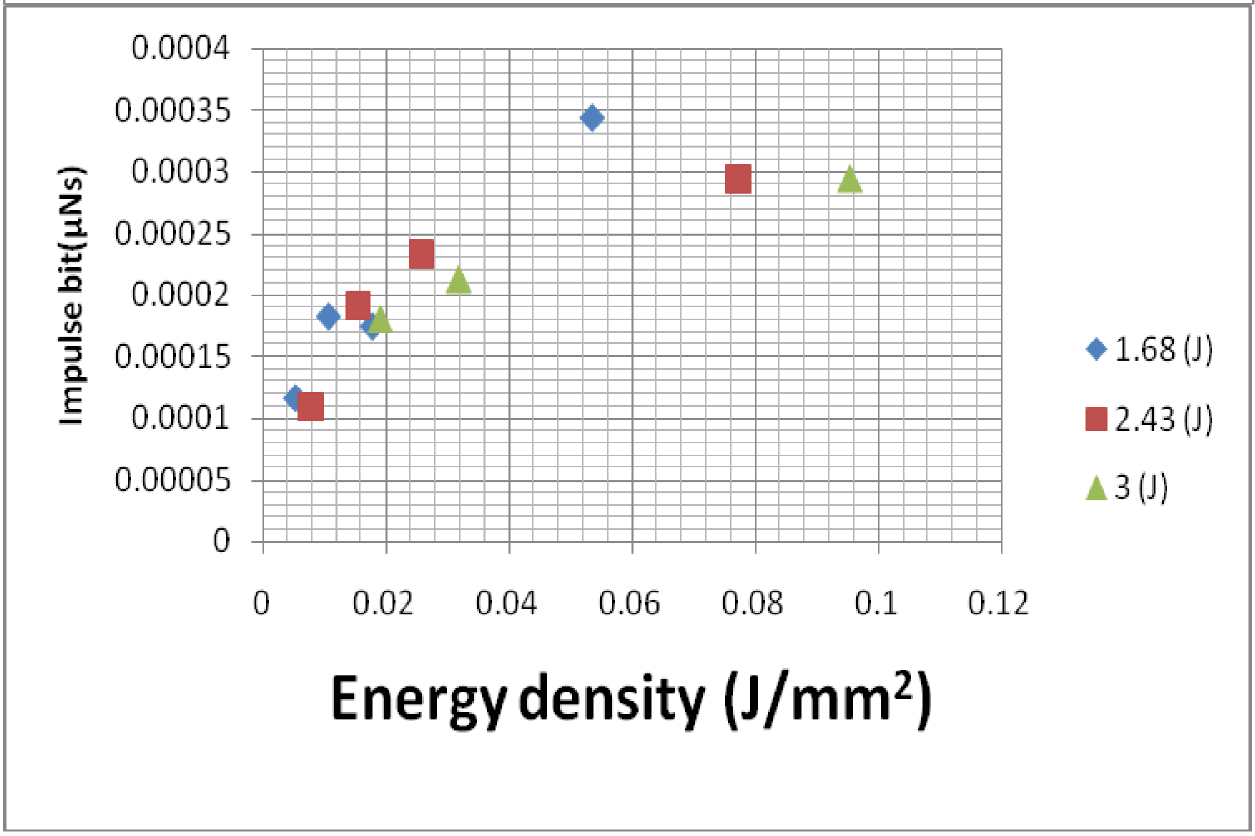
CAVITY DIA	CAVITY LENGTH	L/D	ENERGY	SURFACE AREA	ENERGY DENSITY	MASS ABLATED
mm	mm		J	mm^2	J/mm^2	gms
1	10	10	3	31.4	0.095541401	0.04599
3	10	3.33333333	3	94.2	0.031847134	0.02613
5	10	2	3	157	0.01910828	0.01776
10	10	1	3	314	0.00955414	0.03742

MASS ABLATED PER PULSE	CURRENT	T_{MAG}	T_{GAS}	TOTAL Thrust	I_{SP}	I_{bit}	EFFICIENCY
Kgs	AREA (mm^2)	N	N	N	Sec	Ns	
0.0000511	10.2016	6.40865E-05	0.00023071	294.8E-6	576.9009983	294.8E-6	50.41%
2.90333E-05	18.40356	3.85371E-05	0.000173902	212.4E-6	731.7070975	212.4E-6	46.07%
1.97333E-05	29.02144	3.64625E-05	0.000143369	179.8E-6	911.3099073	179.8E-6	48.57%
4.15778E-05	33.36192	2.0958E-05	0.000208107	229.1E-6	550.9310352	229.1E-6	37.40%


400.0E-6
350.0E-6
300.0E-6
250.0E-6
200.0E-6
150.0E-6
100.0E-6
50.0E-6
000.0E+0
THRUST (N)
0
50
100
150
200
250
300
350
SURFACE AREA (MM²)
1.68(J)
3(J)
2.3(J)


1600
1400
1200
1000
800
600
400
200
0
SPECIFIC IMPULSE (Sec)
0
50
100
150
200
250
300
350
SURFACE AREA (MM²)
1.68 (J)
2.43
3(J)


70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Effieciency
0
50
100
150
200
250
300
350
SURFACE AREA (MM²)
1.68(J)
2.43(J)
3(J)


0.0004
0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
Impulse bit(µNs)
0
0.02
0.04
0.06
0.08
0.1
0.12
Energy density (J/mm²)
1.68 (J)
2.43 (J)
3 (J)

Observation

- Thrust decreased as the surface area increased
- At cavity dia 10mm and length 10 mm thrust increased suddenly due to very high magnetic field interaction.
- Specific impulse increases with decrease in thrust.
- There is increase in impulse bit.

Test- 4

CAVITY DIA	CAVITY LENGTH	L/D	ENERGY	SURFACE AREA	ENERGY DENSITY	MASS ABLATED
mm	mm		J	mm^2	J/mm^2	gms
1	20	20	1.68	62.8	0.026751592	0.0332
3	20	6.66666667	1.68	188.4	0.008917197	0.0056
5	20	4	1.68	314	0.005350318	0.0111
10	20	2	1.68	628	0.002675159	0.0018

MASS ABLATED PER PULSE	CURRENT	T_{MAG}	T_{GAS}	TOTAL Thrust	I_{SP}	I_{bit}	EFFICIENCY
Kgs	AREA (mm^2)	N	N	N	Sec	Ns	
3.68889E-05	4.18611	5.25943E-05	0.000196021	248.6E-6	673.9584204	248.6E-6	49.66%
6.22222E-06	7.37017	3.08663E-05	8.05061E-05	111.4E-6	1789.91271	111.4E-6	59.08%
1.23333E-05	13.21285	3.32012E-05	0.000113343	146.5E-6	1188.199629	146.5E-6	51.61%
0.000002	17.05151	2.14235E-05	4.56427E-05	67.1E-6	3353.308559	67.1E-6	66.65%

Test- 5

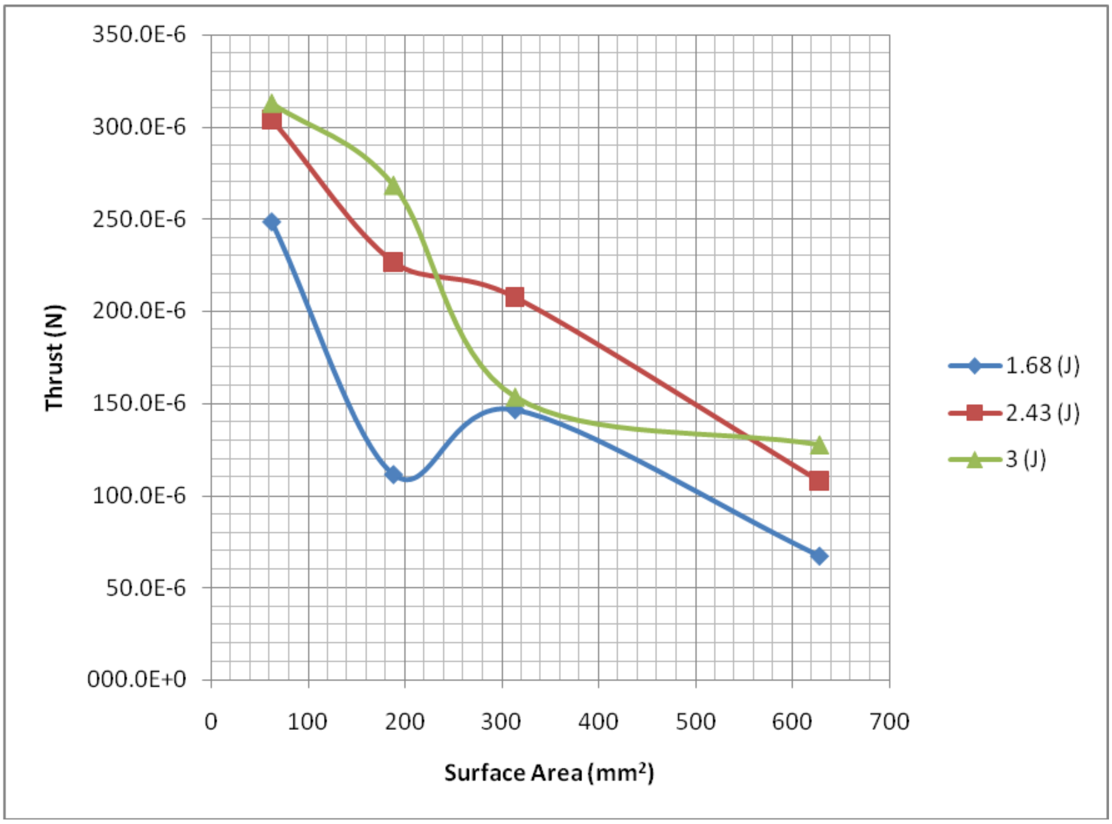
CAVITY DIA	CAVITY LENGTH	L/D	ENERGY	SURFACE AREA	ENERGY DENSITY	MASS ABLATED
mm	mm		J	mm^2	J/mm^2	gms
1	20	20	2.43	62.8	0.038694268	0.0611
3	20	6.66666667	2.43	188.4	0.012898089	0.0288
5	20	4	2.43	314	0.007738854	0.0264
10	20	2	2.43	628	0.003869427	0.0055

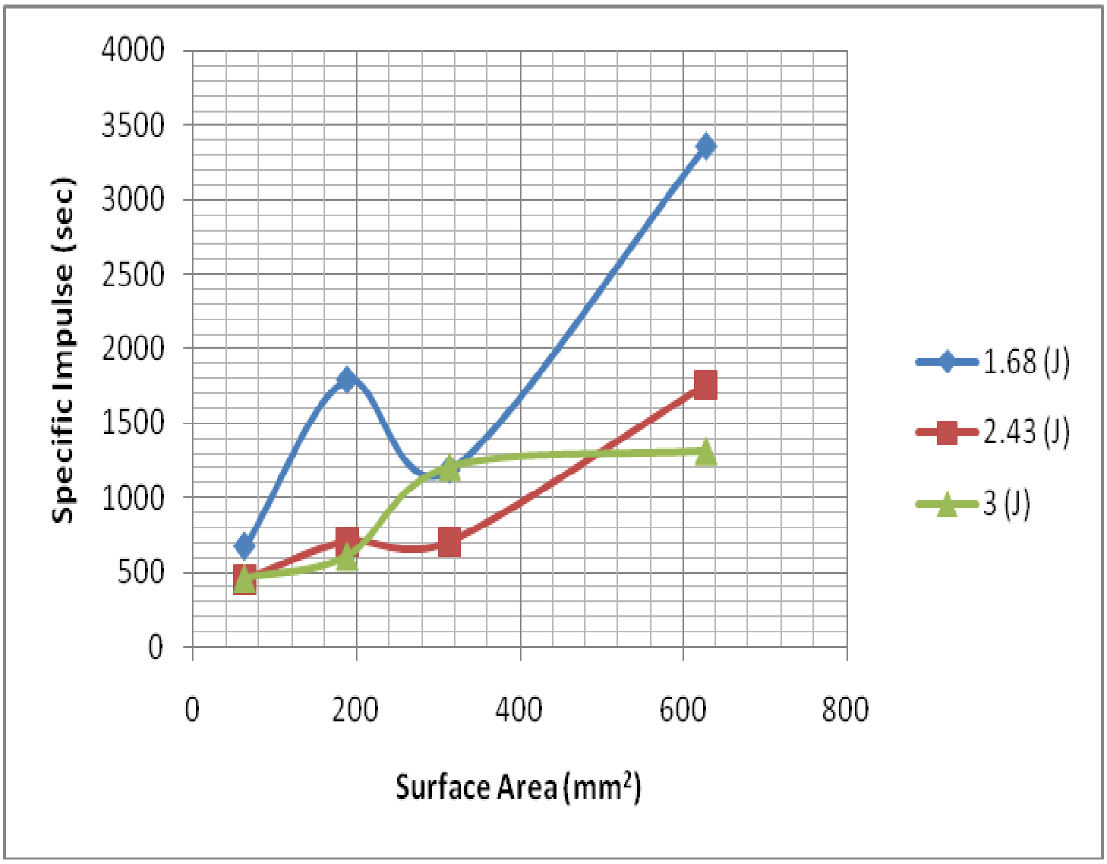
MASS ABLATED PER PULSE	CURRENT	T_{MAG}	T_{GAS}	TOTAL Thrust	I_{SP}	I_{bit}	EFFICIENCY
Kgs	AREA (mm^2)	N	N	N	Sec	Ns	
6.78889E-05	3.0167	3.79018E-05	0.000265923	303.8E-6	447.5318716	303.8E-6	40.30%
0.000032	10.49454	4.39511E-05	0.000182571	226.5E-6	707.8804674	226.5E-6	47.53%
2.93333E-05	12.95005	3.25409E-05	0.000174798	207.3E-6	706.837304	207.3E-6	43.44%
6.11111E-06	22.19046	2.78801E-05	7.9784E-05	107.7E-6	1761.776611	107.7E-6	56.22%

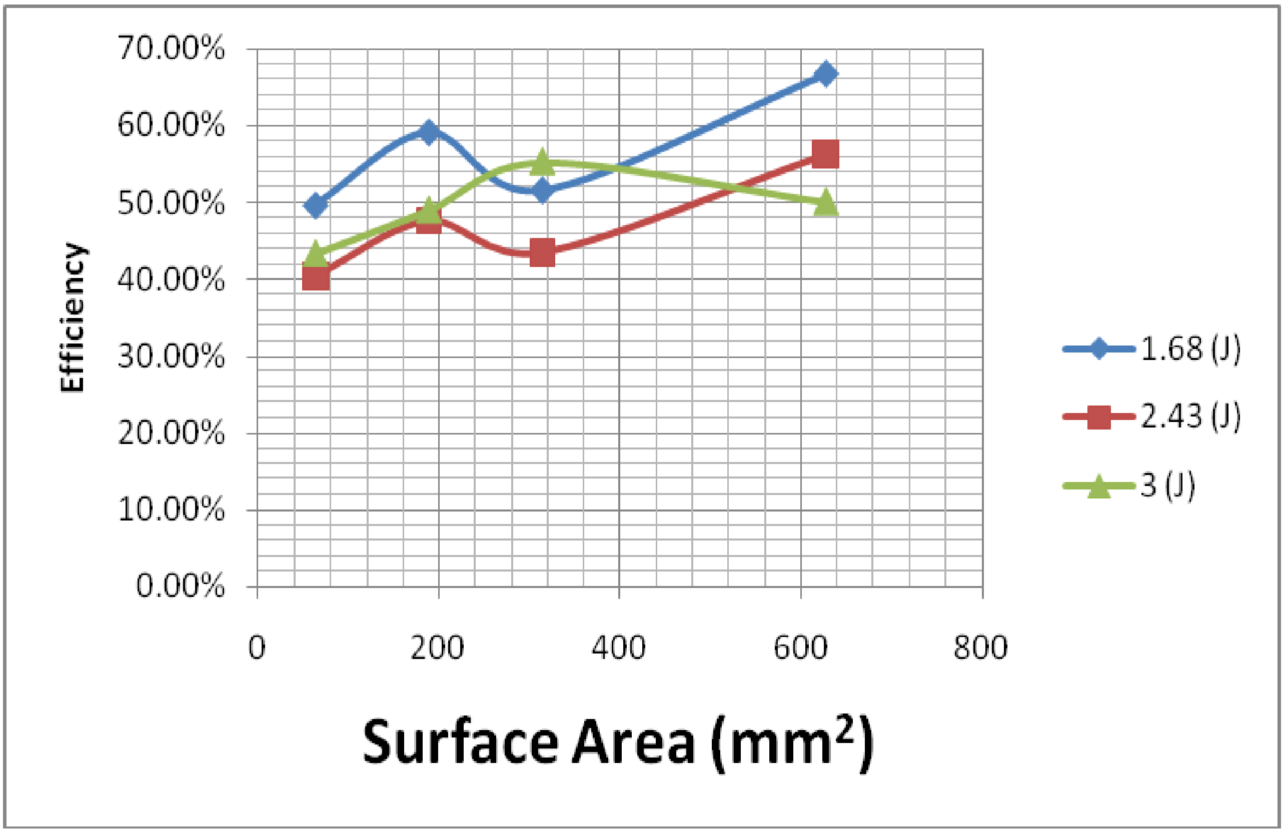
Test- 6

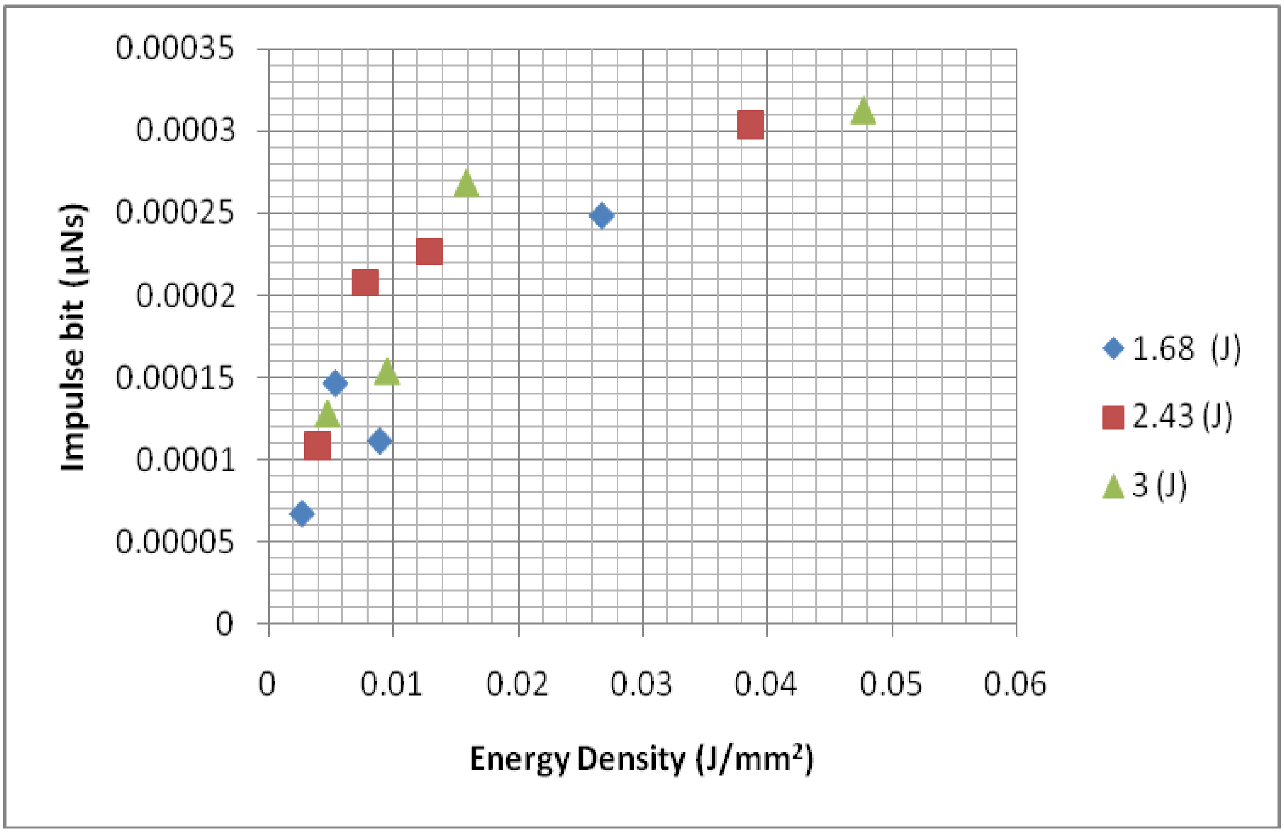
CAVITY DIA	CAVITY LENGTH	L/D	ENERGY	SURFACE AREA	ENERGY DENSITY	MASS ABLATED
mm	mm		J	mm^2	J/mm^2	gms
1	20	20	3	62.8	0.047770701	0.0602
3	20	6.66666667	3	188.4	0.015923567	0.0392
5	20	4	3	314	0.00955414	0.0114
10	20	2	3	628	0.00477707	0.0087

MASS ABLATED PER PULSE	CURRENT	T_{MAG}	T_{GAS}	TOTAL Thrust	I_{SP}	I_{bit}	EFFICIENCY
Kgs	AREA (mm^2)	N	N	N	Sec	Ns	
6.68889E-05	3.88641	4.88289E-05	0.000263957	312.8E-6	467.6197759	312.8E-6	43.35%
4.35556E-05	13.22032	5.53667E-05	0.000212999	268.4E-6	616.1458597	268.4E-6	49.01%
1.26667E-05	15.44897	3.88202E-05	0.000114865	153.7E-6	1213.302622	153.7E-6	55.27%
9.66667E-06	21.85583	2.74597E-05	0.000100345	127.8E-6	1322.113699	127.8E-6	50.08%


350.0E-6
300.0E-6
250.0E-6
200.0E-6
150.0E-6
100.0E-6
50.0E-6
000.0E+0
Thrust (N)
0
100
200
300
400
500
600
700
Surface Area (mm²)
1.68 (J)
2.43 (J)
3 (J)


4000
3500
3000
2500
2000
1500
1000
500
0
Specific Impulse (sec)
0
200
400
600
800
Surface Area (mm²)
1.68 (J)
2.43 (J)
3 (J)


70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Efficiency
0
200
400
600
800
Surface Area (mm²)
1.68 (J)
2.43 (J)
3 (J)


0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
Impulse bit (µNs)
0
0.01
0.02
0.03
0.04
0.05
0.06
Energy Density (J/mm²)
1.68 (J)
2.43 (J)
3 (J)

Observation

- Thrust decreased as the surface area increased
- Specific impulse increases with decrease in thrust.
- There is increase in impulse bit.

Test- 7

CAVITY DIA	CAVITY LENGTH	L/D	ENERGY	SURFACE AREA	ENERGY DENSITY	MASS ABLATED
mm	mm		J	mm^2	J/mm^2	gms
1	30	30	1.68	94.2	0.017834395	0.0307
3	30	10	1.68	282.6	0.005944798	0.0205
5	30	6	1.68	471	0.003566879	0.027
10	30	3	1.68	942	0.001783439	0.0084

MASS ABLATED PER PULSE	CURRENT	T_{MAG}	T_{GAS}	TOTAL Thrust	I_{SP}	I_{bit}	EFFICIENCY
Kgs	AREA (mm^2)	N	N	N	Sec	Ns	
3.41111E-05	0.92265	1.73883E-05	0.000188497	205.9E-6	603.571643	205.9E-6	36.83%
2.27778E-05	3.76098	2.36265E-05	0.000154032	177.7E-6	779.9649973	177.7E-6	41.07%
0.00003	6.9221	2.60908E-05	0.000176773	202.9E-6	676.2133939	202.9E-6	40.66%
9.33333E-06	2.29042	4.31653E-06	9.85994E-05	102.9E-6	1102.67065	102.9E-6	33.63%

Test – 8

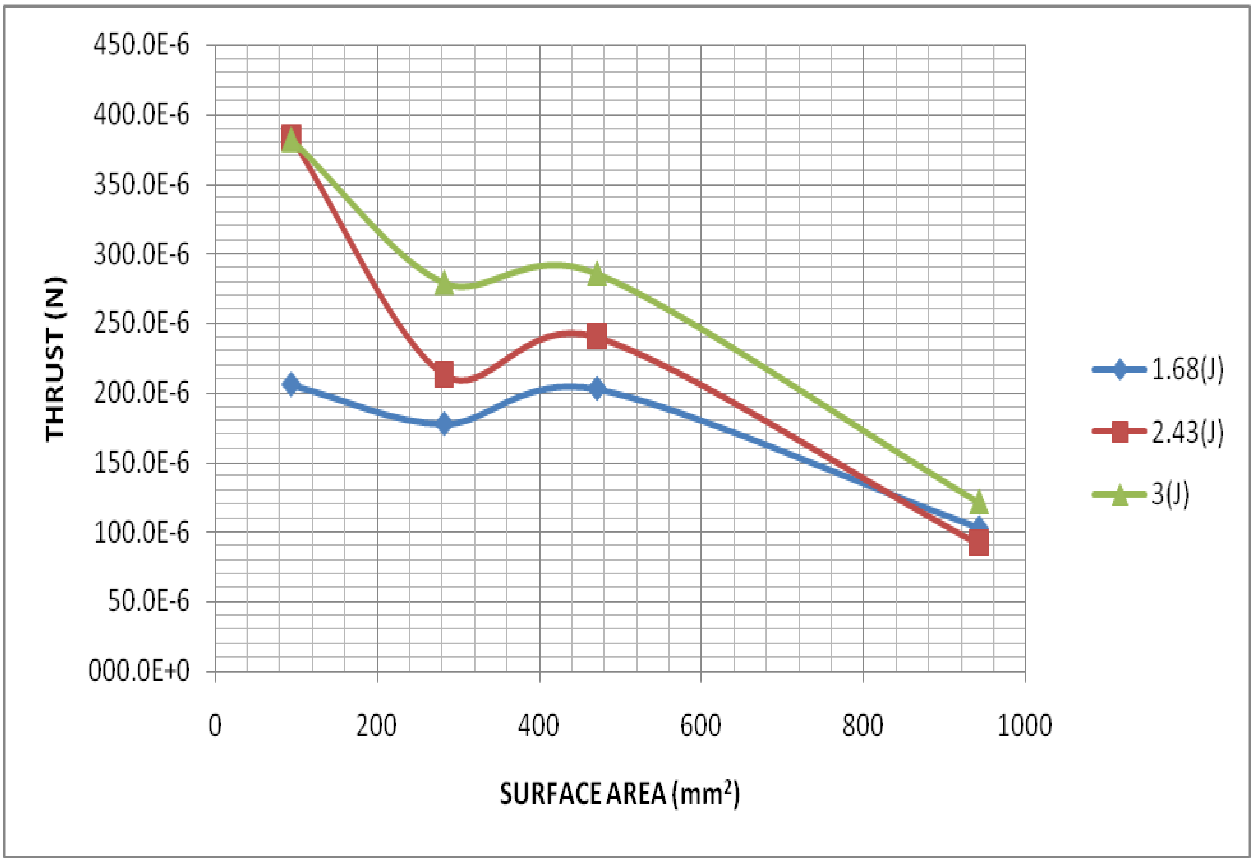
CAVITY DIA	CAVITY LENGTH	L/D	ENERGY	SURFACE AREA	ENERGY DENSITY	MASS ABLATED
mm	mm		J	mm^2	J/mm^2	gms
1	30	30	2.43	94.2	0.025796178	0.0964
3	30	10	2.43	282.6	0.008598726	0.03
5	30	6	2.43	471	0.005159236	0.034
10	30	3	2.43	942	0.002579618	0.0024

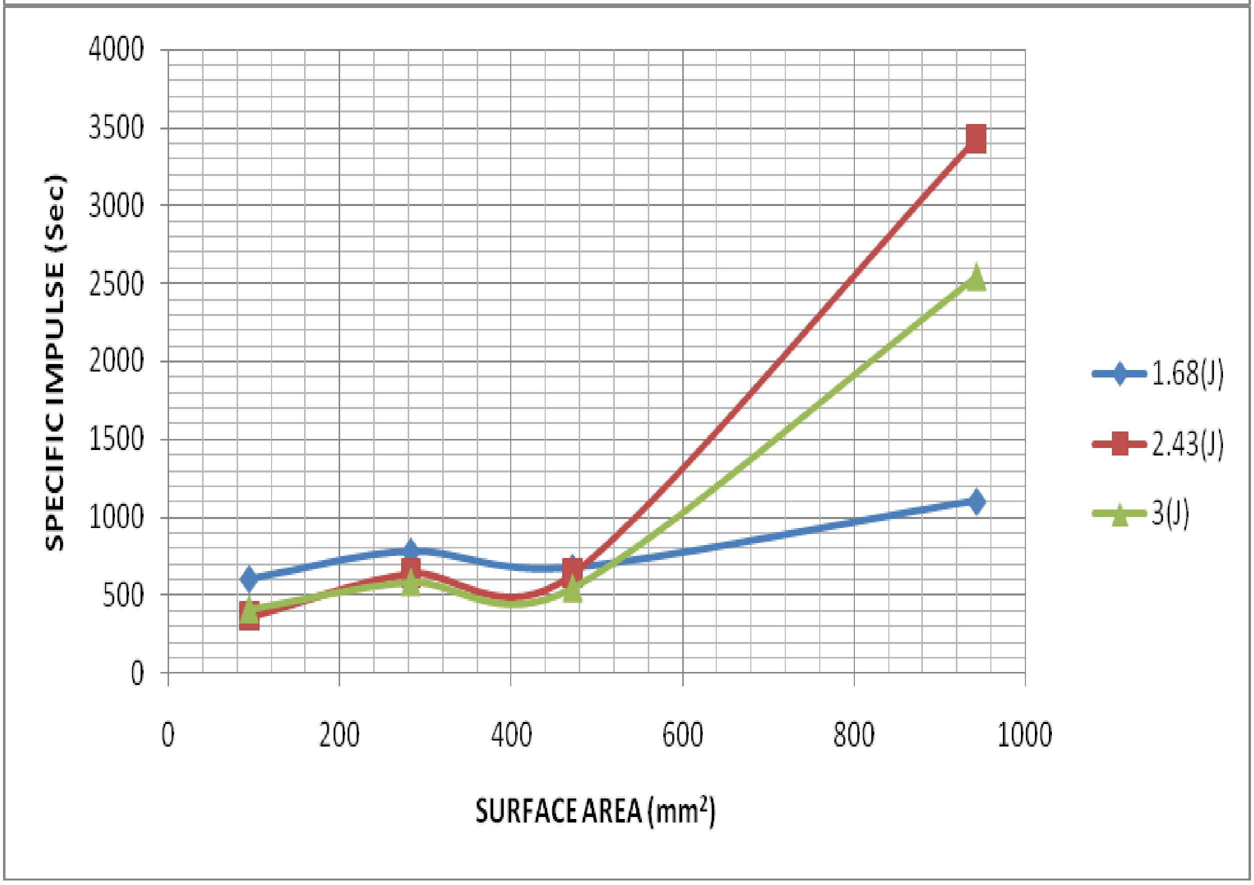
MASS ABLATED PER PULSE	CURRENT	T_{MAG}	T_{GAS}	TOTAL Thrust	I_{SP}	I_{bit}	EFFICIENCY
Kgs	AREA (mm^2)	N	N	N	Sec	Ns	
0.000107111	2.61153	4.92169E-05	0.000334021	383.2E-6	357.794271	383.2E-6	40.64%
3.33333E-05	4.2634	2.67827E-05	0.000186335	213.1E-6	639.3541006	213.1E-6	40.38%
3.77778E-05	11.08064	4.17651E-05	0.000198369	240.1E-6	635.6495687	240.1E-6	45.24%
2.66667E-06	20.57784	3.8781E-05	5.27036E-05	91.5E-6	3430.672291	91.5E-6	93.02%

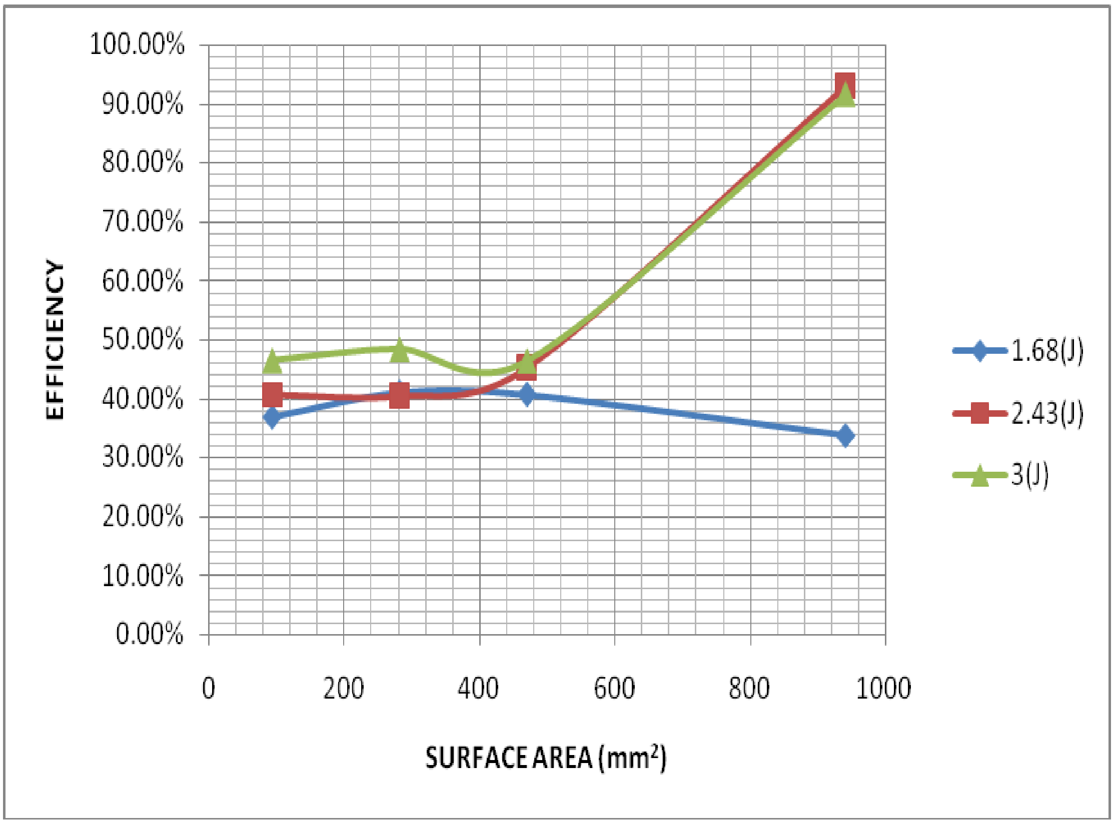
Test- 9

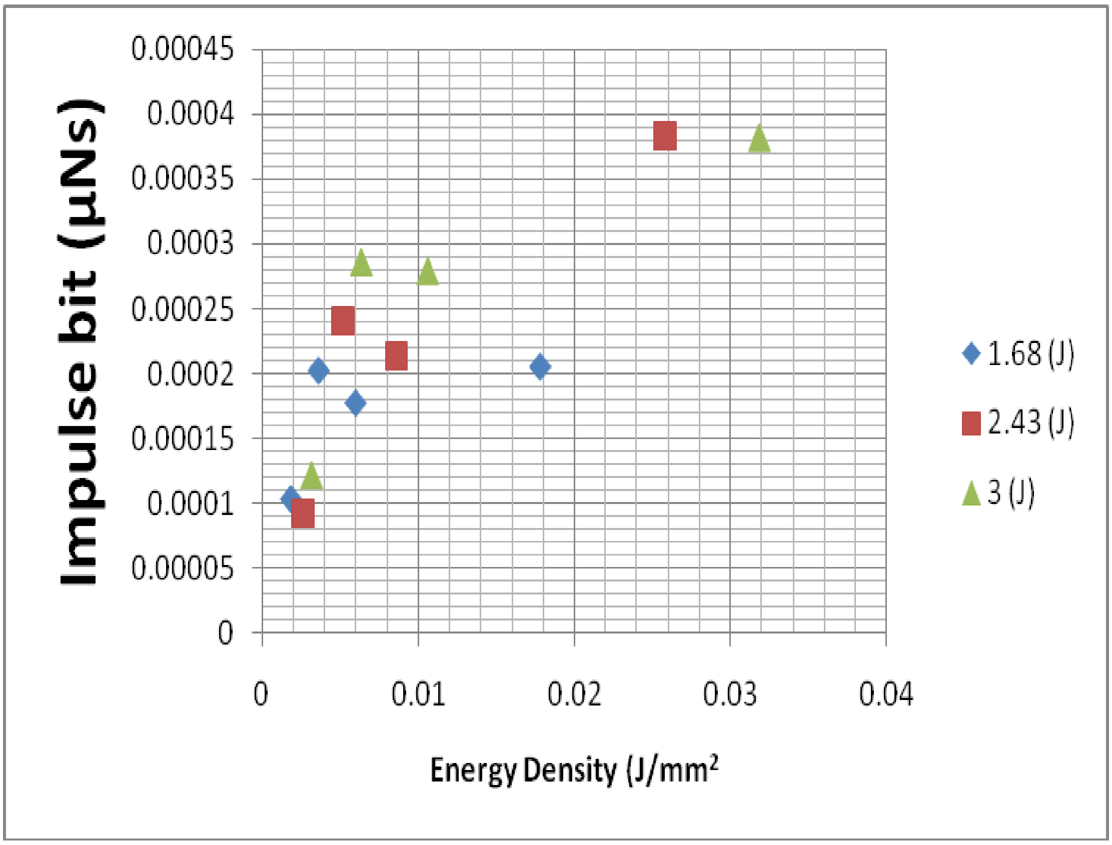
CAVITY DIA	CAVITY LENGTH	L/D	ENERGY	SURFACE AREA	ENERGY DENSITY	MASS ABLATED
mm	mm		J	mm^2	J/mm^2	gms
1	30	30	3	94.2	0.031847134	0.0838
3	30	10	3	282.6	0.010615711	0.043
5	30	6	3	471	0.006369427	0.047
10	30	3	3	942	0.003184713	0.0043

MASS ABLATED PER PULSE	CURRENT	T_{MAG}	T_{GAS}	TOTAL Thrust	I_{SP}	I_{bit}	EFFICIENCY
Kgs	AREA (mm^2)	N	N	N	Sec	Ns	
9.31111E-05	3.7571	7.08063E-05	0.000311427	382.2E-6	410.5133937	382.2E-6	46.51%
4.77778E-05	8.93352	5.61204E-05	0.000223084	279.2E-6	584.3817202	279.2E-6	48.36%
5.22222E-05	13.97252	5.26652E-05	0.00023323	285.9E-6	547.4580663	285.9E-6	46.39%
4.77778E-06	27.03605	5.09521E-05	7.05454E-05	121.5E-6	2542.972323	121.5E-6	91.57%


THRUST (N)
450.0E-6
400.0E-6
350.0E-6
300.0E-6
250.0E-6
200.0E-6
150.0E-6
100.0E-6
50.0E-6
000.0E+0
0
200
400
600
800
1000
SURFACE AREA (mm²)
1.68(J)
2.43(J)
3(J)


SPECIFIC IMPULSE (Sec)
4000
3500
3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
SURFACE AREA (mm²)
1.68(J)
2.43(J)
3(J)


EFFICIENCY
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
0
200
400
600
800
1000
SURFACE AREA (mm²)
1.68(J)
2.43(J)
3(J)


Impulse bit (µNs)
0.00045
0.0004
0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
0
0.01
0.02
0.03
0.04
Energy Density (J/mm²
1.68 (J)
2.43 (J)
3 (J)

Observation

- Thrust decreased as the surface area increased

- Thrust is almost same at cavity dia 10mm for all energy levels

- Specific impulse increases with decrease in thrust.

- There is increase in impulse bit.

Conclusion

The tests carried out demonstrated that it was necessary to maintain a constant energy level. The energy level increased as thruster dimension increased. Hence, tests conducted for cavity length 40mm and above did not produce efficient ablation of the propellant due lack of energy. At 40mm cavity length volatge required for ablation was above 2000 volts. From the experiments we could conclude that as the surface area of ablation increased there was decrease in the Thrust produced. At a certain point when the cavity dia and length were same ie 10mm there were very high magnetic field interaction with the fluid causing high efeect. Whereas this was not seen at other dimensions as the energy supplied was sufficient enough but production higher magnetic fields was not possible..Thrust and Specific Impulse are inversly propotional to each othe ie as the thrust increases specific impulse decreases and as thrust decreases specific impulse is higher. Effeciencies as high as 93% was achieved for energy level of 2.43J at cavity dia of 10mm and length of 30 mm. At 1mm cavity diameter in all energy levels high thrust is produced. Maximum thrust produced is 383.2 µN for cavity length of 30mm for an energy levl of 3J. Highest specific impulse is produced at the cavity diameter of 10mm and length of 30mm for 2.43J energy level which is 3430 Sec. It is observed that the Impulse bit increases as the surface area increases but a variation was observed in the cavity diameter of 5mm

Parameter	PRIMEX EO-1	LES 8/9	NOVA	Our PPT
Maximum Ibit	>750 µN-sec	300 µN-sec	378 µN-sec	>380 µN-sec
Minimum Ibit	<100 µN-sec	300 µN-sec	378 µN-sec	<65 µN-sec
Isp	1150 sec	1075 sec	300 sec	>3400 sec
Thrust/mass ratio	306 µN/kg	82 µN/kg	53 µN/kg	>380 µN/kg
Pulse to Pulse throttleability	Yes	No	No	Yes

Table 5. 3 Comparison of project with other Thrusters

Scope for future work

There are a number of principles in this field which are still not understood and not enough analysis has been carried out due to difficulty in understanding the mechanism. These areas are listed below:

- The mechanism of erosion of mass from electrodes .
- Generation of plasma plume from the electrodes.
- Magnitude and impact of magnetic field induced.
- Arc breakdown: the effect on formation of an initial arc due to the discharge gap has to be modelled in order.
- Modelling Lorentz force : it has been assumed that Lorentz force is originated as the current flows radially, this mechanism needs to be modelled in order to perfectly study the Lorentz force.

The field requires a necessary research work to be done as it can be seen that five decades of research has rendered not much potential to the Pulsed Plasma Thrusters.

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