Electrical Aspects of The Rocket Ion Propulsion System

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Abstract- A rocket is a machine that develops thrust by means of rapid expulsion of matter. The major components of a chemical rocket assembly are a rocket motor or engine, various types of propellants (the majority of which consist of fuel and an oxidizer i.e hypergolic liquid propellants), a frame to hold the components, control systems and a cargo such as a satellite. A rocket differs from other engines in that it carries its fuel and oxidizer internally, therefore it will burn in the vacuum of space as well as within the Earth's atmosphere. The cargo is commonly referred to as the payload. A rocket is called a launch vehicle when it is used to launch a satellite or other payload into space. At present, rockets are the only means capable of achieving the altitude and velocity necessary to put a payload into orbit. Therefore the most important part of the rocket remains the propulsion system. It is the propulsion system that generates the thrust which enables the rocket to achieve the velocity that can counter the earth's gravitational force and take the rocket into space and thus, it is the need of the hour to devote available resources to research about new ways to propel the rockets, increase efficiency and reduce operation costs etc. This paper considers basic functioning of rockets while focusing on ion propulsion systems. It presents calculations to the same effect and briefly delves into both potential power sources and choice of propellants.

Important Terms:

(a) Thrust- It is the force generated by the rocket propulsion system, measured in kilograms (S.I Unit). Thrust generated must be greater than the weight of the complete launch vehicle while standing on the launch pad in order to initiate launch. Once motion is achieved, thrust must continue to be generated to accelerate the launch vehicle against the force of the Earth's gravity and prevent the launch vehicle from falling back to the surface due to overpowering gravitational force.

(b) Mass ratio- It is defined as the total mass at liftoff divided by the mass remaining after all the propellant has been consumed. A high mass ratio means that more propellant is pushing reduced quantity of payload into orbit but results in higher velocity. A high mass ratio is necessary to achieve the high velocities needed to put a payload into orbit.

(c) Ion-Propulsion

(d) Current Density and Ion Current

(e) Nuclear Fission Power Generator

(f) Radioactive Thermal Generator

(g) Propellant

Rocket Structure and Basic Functioning-

The rockets being used primarily consist of two or three stages. The first stage, which is also called as booster stage lifts the rocket and provides propulsion till such time its propellant burns off completely. The quantity of propellant in the booster stage is such that it is capable of propelling the rocket to a predetermined altitude, after which its operation is accomplished. When the first stage runs out of propellant or has reached the desired altitude and velocity, its rocket engine separated. This ensures that the next stage does not have to propel redundant mass. Similarly the second stage falls off the rocket after burning out a particular quantity and reaching a desired altitude. Dropping away the redundant weight of stages whose propellant has been expended enables a less powerful engine to continue the acceleration, which means less propellant has to be carried, which in turn allows more payload to be placed into orbit.

Ion Propulsion System-

Many different type of rocket engines are being used by different countries however they primarily are variants of chemical propellants rocket engines. The other engines being proposed are ion propulsion rocket engines, photon rockets, magneto hydrodynamic drives and nuclear rockets. We are going to concentrate on the Ion propulsion system.

This system works by accelerating positive ions through an electrostatic field. Propellant is first ionized and then accelerated to the required velocities by use of electric fields. The exhaust consists of positively charged ions which result in a retarding force; therefore electrons are discharged to neutralize the thrust beam. This form of propulsion makes efficient use of both propellant and electric power and enables modern spacecraft to travel faster, further and cheaper than any other form of propulsion technology currently available

Ion Thruster Functioning-

The ion thruster is divided into two chambers, the ionization chamber and the acceleration chamber. In the ionization chamber the gas is stripped off its electron which gives rise to a charged particle. The Propellant (in the form of neutral gas molecules) enters the ionization chamber from the downstream end of the ion thruster. A cathode tube emits electrons into the chamber for the purpose of ionization of neutral gas molecules. To make sure that maximum numbers of molecules get ionized the electrons are moved in a spiral path with the help of a radial magnetic field generated by strong permanent magnets. In this way the probability of an electron hitting a gas molecule increases as its total path length increases. The positively charged ions then travel towards the relative negative potential of the accelerating chamber. In the acceleration chamber the charged particle is accelerated through an electric field. The acceleration chamber consists of two grids with very high potential drop across the length of a few millimeters (generally 1-2mm). As soon as the ions enter this chamber they are accelerated to very high speed and are ejected out of the chamber. The opposite reaction force that acts upon the acceleration grid due to the speeding up of ions is the thrust generated by the thruster. The positively charged ions leaving the thruster create an undesirable retarding field. This retarding field is overcome by neutralizing the positive ions by injecting electrons into the ion beam. The neutralization process gives the blue color to the exhaust beam.

Calculations-

- **Thrust-**

This form of propulsion system, like others, works by imparting momentum to the exhaust stream in one direction such that the spacecraft is propelled in the other direction. Thrust is equal to the rate of change of momentum of the propellant, or more appropriately, the ions, as ions constitute the major part of the exhaust.

$$T = \frac{dm_p}{dt} v_{ex} \approx m_i v_i \tag{1}$$

For finding out the exhaust velocity, we equate the work done in moving the ion through the net voltage to the kinetic energy gained by the ion.

$$qV_b = \frac{1}{2} M v_i^2 \tag{2}$$

Where M is the ion mass v_i is the ion velocity, q is the ion charge and v_b is the net voltage through which the ion is accelerated.

Here $$V_b = V_1 - V_2 \tag{3}$$

Where V_1 and V_2 are the potentials at the first and the second grid respectively.

Equation (2) on rearranging gives us

$$v_i = \sqrt{\frac{2qV_b}{M}} \tag{4}$$

- **Current Density and Ion Current-**

The electric field in the acceleration chamber remains constant when there are no ions present in it. However the

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electric field is altered as ions enter the chamber, and there is a limit to how many ions can be present at a given time, this limit is known as the space charge limit. This represents the maximum ion current that can flow. The ions partially shield the first grid and at the limit they completely shield the grid. If the ion current is increased any further, it will create a retarding field at the entrance of the acceleration chamber and prevent more ions from entering. This reduces the mass flow rate and therefore the thrust being produced. However this does not reduce the exhaust velocity as it only depends on the potential drop between the two grids.

The current density at the space charge limit is given by:

$$j = \frac{4\varepsilon_0}{9}\left(\frac{2q}{M}\right)^{1/2}\frac{v_b^{3/2}}{x^2} \quad (5)$$

Where **Ɛo = 8.85** 10^{-12} F/m is the vacuum permittivity

From equation 5 we see that current density can be increased by either increasing the potential drop or reducing the distance between the grids or both. But, both these parameters cannot be varied indefinitely. Therefore, to further increase mass flow rate,, the diameter of the thruster must be increased. To find out the ion current, (Ib), we can multiply the current density to the area of the thruster. This will represent the maximum ion current available for a given value of potential drop and grid separation.

$$I_b = j * A$$

Where A represents the area of the thruster

Results-

A typical ion propulsion system can be depicted as in the diagram given below :

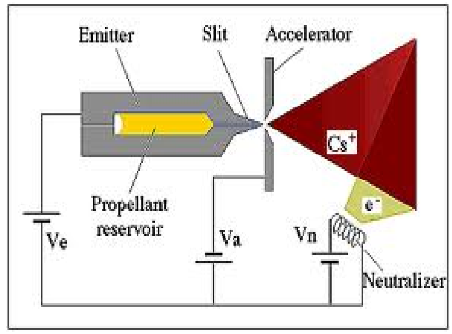
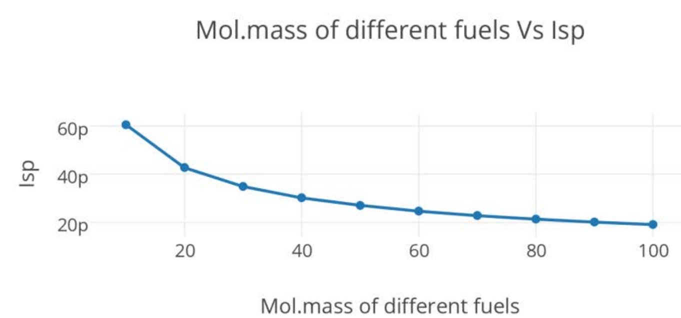


Fig. 1

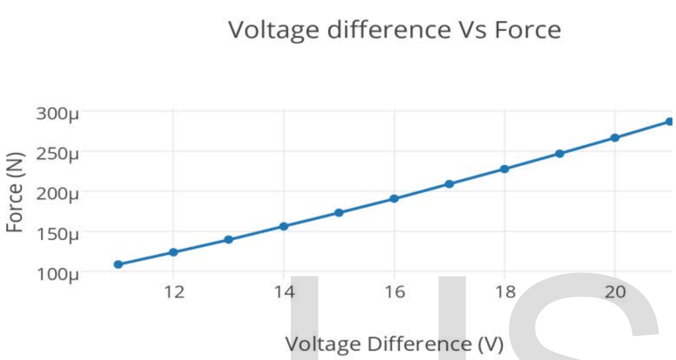
(Picture credits space.com)

Performance parameter	Value
Voltage 1	44 V
Voltage 2	55 V
Propellant	Hydrogen ions
Thruster Radius	0.14 m
Distance Between Grids	0.3 m
Mass of Propellant	8000 kg
Total Mass of the Rocket	10000 kg
Charged particle percentage	50%

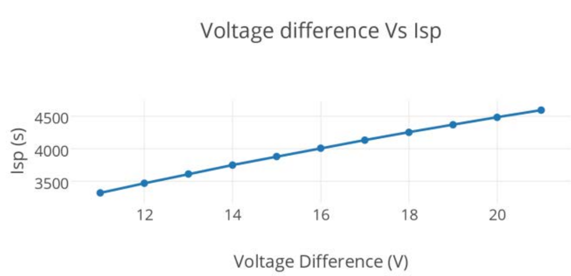
table 3-1: initial values taken for ion propulsion system analysis



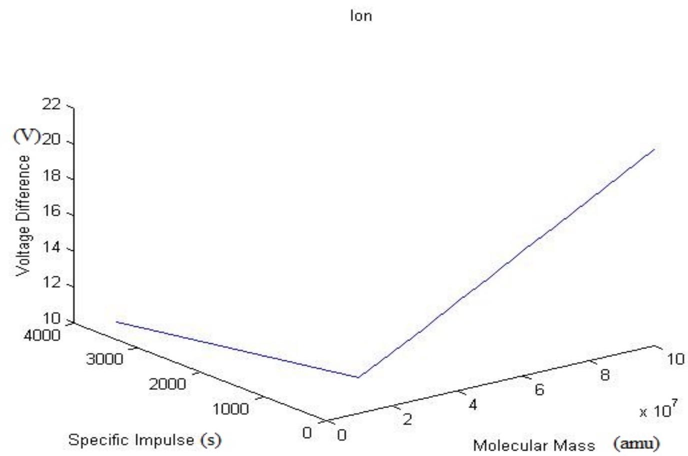
- The low molecular mass propellant like liquid Hydrogen have high tendency to flow and burns easily. This is not the case with the propellants with high molecular mass.
- Therefore as the propellant mass increases the specific impulse of the system decreases as shown in the result above.



- On increasing the voltage difference the beam current in the system increases which increases the production of ions in the system and thus the force (thrust) of the system increases.
- Controlling the Voltage difference is just like controlling the velocity of the rocket and could even be used in manoeuvring of the rocket.



- On increasing the voltage difference the beam current in the system increases which increases the production of ions, and number of ions thus ejected are increased which increases the reaction force on the rocket, thus giving more Specific Impulse.



- The voltage difference is an essential control that is there in an ion propulsion system and that could be used to control specific impulse and force of the system.

Propellant Choice-

In case of combustion engines, the fuel quality is measured by how much energy it releases per unit mass because the heat energy released is converted to desired work output. Similarly, in case of ion thrusters the electrical energy is converted to the desired work output i.e. accelerating the ions. Thus, the ability of a gaseous molecule to undergo acceleration by the electric field per unit mass (charge/unit mass) is of prime importance while choosing the propellant. The higher the charges to mass ratio, the more easily the ions get accelerated, and hence higher exhaust velocity. In equation 2.4, it is clearly stated that the exhaust velocity is directly proportional to the square root of the charge to mass ratio of the positively charged ions.

Therefore a hydrogen ion with the maximum charge to mass ratio (9.58 x 10 4 C g – 1) will be the most ideal propellant for an ion thruster. However, very high exhaust velocity is not always the single most important factor in consideration. Other factors also have to be considered and incorporated into the decision of choosing an appropriate propellant. For example, Deep space 1 probe had an exhaust velocity requirement of about 104-105 m/s. Hence a much heavier xenon ion was used. The reason why only xenon was used instead of other heavy metallic ion with similar or better performance was that, a huge amount of energy was consumed for just to evaporate them. Along with it, for the purpose of evaporation a boiler also has to be incorporated into the engine design. Xenon being a gas at engine operating temperatures relieves one of the extra efforts of evaporation.

So, an appropriate propellant for an ion thruster can be chosen by considering these factors:

(a) Charge to mass ratio as per the exhaust velocity requirements of the mission. In case of deep space propulsion, highest possible charge to mass ratio is preferred.

(b) The propellant should be in gaseous state under engine operating conditions.

Looking at the above two factors, Hydrogen is best suited for a deep space mission with highest c/m ratio as well as its gaseous nature. Also, hydrogen ions can be accelerated to a larger velocity when they are passed through a smaller potential drop as compared to heavier atoms like xenon. However, to produce an acceptable amount of thrust the beam current must be very high, as compared to present ion engines; this would require a large amount of power output from the source which is difficult to produce by conventional solar panels and thus a large power source like a small nuclear reactor would be required. A power source not dependent on the sun, or any other star, would be preferable for a deep space mission as the power available would reduce as the space craft moves further away from the light source.

Power Source-

In an ion thruster, power is consumed mainly in the ionization process and in developing the thrust beam. This power needs to be obtained from a reliable source with high energy to mass ratio. While in space the options for such a source of energy are extremely limited. Some options with their advantages and disadvantages that can be considered are –

- Solar Cells-

The solar cells have been used as a source of energy for nearly all the artificial satellites orbiting the earth. They have an efficiency of about 10-20%. Because of low power output the number of solar cells needed to produce the desired amount of energy supply is very high. For an artificial satellite with very low power requirements of about 10W the solar cell load is manageable. However, for an ion thruster the energy requirement is much higher. To obtain 30KW of power from a solar cell array, the mass of the solar array to be carried would be around 400kgs. Even with the use of very efficient gallium arsenide cells with solar concentrators, this mass can only be reduced to about 90kgs, which is still considerably high for long duration missions. These solar arrays are also prone to radiation damage from the energetic protons coming from the sun as wells as caught in the radiation belts around planets. Also with moving farther away from the sun the intensity of light decreases, resulting in degraded solar cell performance All these disadvantages make solar cells an undesirable power source for an ion thruster.

- **Solar generators-**

A solar generator is very similar to the regular solar electric generator used to produce electricity form solar energy. It consists of solar concentrators which concentrate the solar energy to the boiler containing the working fluid. This fluid gets heated up and moves an engine connected to an electric generator. These generators have a typical efficiency of about 30-40%, which is almost twice that of the solar cells. Another advantage over solar cell is that it is immune to any radiation damage and can perform in high radiation zones. The disadvantage with such system is that it consists of moving parts like coils, bearings etc which make it very open to mechanical failures. No matter how many precautions are taken, moving parts always have a tendency to malfunction. Like solar cells these, generators are also dependent on the solar illumination hence cannot be adopted for longer missions.

- **Radioactive thermal generators-**

Radioactive thermal generators carry a radioactive element instead of depending on an energy source outside to attain propulsion. The heat energy generated from the radioactive decay of the substance is converted to required energy supply by use of thermoelectric generators. The radioactive fuel generally used is Plutonium (Pu238). In this system, special attention is paid in the safety of the radioactive element plates. The element is placed between iridium capsules which can be deformed and stretched without any rupture. These iridium pallets are enclosed within graphite impact shells for protection against foreign impact. This shell is again covered with a graphite shield which can bear extreme temperatures during case of re-entry and launch accidents. The electricity is produced by the generators on the principle of Seebeck effect. The thermoelectric generator has hot as well as cold junctions. The hot junctions are connected to the heater units while the cold junction is connected to the heat radiators which dump the heat energy out in the space. The efficiency of energy conversion from heat to electricity is only 6%. To produce a kilowatt of energy, 175kg of plutonium is to be consumed which weighs much higher than the solar cell weight requirement. But, its advantage lies in the fact that it ensures power supply even deep in the solar system.

- **Nuclear fission power generators-**

With very low power to mass ratio, the radioactive thermal generator can never be suited for a ion thruster. Whereas nuclear fission can release energy as much as 70 times the radioactive decay. Another advantage of nuclear fission is that there is no limitation as of what rate the energy should be consumed while in case of plutonium the rate was fixed and uncontrollable. Uranium is available naturally whereas plutonium is a man-made substance which requires a lot of effort in the making. This makes uranium a lot cheaper than its counterpart. The fact that Uranium is non-poisonous and non-radioactive in its pure stable state makes it a much safer option. However, such reactors require large radiators which are necessary to dump the large amounts of heat produced in the reactions. These radiators are the biggest components of the device whereas the core constitutes a small volume. Such a generator is of extreme importance for deep space missions as it can provide the necessary amount of power for long durations

Conclusion-

Ion thrusters are the highest specific impulse engines man has been able to develop. These engines have general specific impulse of around 3000-5000. The huge variation of Isp can be explained with the variation of applied voltage drop along with either factors like gap between the accelerating grids and the mass of the propellant used. Each factor has its own role in controlling the final value of the specific impulse. Ion thrust engines are practical only in the vacuum of space and cannot take vehicles through the atmosphere because ion engines do not work in the presence of ions outside the engine. Within the earth's atmosphere the ion propulsion system is not efficient enough to generate a thrust for a lift off, therefore conventional chemical propellant rockets have to be used first to place the satellites in the orbit in space. The ion propulsion system can work effectively only in space and therefore once placed in orbit, it takes over and drives the spacecraft further into space. For space travel it is an ideal system that works between 65-80% efficiency.

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