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Hall Thruster: An Electric Propulsion through Plasmas

Sukhmander Singh

Abstract

The chapter discussed the technological application of plasma physics in space science. The plasma technology is using laser-plasma fusion, inertial fusion, Terahertz wave generation and welding of metals. In this chapter, the application of plasma physics in the field of electric propulsion and types has been discussed. These devices have much higher exhaust velocities, longer life time, high thrust density than chemical propulsion devices and useful for space missions with regard to the spacecraft station keeping, rephrasing and orbit topping applications. The mathematical relation has been derived to obtain the performance parameters of the propulsion devices.

Keywords: electric propulsion, Hall thruster, impulse, exhaust velocity

1. Overview of propulsion devices and rocket equation

Electric propulsion (EP) devices use electric power to produce thrust. These devices have much higher exhaust velocities than chemical propulsion devices. Therefore, EP devices require much less propellant mass than chemical systems for a given space task. Here first we have overview of different thrusters and their basic mechanism based on type of propellant used to get the thrust.

The motion of any propulsion devices is given by Newton's 3rd Law of action and equal, opposite reaction which forms the basis for the motivation for the study of electric propulsion. The rocket equation states that a device can accelerate to a desired final velocity by reaction against an expelled propellant stream [1].

Consider a rocket of mass m, which expels an infinitely small unit of fuel dm at an exhaust velocity $\vec{U}_{ex}$. The exhaust velocity $\vec{U}_{ex}$ is almost constant and it is a fixed property of the propellant [2]. Conservation of linear momentum requires that the spacecraft experience a small change in velocity $d\vec{v}$, such that

$$m\frac{d\vec{v}}{dt} + \vec{U}_{ex}\frac{dm}{dt} = 0 \tag{1}$$

Integrating by setting appropriate limits in mass and velocity yields

$$\int_{v_i}^{v_f}\frac{d\vec{v}}{\vec{U}_{ex}} + \vec{U}_{ex}\int_{m_i}^{m_f}\frac{dm}{m} = 0 \tag{2}$$

After simplification, we get

$$\ln\left(\frac{m_f}{m_i}\right) = -\frac{v_f - v_i}{\vec{U}_{ex}} = -\frac{\Delta\vec{v}}{\vec{U}_{ex}} \tag{3}$$

The above rocket equation provides the relationship between the mission velocity and the mass of propellant $m_p = m_i - m_f$ required for a given mission. It is clear that a higher $d\vec{v}$ demands more propellant. Unfortunately, the mass ratio cannot be increased so much to avoid payloads problems in space mission, therefore for a given mass fraction, the exhaust velocity $\vec{U}_{ex}$ of the propellant needs to be the order of $d\vec{v}$ and the higher the propellant exit velocity, the less propellant mass is required.

2. Thrust, impulse and efficiency

The performance of thrusters is usually characterized by a number of parameters. A first quantity relevant to thruster performance is the thrust T, which is the total force undergone by the rocket. The specific impulse is used to compare the efficiencies of different type of propulsion systems [2]. The performance parameter is the specific impulse I_{sp}, defined below

$$I_{sp} = \frac{T}{\dot{m}_p g} \tag{4}$$

Here $\dot{m}_p$ is the mass flow rate and g is the acceleration due to gravity. The specific impulse has the dimension of time and is a measure for the effective lifetime of the thruster, when lifting its own propellant from the earth's surface.

For the case of a constant mass flow rate the thrust is also constant as

$$T = \dot{m}_p \vec{U}_{ex}, \tag{5}$$

and the specific impulse simplifies to

$$I_{sp} = \frac{\vec{U}_{ex}}{g} \tag{6}$$

Finally, the rocket equation turned into

$$\frac{m_f}{m_i} = e^{\frac{-\Delta\vec{v}}{gI_{sp}}} \tag{7}$$

The rocket equation is equally applicable to all type of propulsion systems. Therefore high specific impulse related to better efficiency for a propellant. Based on the acceleration of gases for propulsion, electrical thrusters have been classified into three main categories.

2.1 Electrothermal thrusters

In electrothermal thrusters, the hot gas is expanded through a nozzle without ionizing it. When it is being passed through a thin nozzle, the thermal energy of gas gets converted into kinetic energy and produce a thrust.

2.2 Electromagnetic thrusters

In electromagnetic thrusters an inert gas is used as a propellant and it is ionized by heating to produce plasma. Then these ionized gas (charged particles) are acceleration by electromagnetic force to generate thrust.

2.3 Electrostatic thrusters

In electrostatic thrusters only ions are accelerated by applying direct electric field at the exit side of the thruster to produce thrust.

3. Hall thruster operation

Hall effect thrusters (HETs) were originally developed in United States and Russia about 60 years ago, and the first working devices were reported in U.S. in the early 1960s. Now a days, most of the countries using the Hall thruster technology in their space mission. Unlike chemicals and electric rockets, the propulsive thrust in a Hall thruster is achieved by an ionized inert gas (Xenon) which has high atomic number and low ionization potential. For this Xenon is mostly used. In a Hall thruster, the propellant is ionized and then accelerated by electrostatic forces.

Figure 1 shows the internal parts of a plasma Hall thruster. Generally, the discharge channel is cylindrical shape made up with metallic material. The magnetic field of the order of 150 Gauss is applied to produce closed drift of electrons inside the channel. The applied magnetic field which is strong enough so that the electrons get magnetized, i.e. they are able to gyrate within the discharge channel, but the ions remain unaffected due to their Larmor radius much larger than the dimension of the thruster. Thus the electrons remain effectively trapped in azimuthally $\vec{E} \times \vec{B}$ drifts around the annular channel and slowly diffuse towards the anode. This azimuthal drift current of the electrons is referred to as the Hall current. The propellant enters from the left side of the channel via anode and gets ionized through hollow cathode of the device. The electric field of strength $\sim$1000 V/m gets
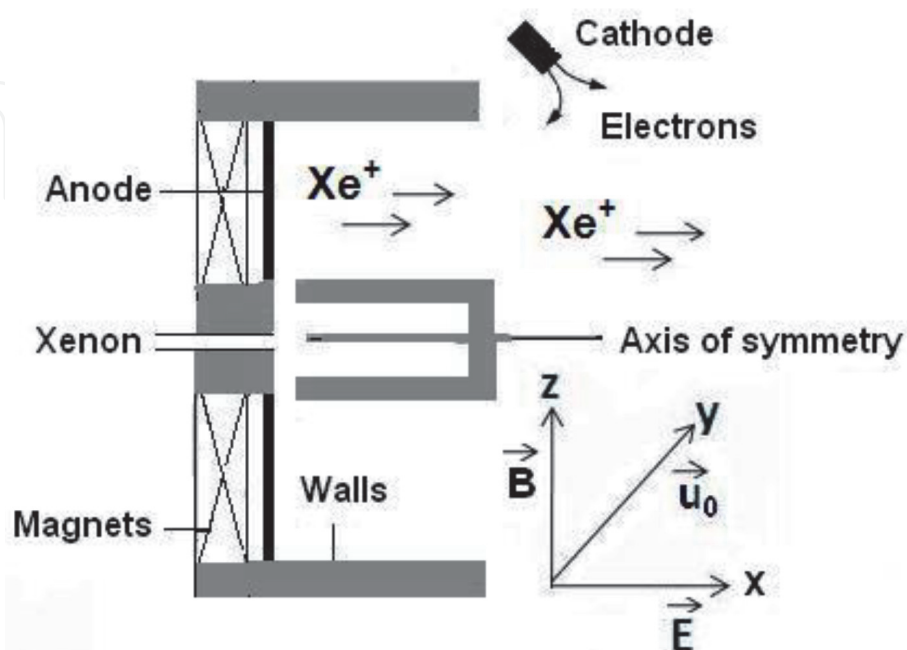

Figure 1.
Schematic diagram of a typical Hall plasma thruster.

generated inside the discharge channel along the axial direction of the device [3]. In addition, these kind of devices have implication in partially ionized plasmas (tokamaks), in ionosphere (base of the solar photosphere), in protoplanetary discs, circum nuclear discs in active galactic nuclei and neutron stars. Hall thruster has high thrust resolution, it is being used for the adjustment of the location of the satellite onboard.

4. Spacecraft issues

The first issue is that the divergence angle of these devices is about 60°, which relatively large and cause problem related to erosion of the channel walls and outer surfaces of the thruster. The erosion of the walls decreases the lifetime of the device. This channel usually has a length of the order of centimeters. In addition, densities in the channel are typically in the range between 10^{17} and 10^{18} m^{-3} for the plasma, and 10^{18} and 10^{20} m^{-3} for the neutral gas [4]. The plasma in a Hall thruster does not stay uniform and an inhomogeneous plasma immersed in the external electric and magnetic fields is not in the thermodynamically equilibrium state, this deviation in general is a source of plasma instabilities. The amplitudes of the waves and instabilities are attributed by the density scale lengths of plasma and magnetic field and other parameters. These waves/oscillation and instabilities may affect the efficiency of the device, hence forth research on studies on oscillation/instabilities always attracted the investigators.

5. Types of Hall plasma thruster

Two types of Hall thrusters have been developed: a thruster with closed electron drift and extended acceleration zone or stationary plasma thruster and a thruster with a very short acceleration channel or thruster with anode layer.

In **Table 1**, typical values of some of the pertinent properties are listed at the thruster exit for the SPT-100.

5.1 Dielectric wall thruster or stationary plasma thruster

Such thrusters have a wall made up of dielectric of boron nitride or silicon carbide and extended channel compared to its width. The role of the wall is that the collisions of the electrons and ions with the wall generate low energy secondary electrons. These secondary electrons keep tending the electron temperature low in the discharge plasma. By reducing the discharge electron energy, a smooth and continuous variation in plasma potential between the anode and the cathode is

Property	Value	Property	Value
Inner diameter	60 mm	Neutral velocity	~300 m/s
Outer diameter	100 mm	Electron temperature	5–10 eV
Plasma density	$\sim10^{17}$/m^3	Ion temperature	1–5 eV
Neutral density	$\sim10^{18}$/m^3	Neutral temperature	0.9 eV
Ion velocity	$\sim10^4$ m/s	Debye length	$\sim10^{-5}$ m
Collision mean free	~1 m		

Table 1.
Typical plasma parameters for Hall Thrusters.

obtained. Since the dielectric walls are not conductive, charge builds up along the length of the acceleration channel that leads to a variable potential profile along its length.

5.2 Thruster with anode layer

Thruster with anode layer also developed in Russia has a narrow acceleration zone associated with the narrow electric field region near the anode. This geometry considerably shortens the electric field region in the channel, where the ion acceleration occurs. However, this configuration does not change the basic ion generation or acceleration method. The channel wall made up of conductor, which is usually also a part of the magnetic circuit, is biased negatively (usually cathode potential) to repel electrons in the ionization region and to reduce electron-power losses. This reduces the loss caused by the ion and electron collisions with the walls. Since the walls are conductive, a constant potential (same as that of the cathode) is observed along the entire wall. Very high electron temperatures, i.e. more than 50 eV, are typically observed in such thrusters [1].

6. Review of status of current research and development in the subject

The range of the oscillations lies from few kHz to MHz in the acceleration channel of the thrusters and has been given in **Table 2**. Rayleigh-Taylor (RT) instability takes place when a lighter fluid supports a heavy fluid. The plasma in the Hall thruster possesses Rayleigh-Taylor instability, resistive instability, transit time instability, electromagnetic instability and sheath instabilities [5–11]. These systems are rampant with plasma instabilities and fluctuations, many of which are responsible for performance, driving electron transport across magnetic field lines and contributing to propellant ionization. Over the last decade several studies have been carried out with HET to characterize the low frequency azimuthal and axial oscillations and optimizing magnetic field profile for a wide range of operating conditions for better efficiency and performance. Singh and Malik [10, 11], investigated that temperature of the ion and drift velocity profiles of the electron modifies the conditions for Rayleigh type instability under the effects of thermal motions of ions.

The plasma resistivity induces resistive instabilities (electrostatic and electromagnetic) [6–9] associated with azimuthal and axial directions. High-frequency (1–10 MHz) instabilities have been studied in the Hall-effect thruster [6–9], where it was found that these instabilities have the highest level near the thruster exit plane. These oscillations in the Hall thruster determine the efficiency of the system and may affect the divergence of the ion beam and electron transport across the

Range (kHz)	Type	Driving mechanism
10–20	Loop or circuit oscillations	Magnetic field, discharge voltage and electron wall collision frequency
5–25	Rotating spokes	Ionization process
20–60	Azimuthal modes or drift instability	Gradient of density and magnetic field
70–500	Transient time oscillations	Plasma density gradient and low ionization
0.5–5 MHz	Azimuthal waves	Drift velocity of plasma species

Table 2.
Range and classification of oscillations in a Hall Thrusters.

magnetic field. Smolyakov et al. reported that sheath instabilities has a vital role in anomalous transport phenomena in Hall plasma thruster [12, 13].

7. Ion stream speed study for electrostatic thruster

Let us consider a Hall thruster having potential difference between anode and virtual cathode is Φ Volt and ions density (mass) n (M). The mass flow of propellant of ions of mass M through an area A is given by $\dot{m}_p = nMA\vec{U}_{ex}$.

The thrust is also constant as

$$T = \dot{m}_p \vec{U}_{ex}, \tag{8}$$

Substituting the value of mass flow rate, the thrust per unit area

$$\frac{T}{A} = \left(nM\vec{U}_{ex}\right)\vec{U}_{ex} = \frac{J_i}{q}M\vec{U}_{ex} \tag{9}$$

where J_i the current density of ions.

From the definition of work energy theorem, that the kinetic energy of each ion should equal to the work done in moving the charge across a potential drop. That is

$$\frac{1}{2}M\vec{U}^2_{ex} = q\Phi \tag{10}$$

Or

$$\vec{U}_{ex} = I_{sp}g = \sqrt{\frac{2q\Phi}{M}} \tag{11}$$

Thus the specific impulse or exhaust velocity of the ions depends on the potential drop developed across the anode and cathode and to the mass of the ion.

8. Conclusions

The $\vec{E} \times \vec{B}$ configurations of fields are used to confine electrons, increasing the electron residence time and allowing ionization and plasma sustainment. The magnetron sputtering used in material science for ion implantation is also based on the same $\vec{E} \times \vec{B}$ drift. The primary concern of the study to enhance the lifetime and performance of the Hall thruster by studying the instabilities that takes place in the channel and optimization of profile of the magnetic field which is the main parameter in respect to the erosion of the channel walls.

Acknowledgements

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