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Aspects of Electric Propulsion System Challenges and Opportunities

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ABSTRACT

The development of the area from its beginnings as the fantasy realm of a small number of visionaries to its transition into the concern of huge enterprises is particularly well-represented in the history of electric propulsion (EP), which now spans almost a century. Electric propulsion (EP) is a field of science and technology that covers a wide range of methods for reaching extremely high exhaust velocities in order to lessen the overall fuel burden and related launch mass of current and future space transportation systems. Electric propulsion is an innovative technology that utilizes electrical energy to propel spacecraft and satellites in outer space. Unlike traditional chemical propulsion systems that rely on combustion reactions, electric propulsion employs electric power to accelerate charged particles, usually ions, to generate thrust. These methods fall roughly into three categories: electromagnetic propulsion, where current driven through a propellant plasma interacts with an internal or external magnetic field to provide a stream-wise body force; electrostatic propulsion, where ionised propellant particles are accelerated through an electric field; and electrothermal propulsion, where the propellant is electrically heated and then expanded thermodynamically through a nozzle.

Keywords: Electric Propulsion, Types, Challenges

INTRODUCTION

Satellite operations and space exploration have been transformed by electric propulsion systems. They can travel farther and quicker while consuming less fuel thanks to their high specific impulse, which lengthens mission durations. Electric propulsion technologies allow satellites to easily maintain their orbits and change their positions, eliminating the need for expensive and cumbersome onboard fuel reserves. Electric propulsion is further useful for missions that call for fine control and manoeuvrability, such interplanetary missions and formation flying. Research is constantly being done to increase system effectiveness, save power usage, and improve thrust performance as electric propulsion technology develops. Future space missions, such as crewed exploration, asteroid mining, and interstellar travel, have a lot riding on the development of improved electric propulsion systems. The limits of human space travel can be pushed farther with the ongoing development of electric propulsion technology, opening up new vistas in our comprehension of the cosmos.

In a family of electrically driven spacecraft propulsion systems known as "Electric Propulsion" (EP), components are designed to employ electric and magnetic fields to accelerate a propellant and transform electrical energy from the spaceship's power sources into kinetic energy. Because they operate at a greater specific impulse (higher exhaust speed) than chemical systems, EP systems typically require a lot less fuel than chemical rockets. The thrust is significantly less compared to chemical systems, but electric propulsion can provide that tiny thrust for a long time. EP systems are more effective than chemical systems for deep space missions because they can eventually accelerate to extremely high speeds.

NASA started researching and testing various electric propulsion technologies in the early 1990s after identifying electric propulsion as a key enabling technology for upcoming deep space missions. Electric propulsion technologies may hold the key to our continued investigation of Earth's neighbouring planets because they are intended to lower fuel weight, shorten journey times to other planets, and allow for greater scientific payloads. Electric propulsion technologies use electrical energy to generate thrust. This electrical energy may come from a nuclear source, such as a space-based fission drive, which splits atomic nuclei to release large amounts of energy, or from a solar source, like solar photovoltaic arrays, which convert solar radiation to electrical power.

Electric propulsion (EP) is growing quickly in use for space applications right now. Numerous operating spacecraft use EP technologies, and according to industry predictions, approximately half of all commercial launches over the next ten years will use some kind of electric propulsion. A power processing unit (PPU), a fluid management system or propellant components, an optional aiming mechanism, and the essential thruster component make up the conventional EP system. The PPU, which processes raw power to suit the thruster as well as to heaters, valves, etc., receives regulated dc bus power from the power system. In order to maintain flow for extended periods of time, accurate flow controls and valves must be designed. The pipe work typically comprises series and parallel valves, pyrotechnically opening or closing valves, etc. The spacecraft's computer, which also manages a range of signals from pressure, sun, magnetometers, passive, and other sensors, issues commands.

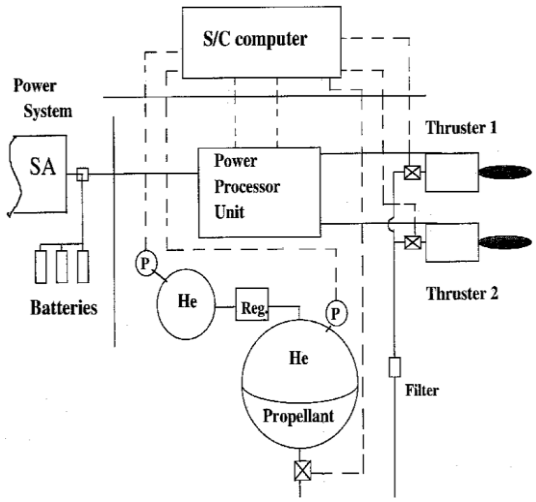

Fig. 1 Schematic of a typical EP system [1]

A collection of parts arranged in such a way as to ultimately transform electrical power from the S/C power system into the kinetic energy of a propellant jet is known as an EP system. The main components of an EP system and its interactions with other S/C systems are shown schematically in Figure 1. Typically, a power processing unit (PPU) and other auxiliary components like valves, heaters, etc. receive regulated dc bus power from the power system. As will be seen in the next sections, the PPU transforms this raw power into the precise form needed by the thrusters. It is typically one of the most difficult and complex EP components [1].

The thruster itself is the system's heart, hence this study will mostly focus on thrusters. It is important to realise that the propulsion engineer must spend a significant amount of time and energy balancing the EP system, which is ultimately typically heavier, bulkier, and more expensive than the thruster(s).

Types of Electric Propulsion

A resistojet (RJ) or an arcjet (AJ) with a physical nozzle or inductively with radio frequency (RF) power and a magnetic nozzle (RF, MN) are two examples of how heat can be introduced to an electrical propulsion system. Electrostatic acceleration uses an electric field that is time-invariant to accelerate ions and create thrust.

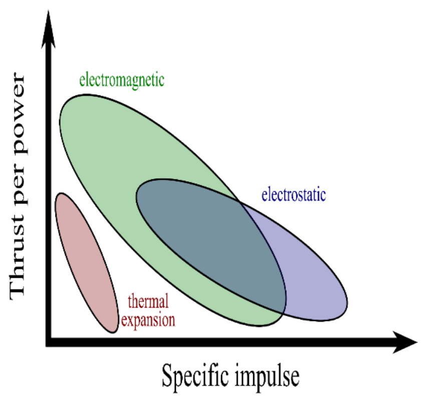

Fig. 2 The three major types of acceleration schemes for electric propulsion in terms of thrust per power and specific impulse

The Hall effect thruster (HET), the electrospray (ES), and the gridded ion thruster (GIT) are three popular technologies that fit into this category. In the first two, the accelerating electric field is created directly by applying a potential across electrodes. Without creating space charge, an electric field forms self-consistently near the exit of Hall thrusters. Magneto plasma dynamic (MPD), pulsed inductive (PIT), and pulsed ablative (or pulsed plasma, PPT) thrusters are examples of ideas that use electromagnetic acceleration. In these systems, the Lorentz force is employed to accelerate a plasma using either constant or time-varying electric and magnetic fields.

Electric Propulsion Development Cycle

We use the "s-curve" convention to visualise the relative maturity of the many electric propulsion technologies in a single framework. The qualitative stages of a technological development cycle can be represented by this frequently used measure [2]. A technology starts off at the preliminary formulation stage, as shown in Figure 3, where theoretical justifications or scaling laws may suggest that the technology promises new possibilities. At this stage, there might even be unoptimized prototypes.

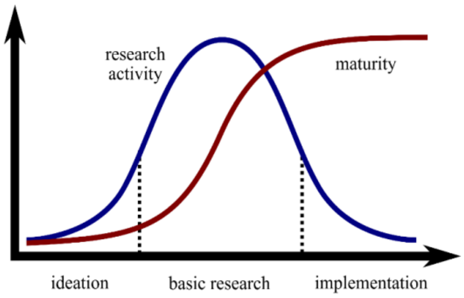

Fig. 3 The typical development of research activity for electric propulsion systems, transitioning from theoretical research to flight the cumulative research activity reflects the maturity of the technology [2]

The technology receives more resources in the next phase of the cycle in an effort to produce the performance predicted by theory. In this situation, performance and implementation have advanced dramatically thanks to basic research. The technology moves from the laboratory to flight at the end of the curve. As a result, the technology moves closer to its performance theoretical bounds, which marks the curve's inflection point.

Challenges for Electric Propulsion Development

Increasing the particular impulse and durability of high-power technologies and enhancing the effectiveness and dependability of low-power technologies are the two primary ways that electric propulsion will be moving in the future. Naturally, this new generation of satellites seeks a low-power electric propulsion option.

1. Low-Power Thrusters

Small satellites are becoming more and more popular, and this has increased the demand for propulsion systems that can operate on limited power budgets. Electric propulsion is a desirable alternative for these spacecrafts because they often have a limited mass budget for propellant. As a result, numerous EP technologies have been scaled down or created for sub-kilowatt installations.

2. Sub-Kilowatt Hall Thrusters

The s-curve for Hall thrusters in Figure 4 inflected many years ago and has been gradually maturing since then. Hall effect thrusters have typically been run at higher power levels than 500 W in order to maintain moderate current densities and reduce the ratio of wetted surface area to volume of plasma. The walls act as an energy sink that prevents the growth of the confined, hot acceleration region that gives this technology its efficiency for magnetic field topographies where the field lines intersect the channel walls almost perpendicularly. Due to this, the majority of flown, high-performance Hall thrusters today are typically >1 kW in power.

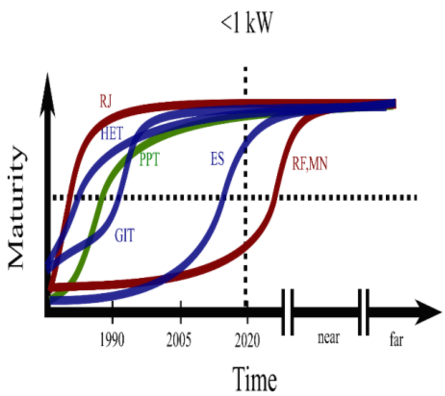

Fig. 4 Notional s-curves for various low-power electric propulsion technologies categorized with the color scheme of Figure 2. Shown are: RJ, resist jet; HET, Hall effect thruster; PPT, pulsed plasma thruster; GIT, gridded ion thruster; ES, electrospray; and RF, MN, radio frequency power paired with a magnetic nozzle [3]

The development of the Fakel Stationary Plasma Thruster family [3], the Central Research Institute of Machine Building (TsNIIMASH) D-55 Thruster with Anode Layer (TAL) [4], the Safran PPS series of thrusters [5, 6], and the Busek BHT family [7] were all notable historical examples of sub-kW device development.

3. Sub-Kilowatt Gridded Ion Thrusters

Similar to the path taken by sub-kW Hall thrusters, the development of low-power gridded ion thrusters saw substantial advancements decades ago, followed by a resurgence of interest in these devices over the past ten years.

4. Electrosprays

Electrospray arrays are possibly the most advanced and effective low-power electric propulsion technology that can fill the arbitrary low power requirement for near-Earth spacecraft. Because there is no ionisation involved, electrosprays do not have an increasing ionisation cost with decreasing size like Hall thrusters and gridded ion thrusters, which have poor geometric scaling. Since they can theoretically be scaled to minuscule dimensions, electrosprays work well at low power.

Twin four-head field emission electric propulsion (FEEP) units were able to achieve the mission's control, noise, and duration goals by using an electrospray system on the ST-7/LISA Pathfinder mission. The multiple anomalies that occurred during the trip, however—one thruster had a slow response time and current spikes, and another thruster developed a terminal short after 1670 hours of operation—made evident the necessity for further development of this technology.

5. Magnetic Nozzles

Similar to electrosprays, interest in microwave and RF thrusters as a workable alternative for electric propulsion has recently come back. Figure 4's s-curve illustrates how low-power RF nozzled thrusters have advanced recently from their relative infancy. Due to the effectiveness of inductive plasma creation and the lack of plasma-wetted electrodes, these devices can be employed with a range of propellants and are also easily scaled to low power.

The bottom end of the s-curve is still occupied by high performance (high specific impulse) variants of these devices.These electronics have been miniaturised and made more affordable over the ensuing decades, and as a result, RF nozzled thrusters are currently being considered for use on small satellites [9, 10].

6. Pulsed Plasma Thrusters

A straightforward electric propulsion method called pulsed plasma thrusters (PPTs) has undergone substantial theoretical and practical research, placing it high on its s-curve in Figure 4. These devices create an arc over a (usually) solid fuel, and then use the Lorentz force to accelerate the resulting plasma along parallel electrodes. Simple charging and discharge cycles of a capacitor, usually using an igniter circuit to start the discharge, are used to do this.

Numerous of these technologies have been created, including those by Austrian Research Centres GmbH [11], Mars Space Ltd. [12], Fotec GmbH [13], and Busek [14], and a number of them have been launched into space, beginning with the Soviet Zond-2 mission [15] and continuing more recently with Busek's PPT on Falcon-Sat 3 [16] and a number of thrusters created by Nanyang University and Kyushu Institute of Technology [17].

The lifetime of these devices, which inevitably strike high-current ablative arcs between electrodes, as well as the theoretical scaling restrictions to very low power present challenges.

7. Moderate-Power Thrusters

The electric propulsion devices with modest power, between 1 and 20 kW, are likely the most developed, as seen below in figure 5. The majority of commercial and deep space missions using electric propulsion in the following decade will rely on thrusters at this power level due to the availability of solar power on contemporary spacecraft, the requirements of flight-readiness, and the constraints of ground testing.

8. Hall Effect Thrusters

One of the most widely used EP technologies to produce relatively high thrust-to-power and efficiency above 1 kW is the Hall effect thruster. According to the figure above, these devices in this power range are at the peak of their s-curve with increasing flying experience. Hall thrusters having a history of poor power.

The effectiveness and durability of Hall thrusters have significantly improved since this technology was first made available to Westerners in the early 1990s.

When particular impulses are greater than 3000 s, Hofer et al.'s study of the plasma lens magnetic field topography demonstrated that Hall thruster anode efficiency can reach almost 70% [18].

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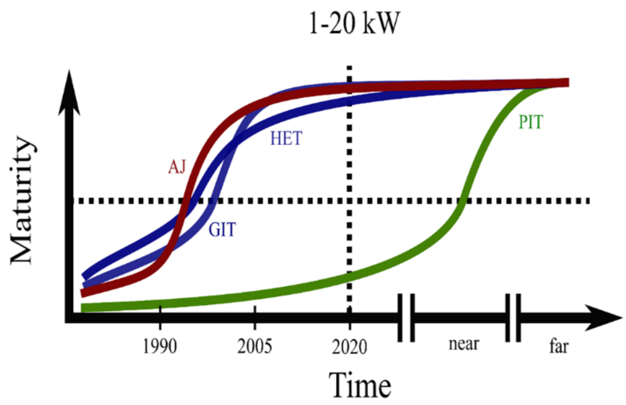

Fig. 5 Notional s-curves for various moderate-power electric propulsion technologies categorized with the color scheme of Figure 1, and additionally including arcjets (AJ) and pulsed inductive thrusters (PIT)

9. High Power Thrusters

There is a significant gap between the applications for which modern electric propulsion devices are suitable and those for which chemical propulsion is more appropriate due to the low thrust that these devices produce. For instance, crewed missions place a premium on quick transit times, necessitating the considerable thrust generated by chemical systems even at the sacrifice of cargo mass. With increased power, EP systems might be able to fill this market niche while yet maintaining the propellant efficiency that distinguishes this form of propulsion. As a result, research into scaling EP devices to higher power levels and investigating novel ideas that might succeed at >>20 kW is ongoing.

10. High-Power Hall Effect Thrusters

Figure 6 shows that, although being reasonably mature, Hall thrusters at high power are developing more slowly than their moderate-power equivalents. Physically scaling up moderate-power Hall thrusters was quickly realised to be impractical in the first decade of the twenty-first century. For instance, designs were made for the "NASA-1000M" thruster, which would have had a record-breaking 1 m in diameter and operate at 150 kW, but this device was never built [19].High-power Hall thruster research has advanced impressively, yet there are still several obstacles standing in the way of their development. First and foremost, the tremendous gas throughput of these devices is difficult for ground testing facilities to handle, casting doubt on the significance of facility effects.

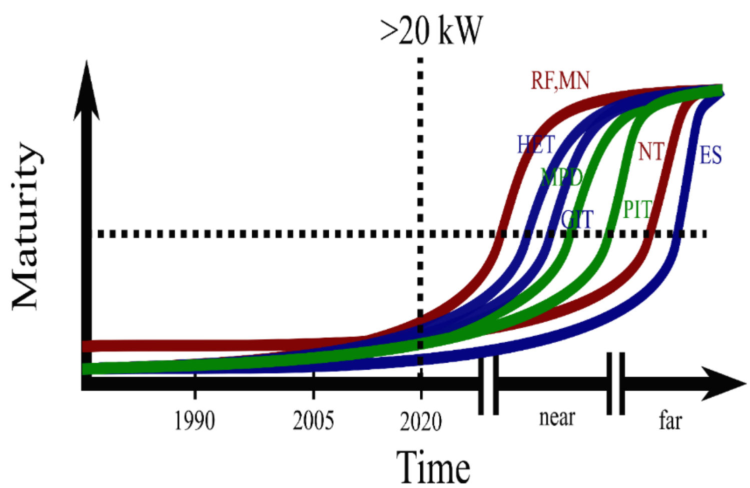

Figure 6 Notional s-curves for various low-power electric propulsion technologies categorized with the color scheme of Figure 1, including magneto plasma dynamic thrusters (MPD) and nuclear thermal propulsion (NT)

11. High-Power Gridded Ion Thrusters

High-power gridded ion thrusters, unlike many types of electric propulsion, were investigated decades ago, including a 130-kW mercury thruster [20], and as a result, they have long since ascended their s-curve in Figure 6. Despite the fact that numerous high-power GITs were built and tested, their complexity and power demands were significantly greater than what was (and arguably still is) feasible for flight. Because of this shift in research priorities, 2.3 kW NASA Solar Technology Readiness (NSTAR) thrusters were employed on the Deep Space 1 mission in 1998 [21].

12. Magneto plasma dynamic Thrusters

Magneto plasma dynamic (MPD) thrusters are an established electric propulsion technology that have long been constructed and tested to high power at ground facilities and have even been fired in orbit. They are similar to high-power gridded ion thrusters. Three decades ago, numerous devices were really pulsed at up to 1 MW [22, 23], and soon after, a 1 kW class unit flew on the Japanese Space Flyer Unit spacecraft [24]. The Lorentz force accelerates the arc plasma along the electrodes and out of the device after these devices create an arc discharge between concentrically spaced electrodes.

13. Large-Scale Electrospray Arrays

In the future, massively scaled electrospray arrays might replace all other types of electric propulsion in terms of thrust-to-power. This technology is still extremely early in its s-curve, as seen in Figure 6, but we anticipate that it will soon mature quickly. Large-scale electrospray arrays could equal the thrust of other technologies while operating with a lot more efficiency thanks to their high efficiencies (>70%), high specific impulse (>1000 s), high thrust-per-mass, and low thrust-per-emitter (1 N) [25].

14. Pulsed Inductive Thrusters

Because we still don't fully understand how these thrusters work physically, creating them with high power is difficult and frequently ineffective. The complex power electronics required to run these devices at high power also pose a significant engineering problem; for example, recent PIT designs as detailed in [26] entail switching components handling about 10 kA over the course of about 10 ns. The power electronics of the thruster's power electronics may consequently soon put a stop to scaling these components for higher power operation.

15. Magnetic Nozzles

Nearly as developed as their low-power counterparts, high-power magnetic nozzles have a substantially broader s-curve. The Variable Specific Impulse Magneto plasma Rocket (VASIMR), an ion cyclotron resonance thruster outfitted with superconducting magnets to form an incredibly potent magnetic nozzle, is the most well-known example of a high-power nozzled EP thruster [27]. Since the 1990s, this gadget has been the subject of serious research. Most recently, the VASIMR has accumulated almost 100 hours of operation at over 100 kW [28] during long-duration testing.

16. Nuclear Thermal Propulsion

Arcjets and resistojet are typically not taken into account for scaling to high power. Nuclear propulsion, which uses a prolonged fission reaction to heat a propellant before it is expanded out of a nozzle to produce thrust, is a logical application of these technologies. Since in-space reactor technology is still in its infancy, there haven't been any flights using nuclear propulsion.

The Nuclear Engine for Rocket Vehicle use (NERVA), one use of this technology, was interestingly ground tested in the 1960s [29]. Similar to those for in-space reactors, effective thermal management, launch safety, and efficient heat transmission are the key barriers to the development and flight of nuclear thermal thrusters.

At this time, more advanced electric propulsion technologies are frequently taken into consideration for usage in space, both in Earth orbit and beyond:

1. Plasma-based, xenon-fueled Hall thrusters
2. Solid Teflon-fueled pulsed plasma thrusters
3. Ammonia-fueledarcjet thrusters
4. Superheated water or nitrous oxide-fueledresistojets
5. Xenon-fueled ion thrusters

In order to test space hardware and electric propulsion capabilities, Deep Space 1, NASA's successful ion propulsion ship, is currently cruising the solar system 137 million miles (220 million km) beyond Earth.

Spacecraft propelled by conventional electric motors can fire propellant up to 20 times faster than those propelled by chemical engines, resulting in substantially higher specific impulse, or the amount of thrust produced per weight of fuel spent. In comparison to conventional, chemically powered craft, electric-based systems also use a lot less propellant mass.

Future interplanetary missions may be made possible by spacecraft with electric propulsion systems, such as ion engines and fission propulsion drives. These missions could range from low-power, automated missions to comets and other smaller bodies to long-duration studies of Europa and other Jovian moons, Pluto, and other large bodies in the outer solar system.

APPLICATIONS

1. Spacecraft Propulsion

Electric propulsion is commonly used in long-duration space missions where fuel efficiency and high specific impulse (thrust per unit of propellant) are crucial. It enables spacecraft to perform precise orbital maneuvers, station-keeping, and interplanetary missions. Electric propulsion systems, such as Hall effect thrusters (HETs) and ion thrusters, have been employed in numerous spacecraft, including communication satellites, scientific probes, and deep space missions.

2. Deep Space Exploration

Electric propulsion is particularly beneficial for deep space missions due to its high efficiency and ability to operate for extended durations. It allows spacecraft to reach distant destinations such as asteroids, comets, and outer planets with reduced fuel consumption. For example, NASA's Dawn spacecraft used ion propulsion to explore the dwarf planet Ceres and the asteroid Vesta.

3. Satellite Station-Keeping

Geostationary satellites require regular station-keeping maneuvers to maintain their position in orbit. Electric propulsion systems, such as Hall thrusters, provide efficient thrust for these purposes. By using electric propulsion, satellites can conserve fuel, extend their operational lifetimes, and maximize their payload capacity.

4. Orbital Debris Mitigation

Electric propulsion can be used for satellite end-of-life maneuvers and active debris removal. By equipping satellites with electric propulsion systems, they can be maneuvered to lower orbits or directed towards atmospheric reentry, reducing the amount of space debris in critical orbits.

CONCLUSION

The last century of theory and research has seen a tremendous evolution in the field of electric propulsion. The discipline has made immeasurable progress over the past few decades thanks to EP research and development. We are optimistic that these developments will continue in the near and long term based on these patterns and the variety of EP technologies that are being researched.Electric propulsion holds great potential for a more sustainable and efficient future. Continued research, innovation, and investment in this technology will drive its evolution, leading to broader adoption and further improvements in performance and affordability.

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