Electric Propulsion

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1 Introduction to Electric Propulsion

Electric propulsion is a from rocket propulsion devices that utilize electrical energy to either heat and/or accelerate propellant. All forms of electric propulsion have three main subsystems in common: (1) energy source; (2) conversion device (transforms electrical energy required voltage, current; (3) propellant; and (4) thruster system (transforms enthalpy into kinetic energy. One of the main reasons why electric propulsion is so attractive is because they are high efficient at utilizing propellant mass. Though it would seem that electric propulsion devices are extremely complex, the principles that govern them are quite simple. As technology further develops electric propulsion devices continue to grow more efficient and powerful making them a viable option for future space exploration missions.

2 Electrothermal Propulsion

Electrothermal propulsion is a form of electric propulsion that utilizes the technique of electrically heating the propellant and then expanding the heated propellant through a nozzle to generate thrust. The level of exhaust velocity attainable is primarily a function of temperature of the heated propellant. There exist three main concepts of electrically heating propellant: resistojet, arcject, and high-frequency excitation. These three concepts are discussed in detail below.

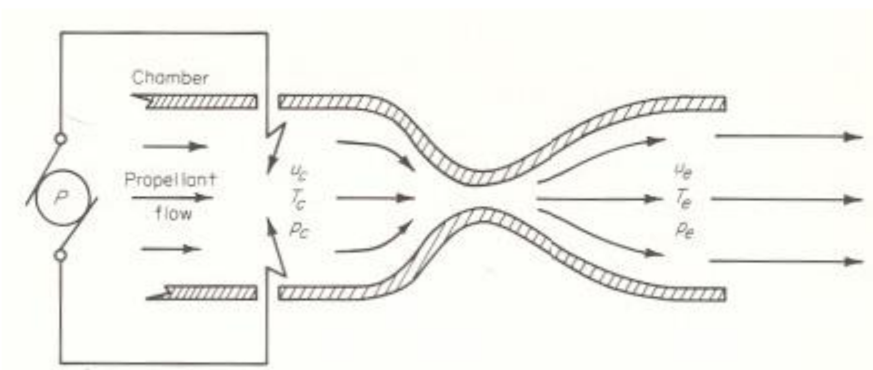

Figure 1: Schematic of Basic Electrothermal Propulsion

Electrothermal engines can use a variety of propellants. The ability to adapt to any propellant in an electrothermal engine is one reason why electrothermal engines are so attractive. Selecting a propellant involves choosing among many conflicting factors. One particular propellant may not be optimum for all types of missions. It is common knowledge to select a propellant with a low molecular mass in order to maximize specific impulse. Other important considerations when selecting a propellant is maximizing specific heat capacity, low tendency toward frozen flow losses (enthalpy not converted into kinetic energy), storability, and corrosiveness. The most common electrothermal propellants include: H_2, He, Li, Be, B, C, NH_3, N_2, N_2H_4, and B_5H_9. Some advantages of hydrogen are a very high specific heat and thermal conductivity, non-corrosive, and stable electrical discharges. Faults of hydrogen as a propellant include difficulty storing, slow molecular recombination rates, and high frozen flow losses. Although helium has a lower specific heat than hydrogen, it has good heat transfer properties and does not incur frozen flow losses until very high specific impulses are reached; however, helium does have its drawbacks such as a low liquefaction temperature which leads to difficulty storing in a space environment. Propellants like lithium, beryllium, boron, and carbon have lower specific heats than hydrogen and helium, but are easily stored which makes them of interest. Ammonia and hydrazine are easily stored and also are of value because they dissociate into low-molecular-mass constituents which improves specific heat capacity; however, ammonia and hydrazine are both highly corrosive which over time will erode the nozzle and chamber walls.

2.1 Resistojet

The resistojet is the least complex of all electric propulsion devices. The resistojet works by passing the propellant over an electrically heated solid surface. Although there exist many resistojet designs, most consist of a coiled wire heating element enveloping the heating surface. Because the resistojet heats the surface of the material to heat the propellant material selection becomes an important issue. Current materials in resistojets limit the maximum operating temperature to no more than 2700 K; therefore, the maximum specific impulses attainable are around 300 sec. The specific impulse is primarily dependent on the molecular mass of the propellant, and the maximum chamber temperature, although other factors do exist. The highest specific impulse is achieved using hydrogen as a fuel; however, due to hydrogen's low density storing hydrogen becomes a burden, and it is more effective to use a propellant such as O_2, H_2O, CO_2, NH_3, CH_4, and N_2. Efficiency losses of the resistojet occur in many areas such as: heat transfer from the heating element to the material, material surface to the propellant, dissociation of propellant byproducts. Resistojet thruster efficiency ranges in value from 65 % to 85%. High chamber pressures help reduce dissociation losses and reduce the size of the chamber and nozzles; however, high chamber pressures add mass to the system and increase erosion at the throat.

One of the major drawbacks of the resistojet is heat transfer from the resistance element to the gas stream is not extremely efficient. Flow in the combustion is usually laminar so it is preferable that the heat transfer from the heat element is conductive. Several resistance element designs exist that try to maximize heat transfer to the gas flow. One of the heat element designs are coils of wire aligned in various configurations either parallel or perpendicular to the propellant stream. Other heat element designs include various geometrical bodies immersed in the flow field in which the current is passed through the bodies to transfer heat as the flow moves around the body. These geometrical shapes include a bed of spheres, knife-edge elements, or simple resistive heating of the chamber walls.

Advantages

The resistojet is a relatively simple device. It is easy to control and has simple power conditioning. The cost to using a resistojet is low, yet the device can achieve a relatively high thrust and efficiency. The resistojet is very diverse since it can use many types of propellant including hydrazine augmentation.

Disadvantages

The resistojet has the lowest specific impulse of all the electric propulsion devices. The loss of heat is substantial and gas dissociation is commonplace. Indirect heating of the gas occurs, and erosion is common.

2.2 Arcjet

The arcjet configuration is much more complex than the resistojet. The arcjet utilizes an electric arc to directly heat the propellant stream. Since the arcjet is not in direct contact with the wall the arcjet can heat the propellant to significantly higher temperatures than the resistojet without increasing the wall temperature. The arc is formed between a central cathode in the propellant flow and an anode which comprises part of the divergent nozzle section. The arc itself is very narrow and therefore not all portions of the gas flow are heated equally. To increase heat transfer to the gas flow the anode is moved either nearer the throat or the voltage is increased. Complex flow fields such as vortex flow or turbulence are desirable because they increase heat transfer in the flow field. Typical efficiencies of arcjet thruster range from 35% to 54%.

There have been many improvements in the arcjet design since its original configuration in order to increase its efficiency. Early arcjet designs featured an arc encased in a cylindrical tube through which the fluid flowed. This early design existed because it was thought that the longer the gas resided in the mixing chamber the closer the gas compound was to thermal equilibrium and therefore the gas would pass through the nozzle at its maximum attainable temperature. However, later experience revealed that the long residence time did not heat the gas uniformly and resulted in excessive heat transfer losses. It was through gradual trial and error that the development of the arcjet reached a level of performance in which the assembly could be powered in ranges of interest. One of the best developed arcjet designs delivered from research was the constricted arcjet. This arrangement was discussed earlier features a central cathode upstream of the throat that arcs between an anode ring downstream of the throat. This arrangement maximizes the arcjet by heating the propellant flow in the sectional with the smallest cross-sectional area, maximizing heat transfer.

Advantages

Advantages of the arcjet are direct heating of gas. The arcjet is run at low voltage which contributes to power savings. Like the resistojet the concept of the arcjet is relatively simple. The thrust achieved from arcjets is relatively high.

Disadvantages

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Drawbacks to the arcjet include: low efficiency, erosion at high power, low specific impulse, high current, heavy wiring, heat loss, and complex power conditioning.

2.3 High-frequency Excitation

High-frequency excitation devices are essentially electrodeless arcjets. Electrodes in flow fields are extremely susceptible to erosion due to continuous electron and ion bombardment. The theory behind high-frequency excitation, or electrodeless discharges, is to heat the gas flow without damaging the heating device. There are two types of electrodeless discharges: E-type and H-type. E-type discharges work by introducing an electric field through the gas flow. Using a high frequency input alternates the electric field which excites the electrons in the flow which increases the heat of the gas. H-type electrodeless discharges also work by high-frequency input signals, but alternate a magnetic field to excite particles in the flow. Both of these concepts cause ions to move rapidly back and forth, constantly increasing the ions energy, until the ions collide with neutral particles and the kinetic energy of the ions is transferred to the particles. Heating the gas to an acceptable temperature is only possible using an extremely high frequency. Efficiency in transferring radio frequency power into plasma enthalpy can reach values between 60 and 70%, but are typically lower due to non-uniform flow losses.

2.4 Electrothermal Propulsion Missions

Resistojets were first used experimentally in space during the mid 1960s. They were first used operationally for north-south station keeping aboard the Intelsat-V series of geostationary communication satellites in the 1980s. Resistojets were also on the Iridium satellite constellation for the purposes of orbit insertion, attitude control and de-orbiting.

Arcjet thrusters were first used commercial for north-south station keeping aboard the Telstar-4 series of geostationary communication satellites in 1993. Arcjets capable of producing higher thrusts due to more massive power supplies have been test flown; however, erosion of electrodes is a major concern and the main reason why this engine has not found more applications.

High-frequency excitation devices are a relatively new concept that has been tested numerous times on the ground, but has yet to be flown.

3 Electrostatic Propulsion

Electrostatic propulsion is by far the most fully developed concept in electric propulsion (Jahn, pp. 143). Electrostatic propulsion, commonly referred to as ion propulsion, involves the simple concept of accelerating an ion through the use of an electrode. The ions are supplied by an ion source that releases ions (charged particles) into a stream where an accelerating electrode supplies a charge opposite to that of the ions which in turn accelerates the ions toward the electrode. Once the ions have passed through the electrode a neutralizer emits ions of equal and opposite charge to create a net charge of zero downstream. The thrust attainable is only a function of the exhaust velocity, the mass of the ion, and the total ion flux.

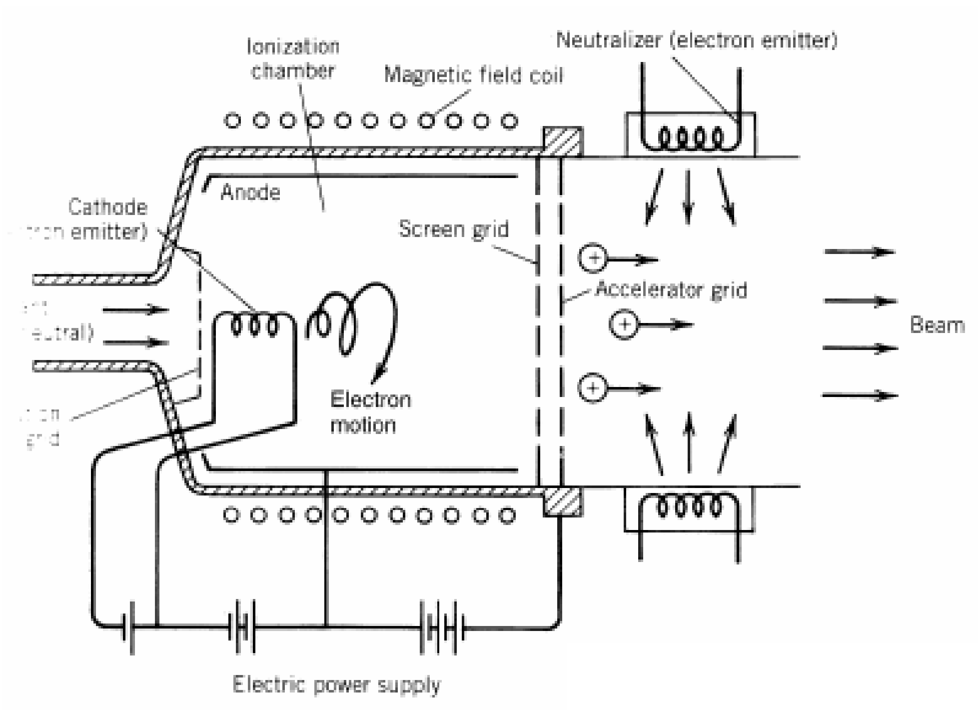

Figure 2: Diagram of an Electrostatic Thruster

Electrostatic thrusters are categorized by their source of charged particles, i.e. how ions are produced, of which their currently exist three types. The first type of electrostatic thruster is an electron bombardment thruster. Electron bombardment thrusters produce positive ions from a monatomic gas by bombarding the source gas with electrons emitted from a heated cathode. A second method of producing positive ions belongs to the ion contact thruster. This thruster produces its ions by passing the propellant gas through a heated, porous contact ionizer made of tungsten; for this arrangement mercury is the most desired propellant, though cesium has been used on occasion. The third type of electrostatic thruster is the field emission or colloid thruster. In this thruster small droplets of propellant are charged as they pass through an electric field discharge.

Advantages

Ion propulsion systems deliver both a high specific impulse and efficiency. Xenon, the only feasible ion propellant, is an inert element posing no safety hazards.

Disadvantages

The power conditioning scheme of the ion engine is extremely complex, and high voltages are needed. Xenon is only propellant available, leaving no other propellant options. The ion engine produces an extremely low thrust per unit area, and the power supply mass is considerable.

3.1 Fundamentals of Electrostatic Propulsion

The following equations show the interrelation of the electrical and dynamical parameters in one-dimension. For all equations let x be the coordinate along the stream. The position of the ion source is located at $x = 0$ which is at a potential $V = V_0$. The position of the accelerating grid is at $x = x_a$, which has a potential of $V = 0$. The potential V, the electric field $E = -(dV/dx)$, the ion density N, and the ion velocity v are all dependent on the location along the thruster, x. In steady state flow, the current density, $j = Nqv$, is constant over the entire length of x. The velocity of the ion at any position follows from the conservation of energy. Therefore, for any ion with charge q and mass M emitted from the source with negligible velocity the velocity along the x-axis can be written as:

$$v(x) = \left[\frac{2q(V_0 - V)}{M}\right]^{1/2}$$ **Equation 1**

Using Poisson's relation of $\nabla \cdot E = -\nabla^2 V$ the potential function $V(x)$ can be related to the ion density $N(x)$. This relation is shown in Eqn. 2.

$$\frac{d^2V}{dx^2} = -\frac{Nq}{\varepsilon_0} = -\frac{j}{\varepsilon_0 v} = -\frac{j}{\varepsilon_0}\left[\frac{M}{2q(V_0 - V)}\right]^{1/2}$$ **Equation 2**

where ε_0 is the permittivity of space.

The equation may be integrated simply when multiplied by $2(dV/dx)$ resulting in:

$$\left(\frac{dV}{dx}\right)^2 - \left(\frac{dV}{dx}\right)_0^2 = \frac{4j}{\varepsilon_0}\left[\frac{M(V_0 - V)}{2q}\right]^{1/2}$$ **Equation 3**

Note that the term $\left(\frac{dV}{dx}\right)_0^2$ is the square of the electric field at the ion source, E_0. Since it is assumed that the ions are emitted from the source with negligible velocity, then E_0 cannot be negative if any current is to be drawn. Therefore the magnitude of the electric field at $x = 0$ must lie within the range show in Eqn. 4.

$$0 < E_0 < \frac{V_0}{x_a} \qquad \textbf{Equation 4}$$

The upper limit of the electric field would exist at $x = 0$ in the absence of any space charge and would be constant over the entire gap. This is known as the pure electrostatic field. The lower limit value is approached when the current is increased to a maximum value consistent with a monotonic voltage profile between the two boundary layers. This case is known to be space-charge limited because the accelerating field is neutralized at the source by all the distributed intervening charge. In the space-charge limited case the electric field is written as:

$$\frac{dV}{dx} = 2\left(\frac{j}{\varepsilon_0}\right)^{1/2}\left[\frac{M(V_0 - V)}{2q}\right]^{1/4} \qquad \textbf{Equation 5}$$

Integrating Eqn. 5 yields:

$$V = V_0 - \left[\frac{3}{2}\left(\frac{j}{\varepsilon_0}\right)^{1/2}\left(\frac{M}{2q}\right)^{1/4} x\right]^{4/3} \qquad \textbf{Equation 6}$$

Inserting the end conditions given in Eqn. 7 into Eqn. 6 yields the space-charge limited current density for the gap shown in Eqn. 8. This relation is known as Child's law.

$$V = 0 \quad at \quad x = x_a \qquad \textbf{Equation 7}$$

$$j = \frac{4\varepsilon_0}{9}\left(\frac{2q}{M}\right)^{1/2}\frac{V_0^{3/2}}{x_a^2} \qquad \textbf{Equation 8}$$

Using Eqn. 1 and Eqn. 8 along with the definitions of thrust and current the thrust per unit area can be written as:

$$\frac{T}{A} = \dot{m}v_a = \frac{jMv_a}{q} = \frac{8\varepsilon_0}{9}\left(\frac{V_0}{x_a}\right)^2$$ **Equation 9**

It is important to note that for a fixed electrode spacing and voltage, the thrust density is independent of the charge-to-mass ratio of the ions. Other the other hand the exhaust velocity depends on the charge-to-mass ratio. This relation is shown in Eqn. 10 below.

$$v_a = \left(\frac{2qV_0}{M}\right)^{1/2}$$ **Equation 10**

The power required per unit area is also a function of the charge-to-mass ratio as shown in Eqn. 11.

$$\frac{P}{A} = \frac{Tv_a}{2A} = \frac{4\varepsilon_0}{9}\left(\frac{2q}{M}\right)^{1/2}\frac{V_0^{5/2}}{x_a^2}$$ **Equation 11**

Both the thrust per unit area and power required per unit area give insight into the performance capabilities of the ion engine.

3.2 Electrostatic Propulsion Missions

The first successful space thruster of any kind was a mercury electron bombardment thruster aboard the SERT 1 spacecraft launched on July 20, 1964. SERT1 was equipped with two electron bombardment thrusters powered with cesium and mercury ions. The cesium ion thruster failed to operate due to a high voltage short circuit.

The European Space Agencies EURECA spacecraft first demonstrated the operation of RITA, an electrostatic thruster employing radio frequency ionization, in 1992. Electrostatic thrusters have been in operational use since the mid 1990s for the purposes of station keeping aboard geostationary satellites. In 1998, NASA’s Deep Space 1 spacecraft became the first interplanetary mission to use electrostatic propulsion.

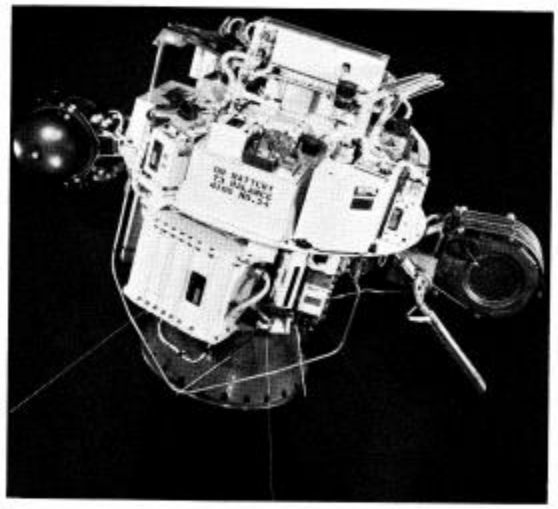

Figure 3: SERT 1 flight-model spacecraft

Figure 4 below shows a cutaway image of the SERT II ion engine. SERT II's predecessor SERT I was the first successfully operational electric thruster in space. This image shows in great detail the complexity of an electric thruster, even though this thruster design is relatively simple in comparison to other electric thrusters.

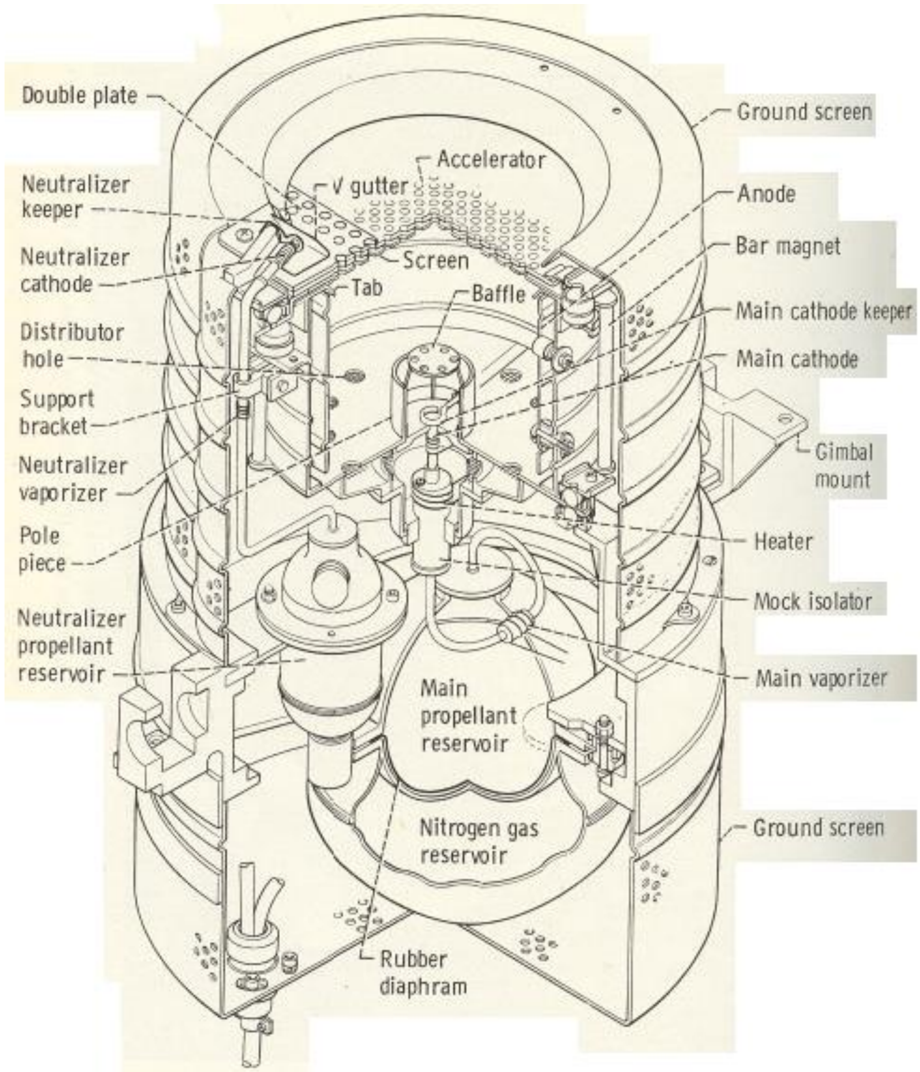

Figure 4: SERT-II Ion Engine System

4 Electromagnetic Propulsion

The third class of electric propulsion, electromagnetic propulsion, deals with the acceleration of highly charged plasmas (mixture of ions, electrons, and neutrals) by the interaction of currents driven through the gas and magnetic fields created by those currents or an external device. One of the many advantageous that electromagnetic engines have over electrostatic engines is that they have a relatively high thrust density, which is about 10 to 100 times that of an ion engine. Unlike electrostatic engines the acceleration process of the electromagnetic engine yields a neutral exhaust beam eliminating the need for an ion neutralizer. Electromagnetic acceleration of plasmas is possible due to the force created by the interaction an electric and magnetic field orthogonal to one another. The direction of this interaction determines the direction of the resulting force.

To better illustrate the concept of electromagnetic accelerators Figure 5 shows how the electric and magnetic fields interact to delivery a body force on the particle in the direction of the incoming velocity field.

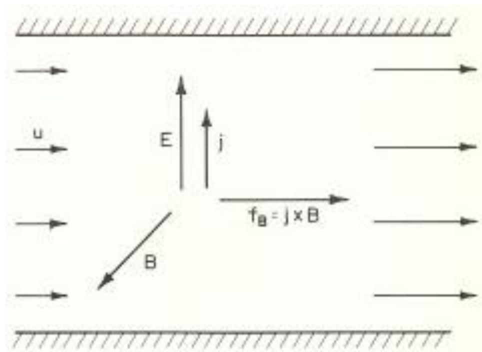

Figure 5: Electromagnetic Acceleration of an Ionized Gas Particle

The force exerted on a charged particle by the interaction between the electric and magnetic field is shown mathematical in Eqn. 12 below.

$$\vec{f}_b = \vec{j} \times \vec{B}$$ **Equation 12**

where $\vec{j}$ and $\vec{B}$ represent the current density directional force and the magnetic field directional force, respectively.

There are two concepts of electromagnetic thrusters each with differing attributes. These two thruster concepts are highlighted below.

4.1 Conventional Thrusters

Within the category of conventional thrusters there exist two types of thrusters: magnetoplasma dynamic (MPD) and pulsed plasma (PPT). Both of these thrusters are based on the Faraday accelerator. These thrusters utilize a plasma conductor that carries a current in the direction of an applied electric field, which is perpendicular to a magnetic field. As mentioned previously, these fields both lie normal to the direction of plasma acceleration. PPTs accelerate plasma between two rail electrodes fed by a capacitor, which is charged by a power supply. As current flows through the plasma the capacitor is quickly discharged. Therefore, in order to run a current through the propellant the mass flow rate must be “pulses” with the discharge schedule of the capacitor. PPTs do no use a nozzle to accelerate the plasma; however, some of the electrical energy is lost to the electrodes, which lowers the efficiency. MPDs are similar to the arcjet in the fact that an arc is used to simultaneously heat the propellant and form the electric field. An electromagnet is placed around the nozzle that creates the magnetic field. The coupling of the magnetic and electric field helps to accelerate the gas.

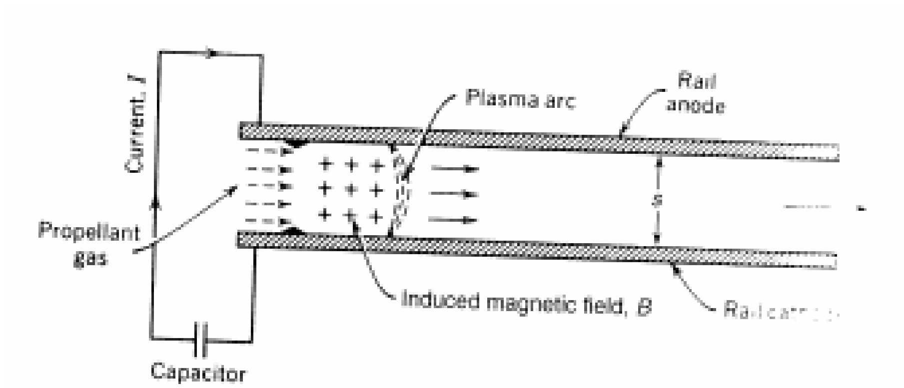

Figure 6: Diagram of a Pulsed Plasma Thruster

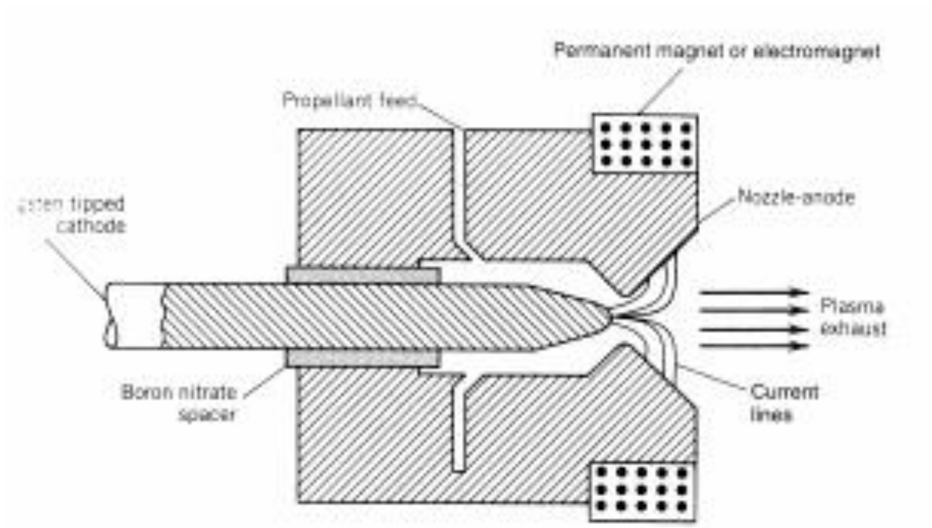

Figure 7: Diagram of a Magnetoplasma Dynamic Arcjet Thruster

Advantages

Advantages of pulsed plasma thrusters include low power and the use of solid propellant (eliminates the need for isolated containment as is the case for gas or liquid).

MPDs can be relatively simple devices to construct. The have a high specific impulse and deliver a high thrust per unit area.

Disadvantages

Downfalls of the PPT include low thrust, toxic reaction products (Teflon reactants), and corrosion.

MPD flow fields can be difficult to simulate analytically leading to difficulty measuring expected performance. They also require a high specific power to operate and as a corollary the power supply is more massive.

4.2 Hall-Effect Thrusters

Hall-effect thrusters utilize the Hall current and the interaction with a magnetic field to produce thrust. In low density plasmas and high magnetic fields the Hall-effect electric field becomes significantly high to be beneficial. The Hall current swirls electrons around a guided center. When a magnetic field is placed radially out from the motion of the Hall current the flow will spiral outward, accelerating.

Advantages

Hall-effect thrusters deliver a desirable specific impulse range. They require relatively simple power conditioning, and the propellant xenon is inert.

Disadvantages

Since xenon is the only safe propellant it eliminates any choice in propellant. The motion of the Hall current propagates the propellant in a spiral-like motion around the core. This motion leads to a high beam divergence which lowers thrust in the axial direction. Another negative from the Hall-effect thruster is that erosion takes place within the chamber.

4.3 Electromagnetic Propulsion Missions

Teflon pulsed plasma thrusters are known to have been used in east-west station keeping as well as sun orienting applications. PPTs would be a prime candidate for many space mission operations; however, their low thrust is of concern and is a major reason why the use of PPTs is not more wide spread.

Magnetoplasma dynamic thrusters have seen continuous performance improvements through continuous research. Though MPDs have great potential for future interplanetary missions due to their extremely high exhaust velocities they have not yet been flown on any operational missions.

5 Performance Capabilities

The wide array of electric propulsion devices produces a variety of performance specifications. Table 1 below lists several electric engine designs along with their corresponding performance data.

Table 1: Summary of Current Technology in Typical Electric Propulsion Engines

Engine Type	Identification (Reference)	Specific power, α (W/kg) (estimated)	Thruster Efficiency, η_t	Specific Impulse, I_s (sec)	Power (W)	Thrust (N)	Lifetime (hr)	Status
Resistojet	N_2H_4 (16, 21) (19–16, 19–21)	333–500	0.8–0.9	280–310	500–1500	0.2–0.8	> 390	Operational
	NH_3 (19–16)		0.8	350	500			
	Primex MR-501B (19–21)			303–294	350–510	0.369–0.182	> 389	Operational
Arcjet	N_2H_4 (19–21)	313	0.33–0.35	450–600	300–2000	0.2–0.25	> 830–1000	Operational
	H_2 (19–16, 19–21)	333	0.4	1000	5–100 K	0.2–0.25	> 1000	R&D
	NH_3 (19–16)	270–320	0.27–0.36	500–800	500–30 K	0.2–0.25	1500	Qualified
	Primex Mr-509 (19–21) (*c*)	115.3	> 0.31	> 502 (545)	1800	0.213–0.254	> 1575	Qualified
	Primex MR-510 (19–21) (*c*)	150	> 0.31	> 570–600	2170	0.222–0.258	> 2595	Qualified
Ion Propulsion	XIPS (19–21)	100	0.75	2800–3500	200–4000	0.015–0.014	> 8000	Operational
	Hughes XIPS-13 (19–21)		0.46, 0.54	2585, 2720	427, 439	0.0178, 0.018	12,000	Qualified
	Hughes XIPS-25 (19–21)		0.65, 0.67	2800	1400	0.0635	> 4350	Qualified
	NSTAR/DS1 (19–13)	45	0.6	3100	2300–2500	0.093	> 10,000	Operational
	RITA 15 (*a*)	9.61		3000–4000	540	0.015	> 20,000	Qualified
	UK-10/T5 (UK) (19–21)		0.55–0.64	3090–3300	278–636	0.010–0.025	10,700	Qualified
	ETS-VI IES (Jap.) (19–21)		0.4	3000	730	0.02		Operational
	DASA RIT-10 (Ger.) (19–21)		0.38	3000–3150	585	0.015		Operational
Hall	Hall (XE) (19–16)	150	0.5	1500–1600	300–6000	0.04	> 7000	Operational
	SPT (XE) (19–21)		0.48	1600	150–1500	0.04–0.2	> 4000	
	ARC/Fakel SPT-100 (19–16)	169.8	0.48	1600	1350	0.083	> 7424	Operational
	Fakel SPT-70 (19–3)		0.46, 0.50	1510, 1600	640–660	0.04	9000	Operational
	TAL D-55 (Russia) (19–21)	~ 50.9	0.48, 0.50–0.60	950–1950	600–1500	0.082	> 5000	Operational
	Primex BPT Hall (*c*)		0.5	1500–1800	500–6000			Development
MPD—Steady	Applied Field (19–16)		0.5	2000–5000	1–100 K			R&D
	Self-field (19–16)		0.3	2000–5000	200–4000 K			R&D
MPD-Pulsed	Teflon PPT (19–16)	1	0.07	1000	1–200	4000 N-sec	> 10^7 pulses	Operational
	LES 8/9 PPT (19–21)		0.0068, 0.009	836, 1000	25, 30	0.0003	> 10^7 pulses	Operational
	NASA/Primex EO-1 (*c*)	~ 20	0.098	1150	up to 100	3000 N-sec		Operational
	Primex PRS-101 (*c*)			1150		1.4 mN, 2 Hz		Operational
	EPEX arcjet (Jap.) (19–21)		0.16	600	430	0.023		Operational

Manufacturers: (*a*): Daimler-Chrysler Aerospace, AG., (*b*): Atlantic Research Corporation, USA Fakel (Russia), (*c*): Primex Aerospace Company

Such a wide array of engines gives engineers a great selection of propulsive devices to choose from that tailor to their specific mission goals.

6 Conclusions

This article has provided a general overview of electric propulsion with some minute derivations. The theory of electric propulsion has existed since the advent of the space program, yet its concepts are still being improved upon. Electric propulsion devices have great potential for future space exploration missions. They are fantastic devices for satellite orbit maintenance and hopefully with some improvements its application will extend to other spacecraft.

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