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HALL-EFFECT THRUSTER (HET)

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Abstract - *HET is a type of electric propulsion system (EPS) that is an effective and powerful alternative to the traditional (chemical) propulsion system for space missions. The thrust produced by Hall thruster is lower, albeit the specific impulse produced by Hall thruster is far higher than traditional thrusters. Hall Thruster with low fuel requirement result in less propellant mass storage compared to chemical thrusters. As a result, the concomitant decrease in propellant mass results in improved payload mass power. Hall Thruster is further known as electrostatic Hall Thruster and electromagnetic Hall Thruster. Hall Effect thruster is a type of electrostatic thruster that uses Coulomb force which accelerates ions in the direction of an electrical field. Applications require the regulation of the inclination and the location of satellites in orbit. Electronic propulsion system advancement is intended to apply innovations to space missions. In this article, we will briefly discuss electrostatic Hall Thruster, particularly Hall Effect thrusters.*

Key Words**: Hall Effect, Hall Thruster, SAT, TAL, propulsion, ion, xenon.**

1. INTRODUCTION

As we learned, scientists are now preparing interplanetary exploration for stars and intergalactic missions, which would raise astounding obstacles for scientists. Still, scientists are using standard propulsion systems that make their mission rockets heavier because of heavy payloads thus this makes them develop a lightweight thruster that is electronic thruster which is also efficient and reliable than standard thrusters. In the field of space propulsion, electric propulsion is the most efficient way to reduce the amount of propellant necessary to achieve a given velocity increment as the electrostatic acceleration of an ionized propellant allows a high exhaust velocity to be reached.

Hall Effect thrusters are plasma propulsion devices used for spacecraft maneuvering, station keeping and orbit transfer missions. Electric propulsion systems (EPS) use electricity and possibly magnetic fields to change the velocity of the system. As in every conventional form of rocket propulsion, Newton's third rule of motion is applied to the ion propulsion system: there is an equal and opposite response with each action. Usually, rocket engines use internal systems to propel some form of exhaust from the rocket to produce force in the opposite direction. Most of the electric thrusters work by expelling propellant mass (reaction mass) electrically to gain velocity at high speed. Significantly, thruster requires that mass be lost from a rocket to exhaust. As a name suggest, Hall Effect thruster works on Hall Effect.

2. PRINCIPAL

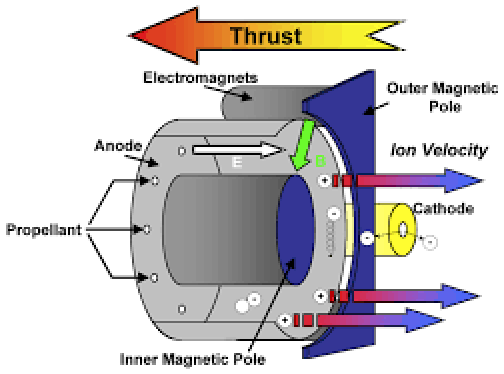

Fig - 1: Diagram of basic Hall effect thruster operation with the propellant distribution, anode, cathode, two magnetic poles, and resultant ion flow direction shown [2]

The above schematic illustrates the function of basic Hall effect thruster operation with the propellant distribution, anode, cathode, two magnetic poles, and resultant ion flow direction shown. Hall thrusters function by use of perpendicular electric and magnetic fields. Neutral atoms of the propellant move from storage tanks (not shown) into the coaxial acceleration channel. Simultaneously, the radial magnetic field acts to impede the flow of electrons from the cathode to anode. The electrons are trapped near the exit of a coaxial acceleration channel. The crossed fields produce a net Hall electron current in the Θ direction. The trapped electrons act as a volumetric zone of ionization for neutral propellant atoms from storage tanks (not shown). Electrons collide with the slow-moving neutrals producing ions and more electrons to both support the discharge and ionize additional neutrals. The positive ions are not significantly affected by the magnetic field due to their larger Larmor radii, which are on the order of meters. The ions are accelerated through the electric field produced by the impedance of the magnetic field on the plasma. Subsequently, the resultant high-speed ion beam is neutralised by an external electron source.

3. ADVANTAGES OF HALL THRUSTERS

Unique designs minimize energy loss to the discharge chamber, which improves discharge efficiency. HET lifetime is extended five times, from approximately 10,000 hours to more than 50,000 hours. Glenn's innovations result in a greater fraction of the electrical energy from the solar array being used to produce thrust, and a decrease in electrical energy being lost as waste heat radiated to space. Hall thrusters have a specific impulse usually in the range of 1,200 to 1,800 sec–even greater than the 300 to 400 sec of chemical rockets. [4] One specific benefit of the Hall thrusters relative to the gridded ion thruster is that the generation and acceleration of the ions takes place in a quasi-neutral plasma, meaning that there is no Child-Langmuir charge (space charge) saturated current constraint on the thrust density.

4. WORKING AND DESIGN OF HALL THRUSTERS

First studies about Hall thrusters began in the early ’60 independently in the URSS and USA. However, Hall thruster technology was developed to flight status in the former Soviet Union, whereas the US research activities focused on Hall Thruster [4][5]. Two types of modern Hall thrusters were developed in the URSS, the stationary plasma thruster (SPT) and the thruster with anode layer (TAL). Two types of Hall thrusters were developed: the stationary plasma thruster (SPT) at the Kurchatov Institute and the anode layer thruster (ALT) at the Central Research Institute for Machine Building (TsNIIMASH).

4.1 Working

Electrons are produced by a hollow cathode (negative electrode) at the downstream end of the propulsion. The anode (positive electrode) or "channel" is charged to a high potential by the power supply of the thruster. The electrons are drawn to the walls of the channel and accelerate in the upstream direction. As the electrons migrate into the channel, they experience a magnetic field created by the thruster's strong electromagnets. This high-strength magnetic field traps the electrons, causing them to form a ring at the downstream end of the thruster tube. The Hall thruster is named for this wave of electrons, called the Hall Current. The propellant, consisting of an inert gas such as xenon or krypton at low pressure, is pumped into the thruster tube. Because Hall thrusters use inert gas for propellant, there is no chance of explosion as for chemical rockets. Any of the trapped electrons in the channel collide with the propeller atoms, forming ions. As the propellant ions are created, they feel the electrical field formed between the (positive) channel and the (negative) electron ring and accelerate out of the thruster, forming an ion beam. The thrust is provided by the force given to the electron cloud by the ions. This force is applied to the magnetic field and, in turn, is sent to the magnetic circuit of the Thruster. The electrons are extremely mobile and drawn to the ions in the beam, allowing an equivalent number of electrons and ions to exit the propeller at the same time. This allows the thruster to remain electrically inert overall.

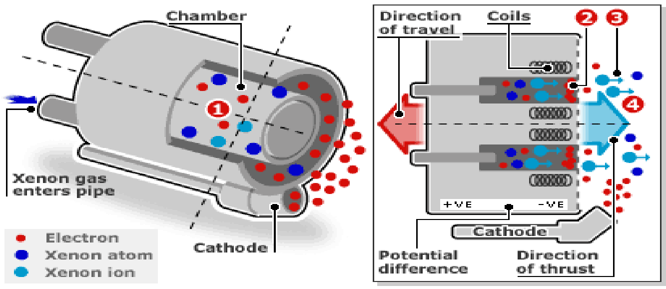

Fig - 2: Movement of the xenon ions and atoms and electrons in the thruster. [6]

4.2 SPT (Stationary Plasma Thruster)

The SPT design was largely the work of A. I. Morozov. [7][8] The first SPT to operate in space, SPT-50 aboard a Soviet Meteor spacecraft was launched December 1971. They were mainly used for satellite stabilization in north–south and in east–west directions. Since then until the late 1990s 118 SPT engines completed their mission and some 50 continued to be operated. Thrust of the first generation of SPT engines, SPT-50 and SPT-60 was 20 and 30 mN respectively. In 1982, SPT-70 and SPT-100 were introduced, their thrusts being 40 and 83 mN, respectively. In the post-Soviet Russia high-power (a few kilowatts) SPT-140, SPT-160, SPT-200, T-160 and low-power (less than 500 W) SPT-35 were introduced. [9] The acceleration region of the SPT is within the thruster itself while in the case. The channel wall in the SPT is coated with an insulator (a ceramic material).

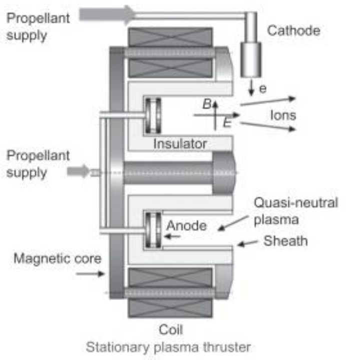

Fig - 3: Schematic diagram of SPT [11]

4.2.1 Design

The Hall propeller was invented in the late 1950s. Until the mid-1990s, it was developed mainly in Russia, where it was called a stationary plasma thruster (SPT). Over the last 30 years, Russia has put more than 100 Hall thrusters in space. The positive charge of the electrostatic ion thruster builds up in the vacuum between the grids, reducing the ion current and, thus, the amount of the thrust that can be achieved. In a Hall thruster, electrons pumped into and locked within a radial magnetic field work to neutralise the space charge. The amplitude of the applied magnetic field is roughly 100–200 G, high enough to capture the electrons by allowing them to swirl along the field lines in the coaxial canal. The magnetic field and the electron cloud locked together act as a synthetic cathode. The ions, too strong to be disturbed by the field, are continuing their path through the simulated cathode. The passage of positive and negative electrical charges through the device results in a net force (thrust) on the thruster in a direction opposite to that of the ion flow.

In the stationary plasma thruster, as shown in Fig - 4, the cathode provides a source of free electrons while the feed tube supplies xenon propellant to an anode which also acts to distribute the propellant throughout the annular discharge chamber. The inner and outer magnets provide an essentially radial magnetic field which traps the free electrons migrating from the cathode. The electrons collide with the xenon atoms ionizing them, permitting them to be accelerated by the electric field and exhausted from the device providing thrust. The thrust can be throttled by varying the flow rate of the xenon propellant. Note that the cathode electron supply also serves to neutralize the exhaust flow.

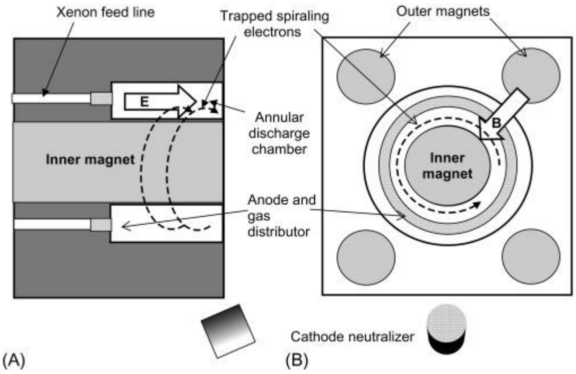

Fig - 4: Schematic diagram of the stationary plasma thruster (SPT) showing (A) cross-section and (B) front view. The inner and outer magnets provide the radial magnetic field B. The cathode supplies electrons that stream toward the anode providing the electric field E and are trapped in helical paths (dotted lines) by the magnetic field.

Stationary plasma, or Hall, thrusters have found application in satellite station-keeping. The typical performance of these thrusters includes high reliability (nominally 4000 on-off cycles) and thrust levels F (in N) for power input P (in W) given approximately by

$$F = 6.67 \times 10^{-5} P$$

Typical power levels are on the order of kilowatts, but higher levels are possible. The xenon propellant mass flow is typically on the order of several mg/s (10– 6 kg/s) and the specific impulse is around 1500 s. The mass of such a thruster is around 3.5 kg and the characteristic dimension is about 15 cm, roughly half that of an ion rocket of the same thrust.

4.2.2 Implementation of SPT

1. SPT-100 is a Hall-effect ion thruster, part of the SPT-family of thrusters. The thruster is manufactured by Russian OKB Fakel, and was first launched onboard Gals-1 satellite in 1994. [12] In 2003 Fakel debuted a second generation of the thruster, called SPT-100B, and in 2011 it presented further upgrades in SPT-100M prototypes. [13] as of 2011 SPT-100 thrusters were used in 18 Russian and 14 foreign spacecraft, including IPSTAR-II, Telstar-8 and Ekspress A and AM constellations. It produced 80 mN of thrust having specific impulse of 1,600s and power output of 1,350W. [14]

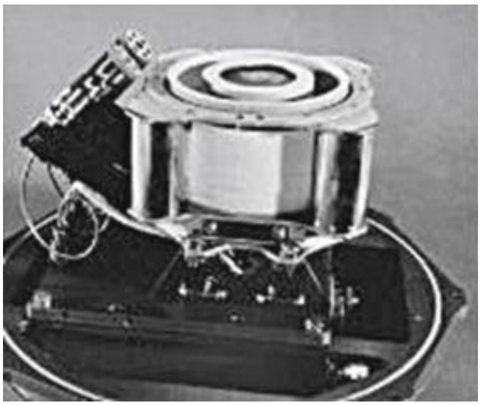

Fig - 5: Photograph of SPT-100 Hall thruster (Stetchkin/Fakel, Russia). Image from Encyclopedia Astronautica, SPT-100 Image

2. The PPS-1350 is built by Snecma, a French aerospace firm, in cooperation with Fakel, who designed the SPT-100, on which the PPS 1350 is based [16]. It was used in the SMART-1 mission to the moon and two geostationary satellites: Inmarsat-4A F4 and Hispasat AG1. It includes change in specific impulse gaining 10mN of more thrust and producing power output of 1,500W (nominal) [14].

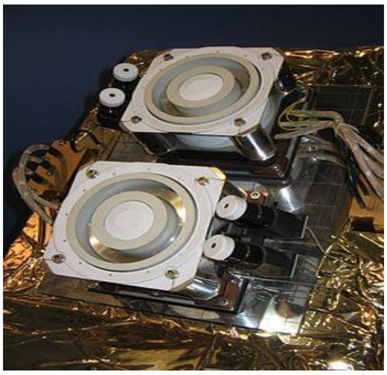

Fig - 6: Two Snecma PPS 1350 at the Paris Air Show 2007

4.3 TAL (Anode Layer Thruster)

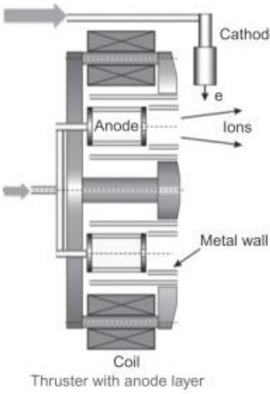

Fig – 7: Schematic Diagram of TAL [11]

A TAL is similar in construction, but the walls of the acceleration channel are made of metallic materials such as stainless steel or molybdenum. The acceleration region of the TAL is in the front of the thruster. Since the walls are conductive, a constant potential is observed along the entire wall. High electron temperatures (> 20 eV) are typically observed in TAL thrusters. In a TAL, ion acceleration occurs in a very thin layer near the anode (in the electrical sheath) with a thickness of approximately one electron Larmor radius, which gave the name to this thruster variant. Recently, new mathematical solutions of the anode layer problem were found, i.e., the so-called B- and E-layers. These solutions are different by the width of ion acceleration zone and by parameters of the cathode plasma. Similarly, in magnetically insulated ion diodes, ion acceleration occurs in a thin electric layer with closed electron drift near the anode. In the TAL, the length of the acceleration channel is smaller (a few millimeters). Fig - 7 shows an example of a TAL type thruster, the D55.

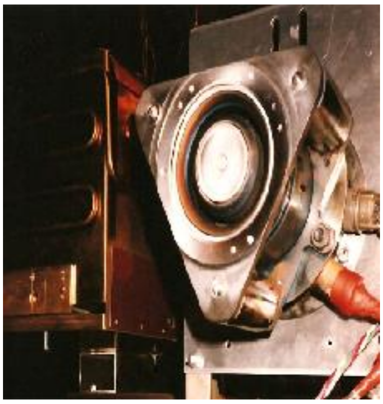

Fig – 7: D55 Hall thruster (Courtesy of PEPL)

Hall propellers were first seen on the western satellite of the STEX Naval Research Laboratory (NRL) spacecraft flying the Russian D-55. The first American Hall propeller to fly in orbit was the Busek BHT-200 on the TacSat-2 technology demonstration spacecraft. The first flight of the American Hall propeller on an operational mission was the Aerojet BPT-4000, which was deployed in August 2010 on the Military Advanced Extremely High Frequency GEO communications satellite. At 4.5 kW, the BPT-4000 is also the most powerful Hall thruster ever flown in space. In addition to the normal stationary functions, the BPT-4000 also provides spacecraft orbit enhancement capabilities. The X-37B was used as a test bed for the Hall propeller of the AEHF satellite series [18]. Several countries around the world are continuing their attempts to qualify Hall propeller technology for commercial use. The SpaceX Starlink constellation, the largest satellite constellation in the world, operates Hall thrusters.

5. HALL THRUSTERS IN SPACE

Hall thrusters have been flying in space since December 1971 when the Soviet Union launched an SPT-50 on a Meteor satellite. [19] Since then, more than 240 thrusters have flown in space at a 100 percent performance rate. Hall thrusters are also regularly flown on commercial LEO and GEO communications satellites where they are used for orbital insertion and stationkeeping. The first [failed verification] Hall propeller to fly on a Western satellite was the Russian D-55, designed by TsNIIMASH, on the NGO STEX spacecraft, launched on 3 October 1998. The SMART-1 spacecraft of the European Space Agency's solar electrical propulsion system used the Snecma PPS-1350-G Hall thruster. [20] SMART-1 was a research demonstration mission that was orbiting the Moon. This use of the PPS-1350-G, which began on September 28, 2003, was the first use of the Hall thruster outside the geosynchronous earth orbit (GEO). As other Hall thruster propulsion systems used in commercial applications, the Hall thruster on SMART-1 could be throttled over a range of power, specific pulse and thrust. It has a discharge spectrum of 0,46–1,19 kW, a specific impulse of 1,100–1,600 s and a thrust of 30–70 mN. Many small satellites of the SpaceX Starlink cluster use crypto-fueled Hall thrusters for position-keeping and deorbiting. [21]

6. UNITS OF HALL THRUSTERS

6.1. Power Processing Unit

They are circuit machines that transform the electrical input from the utility line to the required voltage and current to be used by the system in question. They have the same function as linear amplifiers, but they are much more effective because the use of linear amplifiers results in a lot of power loss due to the use of a capacitor to shift voltage and current. Another usage of the PPU is that the electrical power provided by the power source is transferred by the PPU by providing the necessary power to each part of the Hall Thruster.

6.2. Power Source

The power supply is normally some source of electrical power such as solar or nuclear power. The solar electrical propulsion system (SEP) uses solar panels to produce electricity, and the nuclear electrical propulsion system (NEP) uses a nuclear power source attached to an electrical generator. This production of electricity is due to the power source.

6.3. Propellant Management System (PMS)

The PMS monitors the flow of the propellent from the propellent tank. It's very advanced design. PMD is seen within spacecraft propellent tanks that use surface tension to guarantee the supply of gas free oil. They are manufactured from metals such as titanium to facilitate their use in most corrosive propellants. They still have no rotating parts and are thus extremely durable.

6.4. Hall Thruster

Hall thruster moves ions by electrostatic repulsion. The neutral Xenon propellant enters from the propellant tank. A hollow cathode emits electrons which impact the Xenon atoms, pounding loose an electron and creating positive Xenon ions. The positive ions are then pushed by the magnetic field produced by the electromagnets. Then the electric field produced by the impedance of the magnetic field on the plasma accelerates the ions such that the ion beam is exhausted out through the channel. A hollow cathode plasma bridge neutralizer is placed at the exit of the channel which shoots out electrons to neutralize the ion beam. Otherwise the ions would be attracted back to the accelerating channel, cancelling out the thrust

7. CONCLUSIONS

Hall Thruster has proved to be a feasible and efficient alternative to traditional debugging systems. With very low fuel demand due to the very high specific current generation, Hall Thruster can cope comfortably with chemical systems even though the power production is very low. The system can be used for various mechanical criteria, such as orbit station orbit for geostationary satellite orbit, location monitoring and multi-purpose missions. While chemical resistance is not very suitable for the deep space deployment of Hall Thruster, it is also accessible at high speeds.

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