Chapter

Introduction to Plasma Based Propulsion System: Hall Thrusters

Sukhmander Singh, Sanjeev Kumar, Shravan Kumar Meena and Sujit Kumar Saini

Abstract

Technically, there are two types of propulsion systems namely chemical and electric depending on the sources of the fuel. Electrostatic thrusters are used for launching small satellites in low earth orbit which are capable to provide thrust for long time intervals. These thrusters consume less fuel compared to chemical propulsion systems. Therefore for the cost reduction interests, space scientists are interested to develop thrusters based on electric propulsion technology. This chapter is intended to serve as a general overview of the technology of electric propulsion (EP) and its applications. Plasma based electric propulsion technology used for space missions with regard to the spacecraft station keeping, rephrasing and orbit topping applications. Typical thrusters have a lifespan of 10,000 h and produce thrust of 0.1–1 N. These devices have $\vec{E} \times \vec{B}$ configurations which is used to confine electrons, increasing the electron residence time and allowing more ionization in the channel. Almost 2500 satellites have been launched into orbit till 2020. For example, the ESA SMART-1 mission (Small Mission for Advanced Research in Technology) used a Hall thruster to escape Earth orbit and reach the moon with a small satellite that weighed 367 kg. These satellites carrying small Hall thrusters for orbital corrections in space as thrust is needed to compensate for various ambient forces including atmospheric drag and radiation pressure. The chapter outlines the electric propulsion thruster systems and technologies and their shortcomings. Moreover, the current status of potential research to improve the electric propulsion systems for small satellite has been discussed.

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

1. Introduction

When a satellite is placed on a geosynchronous orbit, the attractions of both the Moon and the Sun disrupt the orbit that must be adjusted. Thrusters are used for space missions with regard to the spacecraft station keeping, rephrasing and orbit topping applications. 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. Let us denote $\dot{m}_p$ is the mass flow rate, the exhaust velocity $\vec{U}_{ex}$ and g is the acceleration due to gravity. The performance of thrusters is usually determined by thrust T, which is the total force undergone by the rocket. Thrust also has same unit as a force in newton, which shows the movement of the propulsion system. Thrust, is generated by the burning of fuel or electrostatic forces. The thrust $T = \dot{m}_p \vec{U}_{ex}$, if the mass flow rate is constant. The specific impulse $I_{sp}$is used to compare the efficiencies of different type of propulsion systems [1]. The specific impulse is expressed as $I_{sp} = \frac{T}{\dot{m}_p g}$. In general, the higher the specific impulse the less fuel that is required. Therefore the specific impulse simplifies to $I_{sp} = \frac{\vec{U}_{ex}}{g}$. The specific impulse has the dimension of time and is a measure for the effective lifetime of the thruster. The high value of the specific impulse reduces the mission time.

2. The Tsiolkovsky's equation

The rocket equation is used in propulsion systems to find out the different parameters. Therefore high specific impulse related to better efficiency for a propellant. If we denote $\Delta\vec{v} = \vec{v}_f - \vec{v}_i$ as the change of velocity of the rocket, then, the rocket's equation was derived by scientist Tsiolkovsky (1857–1935) and given as

$$\frac{m_f}{m_i} = e^{\frac{-\Delta\vec{v}}{gI_{sp}}} \tag{1}$$

Here $m_f$is the final mass and m_i is the initial mass of the rocket respectively. Taking natural logarithm on both sides, we get

$$\Delta\vec{v} = gI_{sp} \ln\left(\frac{m_i}{m_f}\right) \tag{2}$$

With this relation, the change in velocity of the rocket can be found out in terms of specific impulse or force. This equation is called Tsiolkovsky's equation. In term of exhaust velocity it turns out to be

$$\Delta\vec{v} = \vec{U}_{ex} \ln\left(\frac{m_f + m_p}{m_f}\right) \tag{3}$$

Here, the mass of propellant $m_p = m_i - m_f$ and m_f is the dry mass of the rocket. It can be seen from Eq. (3) that the higher $d\vec{v}$ requires more propellant. Therefore to achieve higher $d\vec{v}$, the exhaust velocity $\vec{U}_{ex}$ of the propellant needs to be of the order of $d\vec{v}$. To achieve higher $\Delta\vec{v}$, the electric propulsion play a key role in the current time. Various space mission including GEO communication satellite requires a ΔV of approximately 0.6 km/s for a 10-year period.

2.1 Relation between thrust efficiency and input power

If we denote the Thrust efficiency η and the input power P_t then these are related by

$$T = \frac{2\eta P_t}{I_{sp} g} \tag{4}$$

3. Main classes of electric thrusters

Many types of plasma thrusters have been developed over the last 70 years. Mitsubishi electric corporation developed Kaufman ion thrusters for the Japanese

Names of Thrusters	Typical uses	Working mechanism	Electric power (kW)	Specific impulse I_{sp} (s)	T (N)
Hydrazine	Flight space vehicles	Electrothermal: the electric energy is used to heat the propellant that is expanded through a nozzle [3].	0.3 to 2	500 to 600	10^{-3} to 0.2
Hydrogen	For ground testing work		1 to 100	900 to2000	0.1 to 5
Hall effect thrusters	Flight space vehicles	Electrostatic thruster: the electric energy is used to accelerate propellant ions [3].	0.5 to 5	500 to 3000	10^{-2} to 0.4
Gridded ion engines	Flight space vehicles		0.3 to 5	1000 to 4000	10^{-3} to 0.2
Pulsed Plasma Thruster	Attitude control for small sattelites	to form a plasma and expel it out of the nozzle under a magnetic field [3].	.070	80	860 μN
Lithium	For ground testing facilities	Electromagnetic thruster: electromagnetic systems ionize and accelerate the propellant under the combined action of magnetic and electric fields [3].	200 to 1000	2000 to 5000	2 to 15
Hydrogen	For ground testing facilities		1000	5000	15
Variable Specific Impulse Magnetoplasma	Under development	It ionizes the propellant with radio waves to form a plasma, then accelerate it under a magnetic field [3].			

Table 1.
Classification of some electric thrusters.

engineering test satellite in 1994, which had produced 20 mN of thrust (specific impulse of about 2400 s) [2, 3]. Another ion thruster (for commercial station keeping Applications) called Hughes- 13-cm Xenon Ion Propulsion System was launched into orbit in 1997 on the Hughes PAS-5 satellite [4]. The Hughes thrusters produced 18 mN of thrust at specific impulse of 2500 s (efficiency of about 50%).

Based on the acceleration of gases for propulsion, electrical thrusters have been classified into three main categories namely electro thermal, electrostatic and electromagnetic thrusters. In chemical thruster, the exhaust velocity depends to thermal heating, which cannot reach very high magnitude. In a chemical thruster, the propellant is burned and the hot gas is expelled from the thruster with the help of a nozzle but in plasma thrusters the plasma expels without an explosion taking place [2, 3, 5–18]. The performances of different types of electric thrusters have been discussed in **Table 1**.

4. Electrostatic Hall thrusters

In Electrostatic thrusters only ions are accelerated by applying direct electric field at the exit side of the thruster to produce thrust. Hall thrusters were originally invented in United States and Russia 70 years ago. After that they have been widely researched in Europe, Japan, and the China. Hall thrusters have emerged as an integral part of propulsion technology. Unlike chemicals and electric rockets (solid rocket motors, liquid rocket engines and hypergolic engines), the propulsion thrust in a Hall thruster is achieved by a propellant (usually Xenon). Typical chemical thruster specific impulses range around 200–500 sec, though electric thrusters can have specific impulses up to 3000 sec or greater [1, 5–7, 19]. The pressure inside the channel is on the order of 0.1 Pa. Now a days, most of the countries are 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. The magnetic structure of a conventional HET is constituted of a magnetic circuit with two pole pieces, cores and two magnetic screens, one internal coil and four external coils to achieve a maximum of radial magnetic field in the channel exit. 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. Hall thrusters can be classified into two categories. One of them is a stationary plasma thruster (has an extended acceleration zone) and second is a thruster with anode layer (has a more narrow acceleration zone). The electric field of strength $\sim$1000 V/m gets generated inside the discharge channel along the axial direction of the device [5]. ISRO (India) used Hall effect ion propulsion thrusters in GSAT-4 back in 2010, carried by GSLV Mk2 D3. It had four Xenon powered thrusters for North–South station keeping. Two of them were Russian and the other two were indigenous.

5. Typical parameters of Hall thrusters

In **Table 2**, typical values of some of the pertinent properties are listed at the thruster exit for the SPT-100.

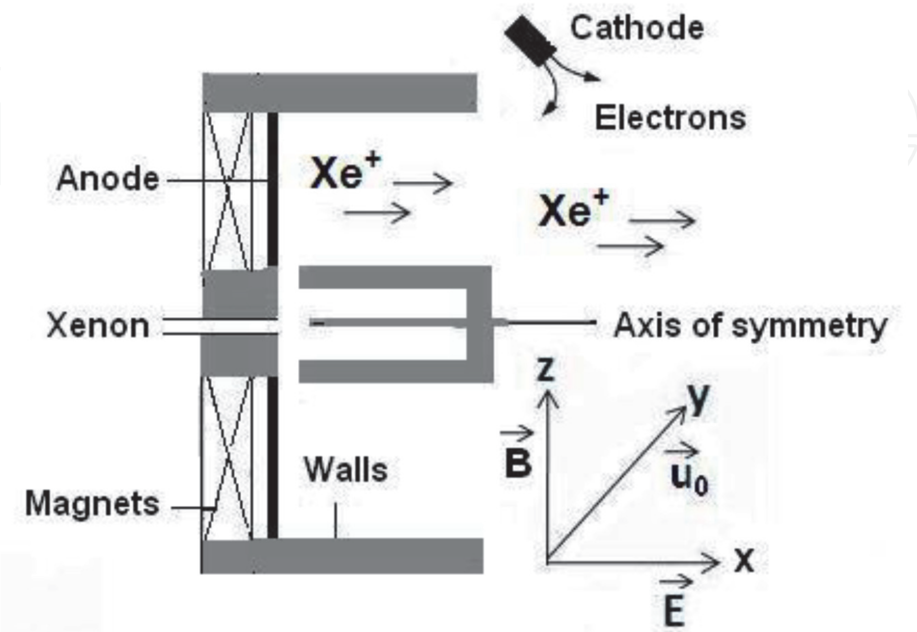

Figure 1.
Schematic diagram of a typical hall plasma thruster.

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

Table 2.
Typical values of parameters used in hall thruster.

6. Components of Hall thrusters

There are several ingredients that are responsible for the proper running of a Hall thruster. Below we discuss some important ingredients.

6.1 Propellant

Most of thrusters use xenon as a propellant because of its higher mass (131.3 amu), lower first ionization potential, less toxicity, ionization cross section of $2.3 \times 10^{-6} cm^2$. Unfortunately, Xenon is very expensive (compared to Krypton high value of first ionization potential) because of its mere availability at the earth's atmosphere [20].

6.2 Anode and cathode

Latest thrusters have hollow anodes through which the propellant is pumped into a closed channel. The propellant Xenon is stored in a tank on the spacecraft and reaches the anode. Hollow cathodes are used in Hall thruster to provide electrons (with the help of DC electron-discharge plasma generator) to neutralize the body of the spacecraft (to manage spacecraft charging) as well to sustain the plasma discharge and. The hollow cathode are made up with refractory metal tube and lanthanum hexaboride [1–20]. The cathode operates at 30 V to 40 V negative of the anode in a mercury thruster depending on the design consideration.

7. Literature review

Various phenomena have been investigated theoretically, numerically (PIC simulation) and experimentally in Hall thrusters. The physical phenomena currently studied in Hall thrusters are the plasma oscillations of different frequency ranges, propagation and neutralization of the ion beam, electron transport, plasma interaction with a dielectric wall and the plasma sheath. Some of them are discussed below.

7.1 Studies on lifetime

Low frequency oscillation and performance are modified strongly, when the magnetic field configuration is changed. The smaller curvature of the magnetic field configuration suppresses the amplitude of low frequency oscillation and enhances the performance of Hall thruster. There have been many studies on the lifetime of the Hall thrusters, including endurance test and erosion measurements, which limits the lifetime of the Hall thruster. The erosion depends on wall material, operating condition, channel geometry, magnetic field design and anode configuration. Garrigues et al. [21] have given an emphasis on the thrusters lifetime and reported that configuration with a zero magnetic field and a smaller region with large magnetic field tend to decrease wall erosion and low frequency current oscillations. Dorf et al. [22] reported that thruster operation is more stable with the coated anode. Barral and Miedzik [23] investigated the role of inductor-capacitor and resistor-inductor-capacitor networks in the stabilization of the plasma discharge. Tahara et al. [24] have studied the effects of channel wall material on Hall thruster performance. Ahedo and Escobar [25] have studied the influence of design and operation parameters on Hall thruster performances.

7.2 Studies on plasma plume

The structure of the plasma plume exhaust from the thruster is of great interest since its huge exhaust-beam divergence may cause communication interference of satellites and electrostatic charging problems. Askhabov *et al*. [26] found that the plasma jet has a half angle of 45° and the electron temperature monotonically decays along the jet and drops by an order of magnitude at 10 m. The plasma potential was found to be substantially increased with the distance from the thruster exit. This is an important result in view of the effective acceleration potential drop [27]. Fruchtman theoretically [28] shown that the control of the electric-field profile in the Hall thruster through the positioning of an additional electrode along the channel is to enhance the efficiency. Keidar and Boyd [29] have studied the effect of the magnetic field on the plasma plume of a Hall thruster.

7.3 Studies on oscillations and instabilities

The plasma density, external electric and magnetic fields in a Hall thruster are in inhomogeneous form and are not in the thermodynamically equilibrium state. These deviations act as a source of plasma instabilities. These oscillations and instabilities in the Hall thruster may affect the divergence of the ion beam and electron transport across the magnetic field which control the productivity of the system. Choueiri [11] has qualitatively discussed the nature of oscillations in 1 kHz–60 MHz frequency range that have been observed during operation of Hall thrusters. The typical range of oscillations have been recognized in Hall thrusters, such as 10–20 kHz discharge oscillations, 5–25 kHz rotating spokes (due to ionization process), 20–60 kHz azimuthal modes (due to drift type instability associated with gradient of density and magnetic field), 70–500 kHz transient time (ion residence time in the channel), 0.5–5 MHz azimuthal wave and high frequency oscillations (**Table 1**). The above waves regulate the efficacy of the thruster. The real frequency, growth rate and amplitude of the oscillations depend on geometry, magnetic field profile, mass flow rate and discharge voltage. Ducrocq *et al*. [30] have studied high-frequency electron drift instability and derived three-dimensional dispersion relation. Keidar [31] has modeled plasma dynamics and ionization of the propellant gas within the anode holes. Barral and Makowski [32] have analyzed transit-time instability in Hall thruster. Kapulkin and Guelman [33] have investigated low frequency instability in near anode region of a Hall thruster. Lazurenko *et al*. [34] have reviewed high-frequency instabilities and anomalous electron transport in Hall thrusters. Researchers have investigated resistive instabilities in a Hall thruster and found that the plasma perturbations in the acceleration channel are unstable in the presence of collisions [13, 15, 17, 35–40]. Fernandez et al. [41] did simulations for the growth of resistive instabilities in $\vec{E} \times \vec{B}$ plasma discharge. The plasma resistivity induces resistive instabilities (electrostatic and electromagnetic) [13, 15, 17] associated with azimuthal and axial directions and it was depicted that these instabilities have the highest level near the thruster exit plane. Smolyakov *et al.* reported that sheath instabilities has a vital role in anomalous transport phenomena in Hall plasma thruster [41]. Plasma sheath plays an important role to control the mobility of electrons inside a plasma channel [42–44].

Range (kHz)	Type	Driving mechanism
10–20	Loop or circuit oscillations	Magnetic field, discharge voltage and electron wall collision frequency [45]
5–25	Rotating spokes	Ionization process [46]
20–60	Drift instability	Gradient of density and magnetic field [47]
70–500	Ion transient time oscillations	Plasma density gradient and low ionization [11, 48]
0.5 to 5 MHz	Azimuthal waves	Drift velocity of plasma [11, 13, 17, 34].

8. Conclusions

The current status of electric propulsion for deep interplanetary missions has been reviewed. The basic working mechanism of electro-thermal, electrostatic and electromagnetic thruster is tabulated. Limitations and shortcomings of Hall thruster system have been discussed. The highlights of potential research are also given.

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