Electrostatic ION Thruster for Spacecrafts

SEMINAR REPORT

Submitted in Partial Fulfillment of the Requirements of B. Tech Degree Course in Mechanical Engineering of University of Calicut during the year 2016 - 2017

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CERTIFICATE

This is to Certify that the Seminar Report on "**ELECTROSTATIC ION THRUSTER FOR SPACECRAFTS"**is the Bonafide Record of the Seminar Done By

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ABSTRACT

ION thrusters have proven to be a suitable and efficient alternative to conventional propulsion systems. With very low demand on fuel due to very high specific impulse generation, ion thrusters can easily compete with chemical propulsion systems, even if the produced thrust is much lower. The system can be used for various mission demands like orbit station keeping for geostationary satellites, orbit and attitude controlling and multi-goal missions. Whereas chemical propulsion is highly unsuitable for deep space missions, ion thrusters are also making it possible to reach out further into deep space. In-space and ground integration testinghas demonstrated that ion propulsion systems can be successfully integrated with their host spacecraft.This paper represents a short report on electric propulsion system, specifically on the Electrostatic Ion Thruster with its design and functions.

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CHAPTER 1

INTRODUCTION

Electrostatic Thruster is a kind of thruster which produces thrust on a spacecraft with the help of accelerating ions. It can offer major benefits for orbit transfermissions where fast delivery is not essential (such as in a launch on schedule environment). For example, if a solar powered, ion based Electric Orbit Transfer Vehicle (EOTV) is used to perform a near-Earth orbit transfer from low-Earth orbit (LEO), 4700 kg is needed in LEO including the Orbit Transfer Vehicle and Payload. This compares to the 17,200 kg needed if an Inertial Upper State (IUS) is used. The total mass of spacecraft with ion propulsion system is comparatively lower than a normal chemical fuelled propulsion system which will allow a reduction in launch vehicle class.The trade-off is a longer transfer time from Low earth orbit to the operational orbit. For certain missions, the potential savings accruing from the use of an EOTV can exceed over ₹700Cr per launch.

Gaseouspropellant atoms are introduced into a discharge chamber where they are bombarded by electrons emitted by a hollow cathode and collected by the anode. The ionization process is enhanced by the presence of a magnetic field. Someof the electron-atom collisions result in the creation of ions which drift toward the accelerating electrodes, which are biased negatively with respect to plasma potential. These electrodes focus and accelerate the ions which exit the thruster in a broad beam. The ion beam is then neutralized by a stream of electrons emitted from an external hollow cathode called a neutralizer. Recent studies indicate that electric propulsion system elements are technically ready to be integrated into propulsion systems and flight demonstrated to enhance user acceptability.Ion propulsion is being developed in many countries for many applications.

CHAPTER 2

WORKING PRINCIPLE

Electrostatic thrusters uses the same basic principle as chemical rocketswhich is basically accelerating mass and ejecting it from the vehicle producing thrust on the spacecraft. The propellant ionized in Ion thrusters is accelerated by the application of electric fields.Thrust is the generated by a rocket engine to its spacecraft. In ion thrusters, ions are produced by a plasma source and accelerated electrostatically by the field applied between two (or more) grids.

Electrostatic phenomenon arises inside the thruster from the forces that electric charges exert on each other which is described by Coulomb's law. The voltage applied between the two grids creates a vacuum electric field between the grids of the voltage divided by a gap.

The electric field between the grips is modified by the ions which is represented as an additional charge. The thrust is given by the time rate of change of the momentum due of the change of mass of the spacecraft because of constant consumption of fuel. The ejected mass from electric thrusters, however, is primarily in the form of electrostatically energized charged ions. This alters performance of the propulsion system and changes the conventional way of determining some of the thruster parameters, such as specific impulse and efficiency compared to other thruster types.

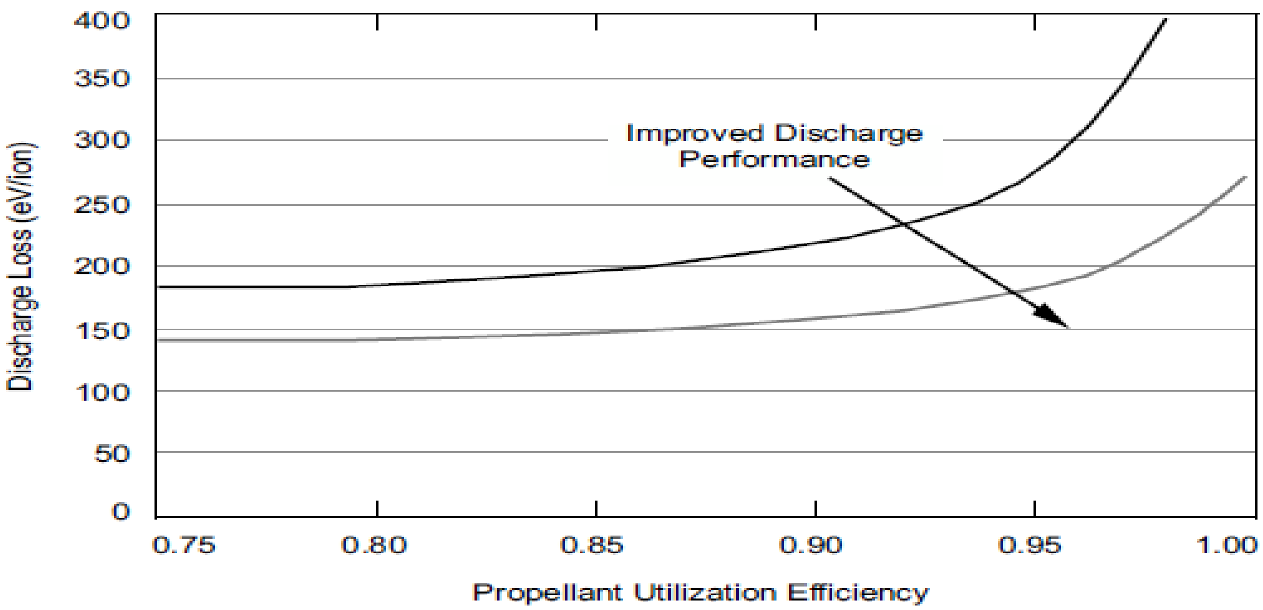

Fig. 2.1. ION Thruster Performance Curves

A discharge loss vs. propellant utilization efficiency curve shows the performance characteristics of a plasma generator. It is illustrated in Fig 2.1. The performance curvegoes flat if propellant efficiency is low because of the high neutral pressure inside the thruster. Increase in propellant efficiency decreases the neutral pressure inside the thruster and increases the electron temperature and the loss mechanisms in the thruster. Thrusters are carefully designed to reduce losses during discharge and to prevent loss when propellant efficiency is high.

Compared to gas jets or chemical rockets, Electric thrusters hasbetter exhaust velocities, which improves the rate of change of velocity available also known asΔv or delta-vand also increases the payload mass it can carry for a given delta-v. The exhaust velocity of electrostatic thrusters can reach 102 km/s for heavier propellants such as liquid xenon and 103 km/s for lighter propellants like helium, whereaschemical rockets has exhaust velocities of 3 to 4 km/s.

CHAPTER 3

LITERATURE REVIEW

3.1 HISTORY OF ELECTRIC PROPULSION

It is only in recent years that electric propulsion has been used in commercial, scientific and military missions. The first rocket which used an Electrostatic Ion thruster for propulsion was Deep Space I which was used to test various new technologies. It launched on 24 October 1998. During the late 2000, many manufacturers began preferring electric propulsion options on their satellites mostly for on-orbit attitude control while some communication satellite companiesstartedusing them for orbit insertion instead ofconventional rocket engines. Most of the electric propulsion systems have low thrust levels compared to chemical thrusters, in the order of some mN up to 1 N, but the overall performance level is greater than that of chemical propulsion systems by a factor of 10 – 20.

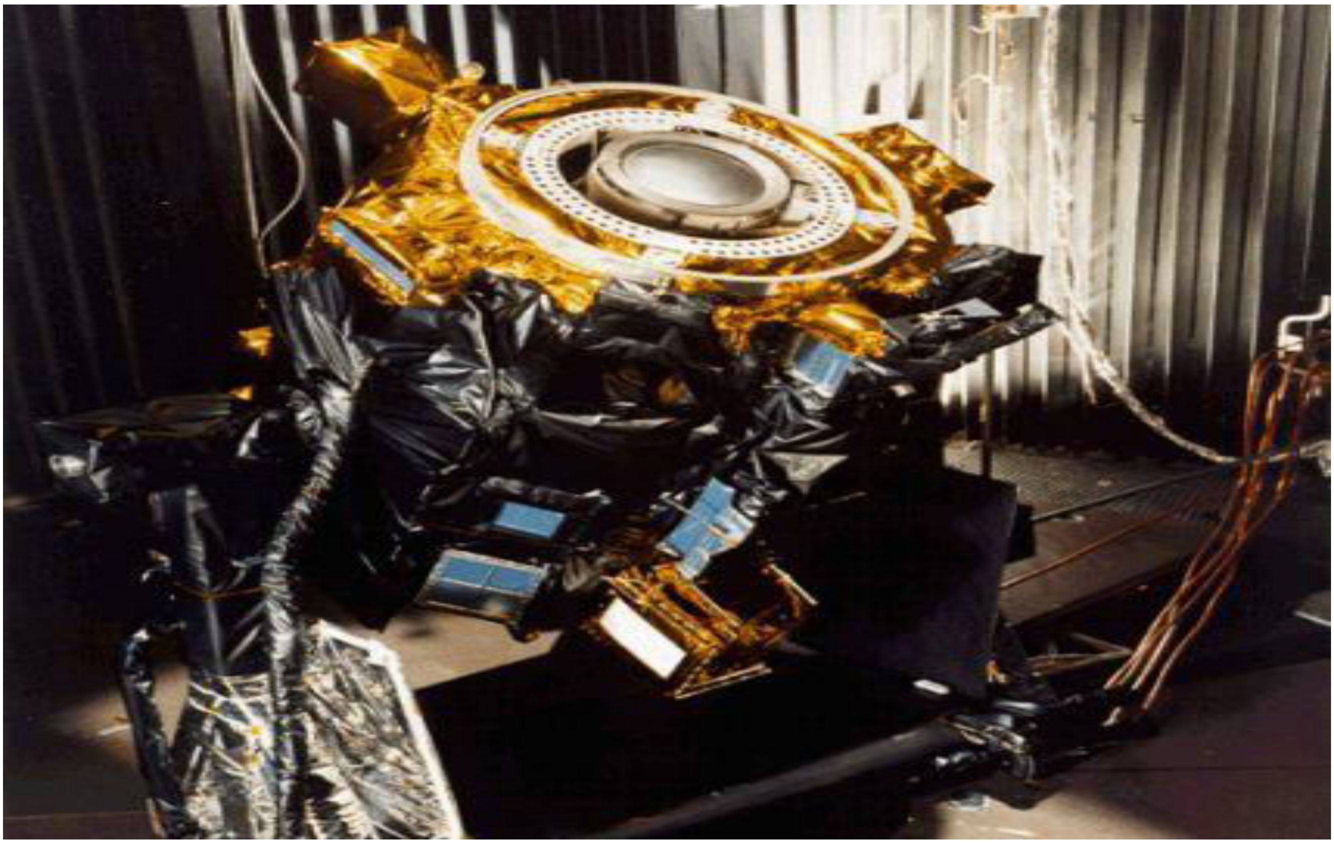

Fig 3.1: Deep Space I

The priitive modern ion thrusters were developed by Mitsubishi Electric Corporation (also called MELCO) for application on a Japanese satellite called Engineering Test Satellite or ETS-6 (1994)which was launched for station-keeping of geosynchronous satellites. The 13-cm Kaufman thrusters,which successfully operated in orbit even after the failure of launch vehicle to reach its planned orbit,produced 20 mN thrust at 2400s Isp. It was again used on the COMETS satellite by ESA in 1996 and a similar event of launch failure occurred. MELCO still continues the development of Kaufman ion thrustersfor communication satellites for station-keeping.

3.2 STUDIES BASED ON ION PROPULSION

Spacecraft types with high specific power level began using Ion thrusters:

This is a study done by Vladimir Grigorian and team from Moscow State Aviation Institute, Volokolamskoe sh. 4,Moscow, Russia in 1996.Many important space missions in the future can be performed using small spacecraft consisting ofthin solar panels and efficientand economicalIon thrusters, especially by h1-41.

Power conditioning requirements for ion thruster systems:

R. Bartlett from NASA performed studies based on power conditioning requirements for ion thrusters in 1970. He discovered that a diverse set of specifications and requirements must be met by the power conditioning unit for an electric propulsion system. To meet these requirements, a typical unit contains power conversion, internal control loops, command subsystem for ground control, and telemetry. A relatively small number of new circuit designs is necessary, depending on the versatility of the design, the number may be as small as two or three. Such circuits could be used in any similar command/register system. Present conventional bipolar or M O S technology is expected to be adequate.

CHAPTER 4

BASIC COMPONENTS

The three basic components of an Ion thruster are:

1. The plasma generator
2. The accelerator grids, and
3. The hollow cathode.

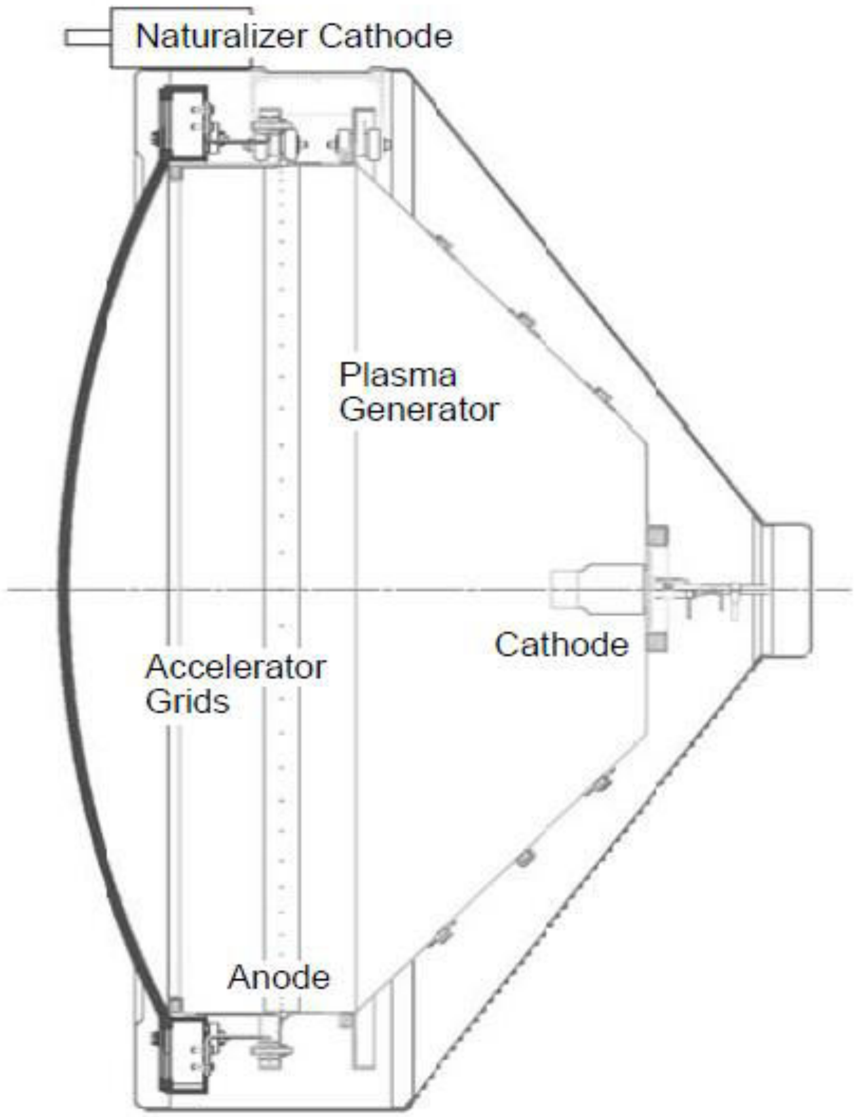

Fig 4.1: Ion Thruster Schematic

Figure shows a schematiccross section of an electronbombardment ion thruster which uses an electron gun which discharges electrons to generate plasma beams. An anode and a cathode is generally used for electron discharge, and are accelerated by grids to form an electron beam.

4.1 PLASMA GENERATOR:

The geometry of a classic DC electron discharge plasma generator is the prime example of an Ion thruster plasma generator. In this type of thruster plasma generator, an anode discharge chamber with a hollow cathode electron source is used to generate the plasma where ions are extracted by the grids for propulsion. A simple diagram of a DC electron bombardment thruster with the previously mentioned components with a multi-grid accelerator is shown in Fig.

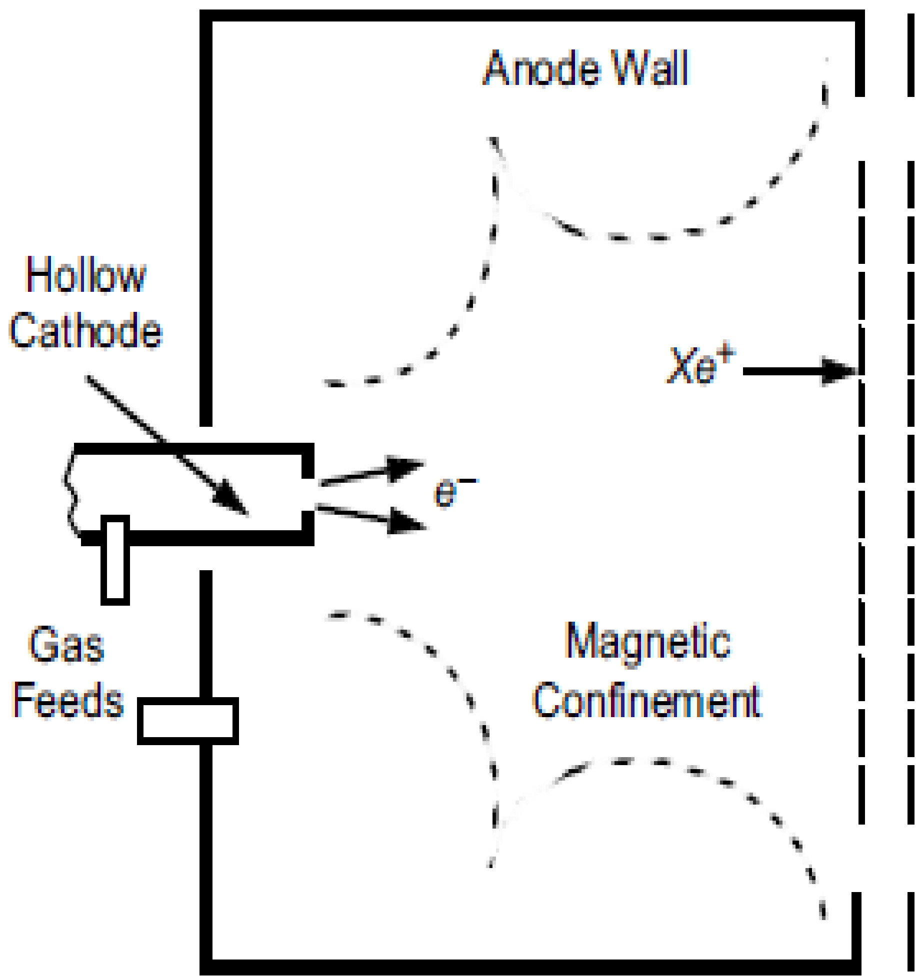

Fig 4.2. ION Thruster with the Cathode Heater And Power Supplies.

A small amount of neutral propellant gas is injected through the hollow cathode into the discharge chamber. To ionize the propellant gaselectrons are injected into the chamber which are extracted from the hollow cathode.

4.2 ACCELERATOR GRIDS:

The characterization of ion thrusters is done basedon the electrostatic acceleration of ions emerging from their respective plasma generator. A photograph of a large, 57-cm-diameter ion thruster fabricated by JPL, called NEXIS, is shown in Fig. This thruster is capable of operating at over 20 kW of power with an Isp exceeding 7000 s and a design lifetime of over 100,000 hours. The ion accelerator consists of electrically biased multi-aperture grids, and this assembly is often called the ion optics. The design of the grids is critical to the ion thruster operation and is a trade between performance, life, and size. Since ion thrusters need to operate for years in most applications, life is often a major design driver. However, performance and size are always important in order to satisfy the mission requirements for thrust and specific impulse (Isp) and to provide a thruster size and shape that fits onto the spacecraft.

Fig 4.3 : NEXIS Ion Thruster Showing

Multi-aperture grids

Grids of an ion thruster is designed by considering many factors. Theyshould be able to extract the ions from plasma beam in the chamber and focus them through the accelerator grid (accelerator grid) and decelerator grid (decelerator grid). The focusing has to be accomplished over the range of ion densities produced by the discharge chamber plasma profile that is in contact with the screen grid, and also over the throttle range of different power levels that the thruster must provide for the mission.

4.3HOLLOW CATHODE:

In Electrostatic ion thrusters,a cathode to used to emit the electrons that will be used later to ionize propellant gas in order to produce thrust force.It also ejects electrons for neutralizing the beam which is leaving the thruster. The performance and life of an Ion thruster is determined by the material, physical configuration and structure of the hollow cathode.

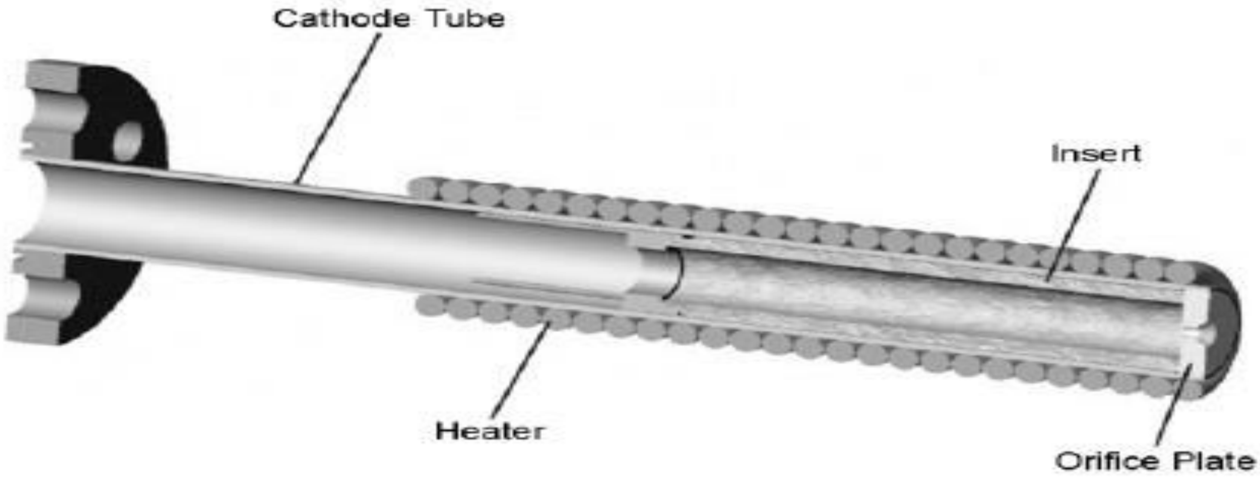

Fig 4.4. Typical Hollow Cathode Geometry

A hollow cathode with a refractory tube with an orifice plate in the end is shown in Fig. 4.4.Hollow tube has an insert gapwhich is shapedcylindrically is placed inside the tube which appears as if it is pushing against the downstream plate. Electron is actively emitted from the insert.Several different materials can be used that gives a low work-function-surface oninside diameter that is in contact with the cathode. Cathode tube isbasically covered with a heater (a co-axial sheathed heater is shown in the figure) for increasing the insert's temperature to the desired emissive temperatures to commence the discharge. A cathode plasma is produced by the electrons from the insert by ionizing the gas from the hollow cathode. From this, discharge-current are extracted through the orifice in the plate into the thruster plasma beam.

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CHAPTER 5

FUNCTIONING IN DETAIL

Long-living small satellites uses2-8mN thrusters having specific impulse more than 35,000 m/s and thrust cost no more than 30 kW/N. The requiredlife of such thrusters must be no less than 10,000 hours.Various types of electric thrusters have flown in space for arather long time. However, their power was ofthe order of 1 kW and above. Reduction of the single module power will worsen the thruster's performance,and therefore an important problem is development oflow power electric thrusters with high performance.

5.1 PROPELLENT TYPE:

Tests shows that for a given power level the thrust obtained using krypton gas was lower than that with xenon, by approximately the square root of the atomic mass ratio.

Thruster efficiencies comparable to those obtained with xenon are achievable, but at specific impulse values higher by the inverse of the square root of the atomic mass ratio. It was also found that the discharge voltage required to reach the xenon efficiencies was much higher with krypton than with xenon (40 vs 27 volts). This would severely limit screen grid lifetime of the thruster with krypton propellant, just as it did in the J-Series thruster. 23 It is expected that a thruster redesign will be required to obtain krypton ion thruster lifetimes of interest. Therefore Xenon gas is preferred for Electrostatic ion thrusters.

5.2 WORKING:

The working fluid used in Electrostatic thruster is Xenon gas. It is fed into the discharge chamber and its atoms are ionized by electron impact in gas discharge burning between the cathode and anode. To enhance the ionization efficiency, magnetic field created by magnetic systemis imposed onto the discharge. The gas is discharged through various apertures on the accelerator grids. This stream of ion jets is called an ion beam. Ion extraction from gas discharge and ion beams formation of low energy andcurrent density is done by means of a three electrode electrostatic system consisting of the emission electrodeaccelerating electrodeand output electrode. At the thruster's outlet there is placed a source of electrons –the neutralizer. The thruster's efficiency depends on how much power is required to produce one ampere of ioncurrent which gives the thrust. Reduction of the discharge chamber dimensions worsens the ionization conditions and results in increase of the relative surface area of ion recombination, therefore, when designing alow power ion thruster, it is very important to correctly choose the configuration and strength of magnetic field, and also improve conditions of ion extraction from the gas discharge plasma through the accelerating system electrodes atsimultaneous reduction of neutral flux from the GDC. These conditions are realized by means of the accelerating system design. The accelerated ionized gas produces thrust in the opposite direction of its flow.

Thrust vector control (TVC) is required to accommodate initial offsets of the thrust vector due to assembly tolerances and to accomplish required thrust vector changes during a mission. These latter changes could be a result of variation in the number and location of operating thrusters, in the location of the spacecraft centre of mass, or in attitude control requirements. TVC for ion thrusters has usually been accomplished with mechanical gimbals. The ATS-6 caesium thrusters employed accelerator grid displacement to achieve TVC by steering the ion beam lets from the screen grid holes through the accelerator grid. This technique produced + 3 degrees of motion in each orthogonal axis.

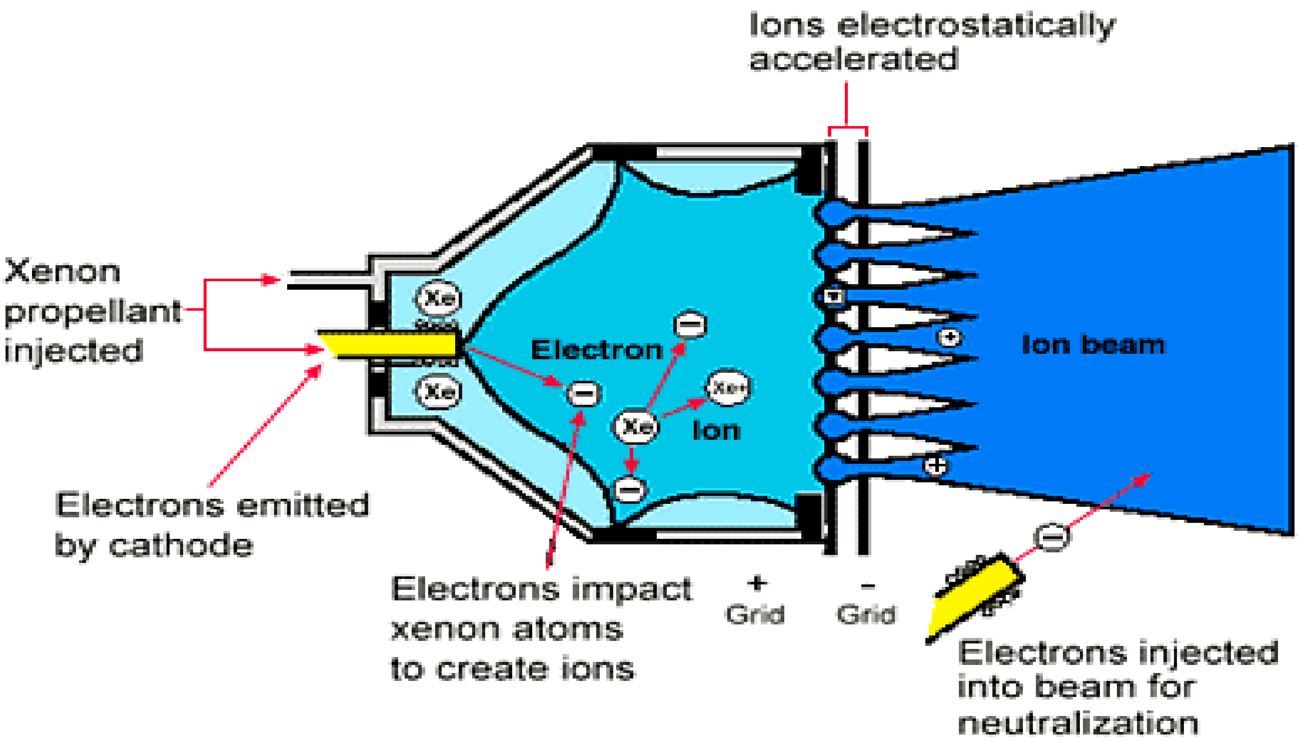

Fig 5.5: Layout of an Ion Thruster

The mass ejected to provide thrust to the spacecraft is the propellant, which is carried on-board the vehicle and expended during thrusting. From conservation of momentum, the ejected propellant mass times its velocity is equal to the spacecraft mass times its change in velocity. The "rocket equation" describing the relationship between the spacecraft velocity and the mass of the system is given below.

$$m_p = m_d\left[e^{\Delta v/(v_{ex})} - 1\right] = m_d\left[e^{\Delta v/(Isp^*g)} - 1\right].$$

Where md= delivered mass, Δv= change in velocity, Isp= specific impulse.

The relationship between the amount of propellant required to perform a givenmission and the propellant exhaust velocity (or the propulsion system Isp) shows that the propellant mass increases exponentially with the delta-v required. Thrusters that provide a large propellant exhaust velocity compared to the mission Δv will have a propellant mass that is only a small fraction of the initial spacecraft wet mass.

CHAPTER 6

MERITS OF ELECROSTATIC ION THRUSTERS

1. Fuel in ion thrusters lasts longer than conventional chemical thrusters. A nuclear pile can be used as the power source for an ion thruster (much less fuel to carry). It could also use a scoop/collector to harvest ions as the spacecraft move through space.
2. It is comparatively safer than a chemical fuelled thruster because it operates at lower temperatures and pressures. They are much easier to control. Toggling between on and off of power supply is easier where it is not, for a chemical thruster.
3. Chemical propulsion provides lots of acceleration, but relatively little exhaust velocity. In other words, it's not very efficient (requires lots of fuel to make small course corrections), but it'll get the spacecraft off the Earth. Ionic propulsion provides lots of exhaust velocity, but very little amounts of thrust. In other words, an ion thruster could let us explore everything in the Solar System sparing lots of time.
4. Ionic propulsion lets spacecraft reach their destination using very small amounts of fuel. This reduces risk, design complexity, and cuts down on cost.
5. It weighs less than a conventional rocket engine. So, a cheaper launch vehicle can be used reducing launch cost.

CHAPTER 7

APPLICATIONS

Electrostatic Ion thruster are mainly used for orbittransfers, adjusting attitudes, compensating for drag force exerted by earth's gravitational pull in low Earth orbits, fine adjustments during cargo transports in space stations and various other scientific missions.Ion thrusters are seen as the best solution for the following missions which only require high change in velocity and rapid acceleration isn't necessary.

Ion propulsion systems were first demonstrated in space by the NASA's Lewis test missions namely Space Electric Rocket Test (SERT)-I and-II. The SERT-I mission was a success and worked without any flaws. It was launched on July 20, 1964 and they used mercury and cesium as the fuel. SERT-II pulled off successfullyon February 3, 1970. The mission verified the operation of two mercury ion engines for thousands of running hours.For station-keeping of commercial and military communication satellites which are in geosynchronous orbits, Ion thruster are the appropriate one to be used. Stationary Plasma Thruster (SPT)was the first ion thruster that was used by the Soviet Union in early 1970s.

It is ideal for long term deep space mission like the one done by NASA with Deep Space I which used electric propulsion as the interplanetary propulsion system on a science mission. Based on the NASA design criteria, Hughes Research Labs, developed the Xenon Ion Propulsion System (XIPS) for performing station keeping on geosynchronous satellites.Future missions like BepiColombo uses ion thrusters in combination with swing-bys to get to Mercury, where a chemical rocket will complete orbit insertion.

CHAPTER 8

CONCLUSION

For more than 30 years, Space agencies like NASA, has conducted ion propulsion programs, mainly with Electrostatic ion thrusters, which has resulted in several experimental space flight demonstrations and the development of many supporting technologies. Technologies appropriate for geosynchronous station keeping, Earth orbit transfer missions, and interplanetary missions have been defined and evaluated. As a result of the ion propulsion program, unique and extensive in-house, industrial, and academic capabilities have been developed.Ion thrusters for primary propulsion have evolved over the past 30 years, and currently emphasis is on xenon and krypton fuelled ion thrusters which can operate from 5 to 10 kW. They are also the most efficient thrusters ever found by mankind.Ion propulsion system interactions with spacecraft have been extensively investigated so far by various space agencies all around the world and has found that they are perfect for missions which doesn't give importance to time. However, thruster is designed very carefully in order to avoid corrosion and degradation of the electrodes because of the everlasting contact with the highly accelerated ions.Countless number of tests in space and ground has proved that ion thrusters can be successfully integrated with their host spacecraft no matter how complicated it is. Ion propulsion system technologies are mature and can significantly enhance and enable a wide variety of space and planetary missions in the various space propulsion programs in the mere future.

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