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Design and Development of a Plasma Micro Thruster

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Abstract

Plasma Propulsion is a state of the art modern technique for Spacecraft Attitude Control as well as the primary source to propel Deep Space Missions. Under High Vacuum to mimic the Space Environment, experiment using High Voltage of around 0.5kV was applied in a glass tube to generate Plasma. The Plasma generated was subjected to Lorentz force using Permanent Ring Magnets to accelerate the ion bean to be ejected from the Nozzle at the end of the Plasma tube. The experiment is being tested with and without Electric field for best and most efficient results. The success of this experiment would be followed by a Prototype Design of the Thruster using the above described experiment incorporated in the working mechanism. Optimized and easier Plasma Generation Techniques such as Microwave Generation would also be tested at the finishing stages to give way for a better and efficient Plasma Micro Thruster research and development program in the future.

***Keywords:* Thrust; Plasma; Propulsiom; High voltage; Lorentz force**

Introduction

Propulsion deals with the aspects of energy conversion of a fuel to be turned into Kinetic Energy for motion of the body either through the Atmosphere or Space. From Engine design to its Physics, Chemistry and Mathematics to its Mechanical output from the Nozzle of the Engine, it is all included under the umbrella of Aerospace Propulsion [1].

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Classification of Propulsion is done on the basis of Propellant used by the Engine as well as the Medium where Thrust is required for motion. Aerospace Propulsion is mainly subdivided into Aircraft and Rocket/Spacecraft Propulsion. Aircraft Propulsion uses Piston, Rotary, Gas Turbine and Turbo Prop Engines where the Jet Fuel is primarily the propellant and combustion takes place to provide the driving force. Rocket Propulsion serves the purpose of in Atmosphere flights as well as Space Missions. Rocket Propulsion is the main system behind a Space Mission and a Rocket is used to serve that purpose. The scope of this study/thesis also falls under Rocket Elements and Design.

A. Rocket has six fundamental elements

1. Propellant: A substance which provides the thrust for momentum, it can be a liquid, solid or a gas
2. Propellant Storage: A chamber where propellant and stored before being entered into the combustion chamber
3. A feed system: It is used to transfer the propellant from storage to the combustion chamber
4. Energy Source: They consist of a chemical reaction, electrical and nuclear
5. Energy Conversion: The process of converting propellant into kinetic energy using the energy source
6. Accelerators: The propellant mass is taken to the desired thrust for momentum generator under this process [2]

These six elements are differed to achieve the many different forms of Rocket Propulsion in the modern age of research and development.

B. Rocket equation and specific impulse

Considering no external forces, the ideal rocket equation is

$$\Delta V = -V_e \, ln\left(\frac{m_f}{m_i}\right)$$

Where ΔV is the change in velocity, V_e is rocket relative exhaust velocity and m_i and m_f are vehicle initial and final masses respectively.

Another very important parameter which will continuously be discussed to determine the quality of Rocket Engines throughout this study is the Specific Impulse of the Engine. Specific Impulse is the amount of thrust produced or the change in momentum per unit mass of propellant used/burned for generating that thrust. It is the parameter used to determine the efficiency of the engine and varies accordingly with the technique of Propulsion used [3].

$$I_{SP} = \frac{F}{\dot{m}\, g_0}$$

C. Types of propulsion systems

Propulsion systems vary primarily because of the type of propellant used to generate thrust and the techniques vary respectively for accelerating the propellant inside the rocket for ejection and providing force

i. **Liquid propulsion:** As the name suggests, a liquid propulsion system uses liquid propellants to be combusted inside the chamber. They are high on density and less space is taken up by the fuel tank. The propellant is pumped into the combustion chamber using lightweight pumps or inert gas pressure technique. Liquid Propulsion systems can be further divided into monopropellant, bi propellant and tri propellant systems on the basis of number of propellants the system is using.

A wide number of combinations of propellants have been used for different missions, most commonly used are LOX, Liquid Hydrogen, Hydrazine, Nitrous Oxide etc.

The popular engine cycles of a liquid rocket are Gas generator, Expander cycle, Staged Combustion and Pressure fed with their respective advantages and disadvantages. It depends on the type and scope of the mission to implement the best engine cycle [4].

ii. **Solid propulsion:** They were first used in the early thirteenth century powered by gunpowder and has become a very widely used propulsion system in the modern era. Due to their ability to be stored for longer times, solid propellants are preferred in missions but give less performance as compared to the liquid propellants therefore they are mainly use for missions take to Lower Earth Orbit which are also smaller in mass. Solid propellants used are Gunpowder propellants, Zinc Sulfur Propellants, Double base and Composite propellants. The Intercontinental Ballistic Missile Jericho uses Solid Propellants and Orbital Missions Taurus, Atlas 5, Delta 2 etc use Solid Propulsion Engines [5].

iii. **Hybrid propulsion:** To attain higher Specific Impulse and ensure safety as well as a controllable design, Liquid and Solid Propellants are used in a combination in hybrid propulsion. The solid propellant in the combustion chamber reacts with the liquid propellant flowing from the fuel tank to generate thrust for rocket's change in momentum [6].

iv. **Nuclear propulsion:** It differs from Liquid in terms of the heating mechanism only. The liquid is pumped into the combustion chamber from the fuel tank just as in the Liquid Propellant Propulsion but here a Nuclear Fissions heats the propellant and an expanding gas forms which provides thrust to the rocket. Nuclear propulsion is not widely accepted due to its political and safety issues but can prove to be a very good Propulsion system due to its high performance [7].

D. Electric propulsion

Relatively a modern technology as compared to other forms of Rocket Propulsion. Electric Propulsion comes in with a lot of advantages especially to be used for faster and cheaper deep space missions. It gives a very high specific impulse as compared to any other propellant driven engine but gives very less thrust which is of the order of milli newtons. Electric Propulsion cannot be used for lift off missions due to the very low force it provides but is an efficient method for Satellite attitude control and has recently been used for Deep Space Missions [8].

Even with the low thrust, Electric Propulsion gives high exhaust velocities and in a Space environment with very less gravity affecting the spacecraft, the exhaust velocity builds up and with time the spacecraft can achieve speeds upto 90,000 mph making Space travel very fast and cheap as this type of Propulsion has a cheaper fuel system which lasts for a much longer time compared to the other forms. Electric Propulsion is also known as Plasma Propulsion and has various different types depending on the Plasma Source type and the type of mechanism to accelerate the plasma for exhaust acceleration.

Method	Effective Exhaust Velocity (km/s)	Thrust (N)	Specific Impulse (s)	Maximum Delta V (km/s)	Firing Duration
Liquid Propulsion	<~4.4	<~10^7	Upto 455	~9	minutes
Solid Propulsion	<~2.5	<~10^7	250	~7	minutes
Hybrid Propulsion	2.3-2.7	<~10^7	400	>3	minutes
Nuclear Propulsion	10^3	10^3-10^6	Upto 900	>~20	-
Electric Propulsion	15-200	10^-6-10^-3	3000 and above	>100	Months/years

Table 1. **Propulsion system characterstics.**

i. Plasma: The three commonly known states of matter are solid, liquid differentiated by particle arrangement, energy and distribution in space. Changes in temperature alter these arrangement and energies and phase change takes place. The higher the temperature, an element or compound shifts from a solid towards a gaseous state with the liquid phase in between. If a compound/element is superheated, the electrons in the outer shells strip off from the shells and ionization occurs. The positively charged ions and electrons collectively behave as a neutral gas but at the atomic level, the gas is ionized. This gas is Plasma and is known to be the fourth state of matter. Plasma is a very good conductor of electricity and is highly affected by electric and magnetic field due to its ionization. From Stars to Intergalactic Region, Plasma is an important constituent of the Observable Universe and it occurs naturally in the form of lightening, auroras, flames on Earth and has been developed in laboratories to be used as industrial etcher and to the greatest experiments for unlimited energy in Plasma Fusion Reactors. As an application of Plasma, the scope of this paper deals with plasma propulsion only.

Plasmas are produced and categorized by two ways, superheating a gas results in electrons being separated from the atoms and hot plasma is formed whereas using wavelength for specific removal/ionization of ions results in Plasmas at low temperatures known as cold plasmas. Plasmas are of different ionization levels.

Measurements and recordings in Plasma are done using numerous methods which include Invasive Probes, Active and Passive Spectroscopy, Optical effects from electrons and Neuron Diagnostics. Widely used instrument is the Langmuir Probe which falls under the Invasive Probe method.

A phenomenon in Plasma is Debye Length which is the shielding effect of electrons on ions creating a Debye Sphere around the ions given by,

$$\lambda_D = \left(\frac{\varepsilon_0 K T_e}{{n_e}^2}\right)^{\frac{1}{2}}$$

Where

D= Debye Length

ε_0 = Absolute Permittivity

K= Boltzman Constant

T_e= Electron Temperature

N_e= Electron Density

Plasma behaves as a fluid and has all the mathematical equations such as the Equation of Continuity and Fluid Drifts are applicable but consideration of the forces of electricity and magnetism is an added factor when dealing with Plasma.[9] Plasma resonates at a particular frequency known as the

Plasma Frequency in which the electrons move with a specific frequency which is so fast that the massive ions do not have sufficient time to move resulting in the movement of only the less massive electrons

For a charged fluid to be categorized as Plasma, three conditions need to be satisfied which are:

a. Debye Length should be very less than the characteristic length of the Plasma
b. Number density of charged particles is much greater than one
c. Wtau>1

ii. Electric thrusters: Having explained Plasma in detail, we come back to the main topic of Electric Propulsion. Electric Thrusters are divided into three categories and are further categorized upon two variables of Plasma Source used which is the type and method of producing Plasma and the type of method used to accelerate the Plasma generated in the chamber to produce thrust.

a. Electrothermal propulsion: It is closest to a Chemical Rocket system where Electrical Energy is used to heat the fuel and it expands. Further downstream the expanded fuel is accelerated out of chamber using a converging diverging nozzle to attain higher exhaust velocities and generate thrust. The two Electrothermal systems in use are the Resistojet and Arcjet.

b. Electromagnetic propulsion: Plasma is affected by Magnetic fields and this technique exploits this ability for acceleration of the fluid downstream. This electromagnetic force on the Plasma fluid is given by

$$F_m = jXB$$

Where,

Fm= Electromagnetic Force

j= Electric Current Density

B= Magnetic Field

This relationship uses the high school Physics Flemings Left Hand Rule where perpendicular electric and magnetic forces produce force and applying the same law here, the force produced accelerates the fluid downstream. Instead of a permanent magnet a solenoid can be used to provide the magnetic force for Plasma acceleration. Propellant is flown in the chamber where electric field application results in arc discharge Plasma and the magnetic field combined with the electric effect accelerates Plasma in the direction perpendicular to both the fields of electricity and magnetism.

c. Electrostatic propulsion: This type of Propulsion does not fall into the category of Plasma Propulsion but it falls in another category of Electric Propulsion known as Ion Propulsion. In electrostatic thrusters, a source is used to spray charges of similar type in a chamber which has gridded electrostatic field around it. This field accelerates the charges downstream to generate thrust. The ions exiting the thruster can cause charge accumulation but a neutralizer is used to spray electrons on the charges to stop accumulation from happening and an overall neutral fluid flowing away from the Space Mission/Satellite [10].

This paper discusses the design and development of Pakistan's first ever plasma thruster based on the theory of electromagnetic propulsion. Propulsion in Pakistan has always been thought of something related to solid and liquid propellants since the amount of thrust produced by plasma thrusters is not enough for lift off missions. This is the first step into the field of plasma propulsion where the research is limited to only generation of micro level thrust since it can always be optimized at a later time.

Methodology and design process

In the initial stages of the design process, authors had multiple options for the techniques of plasma generation and two options for plasma acceleration. In the first attempt of designing a plasma micro thruster, it was decided to use 13.6 MHz radio frequency for the generation of plasma. However, due to limited resources and costly setup of RF source matching network, this idea was immediately dropped.

After that, the team decided to go for 2.45 GHZ microwave frequency source for plasma generation. A magnetron from household microwave oven was decided to be used as the source of microwave frequency. The magnetron operates at 220V which is available in households. The step-up transformer attached to the magnetron steps up the voltage from 220V to 4000V at which magnetron operates. This idea was dropped after knowing that a waveguide is required between the magnetron and source gas to ionize the gas since the microwave frequency is of very low energy and it needs to be amplified to ionize the gas molecules. The procedure of procuring this wave guide could take up to 6 months which was not possible considering the time constraint for the project (**Fig. 1**).

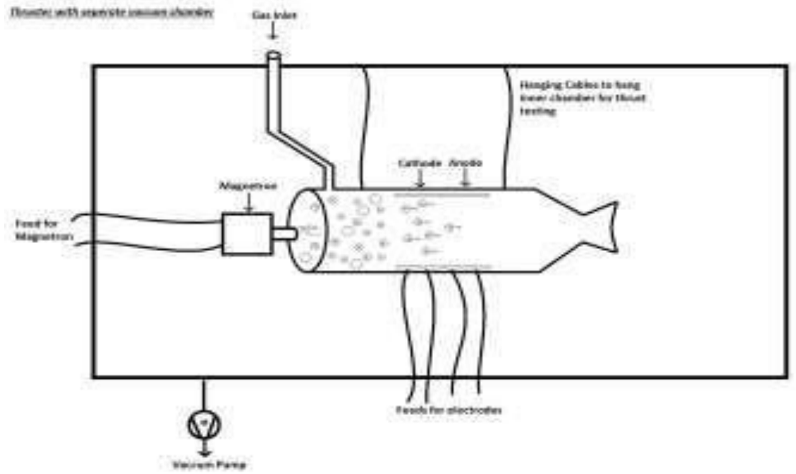

Fig. 1: **2.45GHz Microwave Plasma Thruster Setup**

Finally the most easy and suitable way of plasma generation was opted and that was to generate plasma using DC voltage source (**Fig. 2**).

A glass tube with two wires inside it was used to generate plasma. A voltage of 0V-415V was applied on one were and the other was grounded. The glass tube was place under high vacuum of up to 0.25 mbars to mimic conditions in space. After plasma generation, the tube was passed through ring magnets and the complete procedure was repeated again.

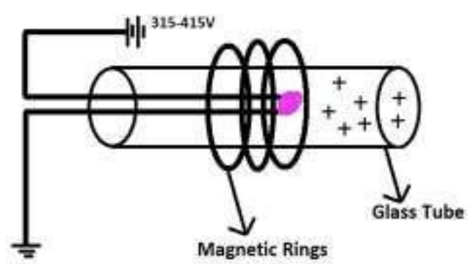

Fig. 2: **DC Discharge Plasma Thruster Setup**

Results and Conclusions

On application of high voltage to the wires in the glass tube, while moving from 0V to 315V, discharge was observed at 315 volts under high vacuum conditions. The glow increased as voltage was increased. Glow was stable up to 415 volts at 0.25 mbar pressure and dissipated to the chamber walls above that voltage, reason for which was unknown. However, after repeating the same process using magnetic rings around glass tube, it was observed that the discharge formed shape of a jet moving towards the nozzle of the tube. Since there is no system designed for the testing of thrust this small, an aluminum foil was placed at the end of the nozzle which was influenced by the bombardment of high energy ions and this was the evidence that some amount of thrust is present.

Future Modifications

This study can be modified and the thruster design can be optimized using different plasma generation and acceleration techniques. However, the system for testing thrust this small is being designed by the students of Institute of Space Technology that will be able to measure thrusts as low as 5N and can then be further optimized to measure thrusts of the level of milli newton.

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