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Electric Propulsion: Systems Analysis and Potential Application in Space Exploration

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Abstract:
Electric propulsion is a technology which has the potential to achieve success in deep space interstellar travel as well as space tourism. Electric propulsion is the new age technology, emerging into a more practical concept andenabling us to foster new capabilities and achievements for space missions. The first phase of electric propulsion i.e. the history accounts from the first electric propulsion demonstration of Ion propulsion in SERT-1, 1964 to the NSTAR thruster which has 16,246 hours of operation and the successful missions to which electric propulsion was associated. The purity of the conceptis embedded in the understanding of fundamentals and principles i.e. rocket acceleration$\propto$ discharge of propellant mass, its equation of motion follows directly from conservation of the total momentum of the spacecraft and its exhaust streammatching the propeller and the engine, one must pay particular attention to the dependency between the power P and the generated thrust k. Electric propulsion systems and its particular application-based design is classified in ion & plasma drives and non – ion drives, where the former is sub-classified in electrostatic, electrothermal and electromagnetic propulsion while the latterinto photonic propulsion and unconventional propulsion.The comparative analysis provides critical information about the parameters deciding its application in real time scenario such as exhaust emission,efficiency, SPED value, power-to-weight ratio along with the future scope for potential research.

KeyWords*:Electric propulsion; Space propulsion; Electrostatic; Electrothermal; Electromagnetic; Thrusters.*

I. Introduction

Many missions that fulfill the strategic goals of NASA or any other space agency, such as exploring our Solar System, discovering new planets, stars, and galaxies, not to mention other Earths in neighboring planetary systems, and looking for life beyond our reach, are made possible by electric propulsion [1]. The advancement of electric propulsion (EP) technology is aimed at assisting missions by integrating and incorporating new technologies into projects. This paper is a study of electric propulsion systems. The future of electric propulsion is mainly pushing in two directions: increasing the specific impulse and longevity of high-power technologies and improving the efficiency and reliability of low-powertechnologies [2].Intheformer,thrusterswithlongerlifespansandgreater“fueleconomy”will enablenewdeepspacesciencemissions,andthusareofprimaryinteresttocivilianinstitutions.Inthe latter,droppinglaunchvehiclecostshasignitedinterestinsmall-scalesatellitesandconstellationsfor both commercial and scientific near-Earth applications. Naturally, a low-power electric propulsion solutionissoughtforthisnewwaveofsatellites. The benefits of electric propulsion systems are now being realized in low power on orbit applications [1, 2]. Electric Propulsion is more efficient and less expensive type of propulsion once a vehicle reaches orbit, so it is not yet used for early stages of rocket, Among the types of Electric propulsion thrusters, ion and plasma type are used most [3]. Currently,0.5kW-classelectricallyaugmented hydrazine thrusters **(EHTs)** are being used for North-South Stationkeeping (NSSK) of geosynchronous commercial communications satellites and very low power, pulsed plasma thrusters are in use for precise orbit control on U.S.Navysatellites [2].

II. History of Electric Propulsion

Electric Propulsion has over 50 years of development history from initial laboratory tests to demonstratebasicphysics to today's extensive system level tests to validate our understanding of complex spacecraftinteractions and life limiting mechanisms [4]. EP has a rich history of ground and flight testing in the U.S.,Europe, the Soviet Union and Asia. Ground testing has taken EP from paper through laboratory modelhardware to the qualification hardware that satisfies the "test what you fly" expectation/requirement of mission managers. One reference on the historical background and characteristics of the experimental flights ofU.S. ion propulsion systems and the major ground-based technology demonstrations is provided by Sovey[4]. The first successful ion engine flight occurred in 1964 on SERT I. This flight demonstrated ion beam neutralization. It was not until 1970 on SERT II, that extended operation of an ion thruster was demonstrated.These results together with the technology tested on the early AST series cesium engine flights and theground-test demonstrations provided the evolutionary path for the development of xenon ion thruster component technologies, control systems, and power circuit implementations [5].In 1961 the U.S. Air Force developed a cesium ion propulsion system (IPS) for three sub-orbital test flights,which collectively were called Program 661A, and were launched in November 1962, August 1964, and December 1964. The first successful ion engine flight occurred in July 1964 on NASA's SERT I, which hadboth a cesium and mercury IPS and demonstrated ion beam neutralization [4]. SNAPSHOT was launched inApril 1965 and included a cesium ion engine as a secondary payload to a nuclear reactor demonstration [5].Two cesium ion engines were launched aboard the ATS-4 spacecraft in August 1968, which measured thrustand demonstrated no electromagnetic compatibility problems with other spacecraft systems. ATS-5 waslaunched in August 1969 to demonstrate north/south-stationkeeping (NSSK) of a geosynchronous satellitewith cesium ion engines [4]. It was not until 1970 on NASA's SERT II, that extended operation of an ionthruster was demonstrated with two mercury ion engines.

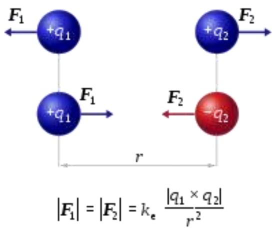
The purpose of the ATS-6 flight experimentlaunched in May 1974 was to demonstrate NSSK of a geosynchronous satellite using two cesium ion engine systems. The SCATHA spacecraft used xenon ion engines forcharged particle injection and demonstrated that ion engines could safely discharge a charged spacecraft toambient plasma conditions [5]. Major ground-based demonstrations of IPS include programs which althoughnever were flown, helped in the evolution of IPS development in the U.S. The objective of the Solar Electric Propulsion System Technology (SEPST) program was to demonstrate a complete breadboard mercury IPSthat would be applicable to an interplanetary spacecraft [6]. A mercury ion engine, called SIT-5 was developedaround 1970 for attitude control and NSSK of geosynchronous satellites.The Solar Electric Propulsion Stage (SEPS) was started in the 1970s to develop a mercury IPS capableof operating at a fixed power for Earth orbital applications or over a wide power profile such as would beencountered in planetary missions [6]. The Ion Auxiliary Propulsion System (IAPS) developed a mercury IPS inthe 1974 to 1983 timeframe to meet the objectives for operations required for stationkeeping, drag makeup,station change, and attitude control. During the 1980s and 1990s the XIPS-25 program developed xenonIPS at two separate power levels for stationkeeping, attitude control, and momentum dumping maneuversfor commercial geosynchronous communications satellites.In the 1997-1999 period, the communication satellite flights using ion engine systems [[5],[6]] and the DeepSpace 1 flight confirmed that these propulsion systems have advanced to a high-level of flight-readiness[7].The successful implementation and operation of the xenon ion propulsion system on Dawn[8] was theculmination of all of these technology development efforts.

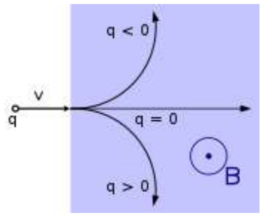
III. Electric Propulsion Fundamentals and Principles

Since the foundation of Electric spacecraft propulsion has been laid by the experiments of Robert Goddard with electric gas discharge tubes, electric propulsion systems have been developed and used at a remarkably high pace that can be described through its evolution from just satellites of few countries in 1950's to almost all satellites operating on electric propulsion systems at present. These capabilities of electric propulsion make it applicable to a large range of missions from micro-thrust for precision formation flying, to solar electric propulsion (SEP) for primary propulsion of near-Earth missions or satellite positioning, to high power nuclear electric propulsion (NEP) for deep space primary propulsion, and to mega-watt class thrusters for exploration missions. [9] The term electric propulsion encompasses any propulsion technology that uses electricity to increase the propellent exhaust velocity. Electric spacecraft propulsion systems had revolutionized the deep space industry due to their advanced performance metrics. Although this technology cannot be used as a rocket propulsion system to lift a certain mass from ground to space, it brings in a wide range of advantages for the spacecraft or satellite from being best compatible for deep space missions to performing the role of thermal ejection system. The U.S. and the Russians have now each flown well over a hundred thrusters in communications satellites and will continue to launch more ion and Hall thrusters in the future[10]. Electric propulsion systems provide the mission with several benefits from its high Fuel Efficiency (High Isp), ability to carry 2 to 10 payload increase compared to chemical thrusters and reduced trip time up to 3 times for many missions.Such electric propulsion systems work by accelerating the reaction mass or the fuel and ejecting it at extremely high velocities. Electric thrusters typically utilize less propellent than chemical. Due to limited electricity supply onboard the satellite or the spacecraft, electric propulsion systems are designed to be energy efficient at certain aspects like electricity consumption, overall efficiency, and specific impulse [10]. There are several kinds of electric propulsion systems currently in operation, but they are primarily categorized into 3 types i.e., electrothermal, electrostatic and electromagnetic thrusters. These are the ion thrusters that are considered an efficient way to travel farther, faster, and cheaper than any other propulsion technology currently available. Ion thrusters have demonstrated fuel efficiencies over 90 percent. Space crafts powered by these systems can reach speed up to 90,000 meters per second [10]. Current ion thrusters can provide only 0.5 newtons, but the acceleration continues throughout the journey. Statistical data from the Deep Space 1 probe shows that the ions were shot out at 146,000 kilometers per hour (more than 88,000 mph). Therefore, electric propulsion is suitable for low-thrust (micro and milli-newton levels) long-duration applications on board spacecrafts[11].

Working principle of Electric propulsion:

Electrostatic ion thrusters use coulomb force whereas electromagnetic thrusters use Lorentz force as their working principles.Coulomb's law (also known as Coulomb's inverse-square law) quantifies the force between twostationaryelectrically charged particles. This force is also referred to as electrostatic force. The law states that the magnitude of the electrostatic force of attraction or repulsion between two-point charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them[12]. Lorentz force is the combination of electric and magnetic force on a point charge due to electromagnetic fields. A particle of charge q moving with a velocity v in an electric field E and a magnetic field B experiences a force of **L= qE + qV x B**





The charged particles may undergo a large number of collisions with each other, and in some cases with the other species (ions, electrons, and/or neutrals) in the plasma. The effect of collisions is to develop a distribution of the velocities for each species[9]. Most of the charged particles in electric thrusters have a Maxwellian velocity distribution, which is the most probable distribution of velocities for a group of particles in thermal equilibrium. The Maxwellian velocity in one dimension can be determined using the formula:

$$f(v) = \left[\frac{m}{2\Pi kT}\right]^{1/2} exp\left[-\frac{mv^2}{2kT}\right]$$

M = mass of the particle
K = Boltzmann constant
T = Temperature

The ions in thrusters, have relatively low random velocities and temperatures. Hence, they are relatively low in temperature [9]. This occurs because the ions are not well confined in the plasma generators because they must be extracted to form the thrust beam, and so they leave the plasma after perhaps only a single pass. Therefore, the plasmas in ion and Hall thrusters are usually characterized as having cold ions and Maxwellian electrons with a high electron-to-ion temperature ratio ($T_e/T_i \approx 10$)[9]. Power supply for ion thrusters is usually through solar panels and nuclear power for large distance deep space missions.Electric thrusters provide low thrust and thereby low acceleration.An ion drive would require two days to accelerate a car to highway speed in vacuum. However, this acceleration can be sustained for months or years at a time, in contrast to the noticeably short burns of chemical rockets[12]. The power imparted to the exhaust increases with the square of exhaust velocity while thrust increase is linear.

$$F = 2\left(\frac{\eta P}{g(Isp)}\right)$$

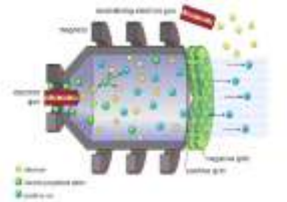
F = thrust force in N, η = efficiency, P = electrical power used by the thruster in W, I_{sp} = specific impulse in seconds.

IV. Types and Thrusters of Electric Propulsion

There are twoprimary categories of electric propulsion dividing thrusters as either ion and plasma drives or non-ion drives [13].Thrusters in these groups can be broken down into the different types of electric propulsion. Of theion and plasma drives there are three primary styles of electric propulsion that are used today. These areelectrostatic propulsion, electrothermal propulsion and electromagnetic propulsion [13]. These are more widelyused in the electric satellite field and have provided the thrust for multiple successfully operating satellites.Of the non-ion drives there are photonic thrusters, electrodynamic tethers, and unconventional propulsiontechniques. The working versions of these are not as widely used and many techniques are still concept ideasthat may prove to become successful thrusters in the future[13].

Ion and Plasma Drives

Electrostatic Propulsion: Electrostatic propulsion utilizes a propellant that can be ionized, such as Cesium, Mercury, Xenon, Argonetc. [13]. The propulsion in thistype of thrusters is created by accelerating ions using an electric field andallowing those ions to pass through a grid. The ions are then neutralized by a stream of electrons to preventany kind of charge build up on the bus. This technique provides a very low thrust but makes up for thelack of thrust by supplying very high specific impulses of around 3000-5000 seconds [13]. Thrusters of thistype are now being used more commonly for orbital transfer and orbital stabilization. The transfers usingelectrostatic propulsion have a far greater transfer time, but they have been proven to be more efficient. Thisis determined because the high Isp allows for thebus to submit low thrust for long periods of time and usevery little propellant. The ability to take only a fraction of the propellant mass to LEO and GEO makesthe takeoff require less propellant as well. In the cases that time is not of great importance these type ofthruster is one of the best choices for orbital maneuvers.



Electrothermal Propulsion: Some examples of Electrothermal propulsion are Arcjet, Microwave arcjet and Resistojet. This type of propulsion can be used with monopropellant and bipropellant rockets. The idea for this system is to aid what would normally be a cold gas system. Although this type of propulsion increases the Isp compared to chemical engines, the resulting Isp usually does not surpass 1000 seconds. This fall short of some of the other electric propulsion techniques, but it allows for a greater thrust [13].

Electromagnetic Propulsion: Electromagnetic propulsion utilizes plasma as its propellant. This is done by heating the propellant to temperatures of over 5000 degrees Kelvin [13]. By suppling a magneticfield, the conductive plasma portrays the Lorentz force. The plasma ions are accelerated via the magnetic forces created rather that needing an anode grid [13]. This technique also allows the particles to become accelerated without becoming fully ionized resulting in a higher efficiency. Electromagnetic propulsion can create thrust levels up to 100 times larger than electrostatic propulsion can. The high Isp and relatively low thrust compared to chemical thrusters makes this type of thruster best suited for long orbital transfers. These thrusters are used similarly to electrostatic thrusters although they are not as common because of the higher difficulty of producing them and maintaining them [13].

Non -Ion Drives

Photonic Propulsion: This type of thruster produces all its thrust with the use of photons, thus avoid having to carry and expel and kind of propellant for propulsion. The types of propulsion in this category include laser propulsion techniques. Laser propulsion uses a solar sail type system that utilize laser shot from the ground to propel the bus. Photonic laser thrusters use a stationary mirror to shoot lasers and reflect off. The laser is amplified off the mirror and propels the bus via its solar sail [13].

Unconventional: There are some unconventional types of electric propulsion that don’t fit in the other categories. These include quantum vacuum plasma thrusters, EM drives, and Cannae drives. These are mostly theoretical or are experimental only. These types of propulsion could be one of the prominent future type of electric propulsion but as of now we do not utilize any of these types of propulsion commercially [13].

Future

Photon Laser Thruster: The photon propulsion systems are not being utilized commercially yet, but they are theoretically one of the most efficient forms of travel even with a very minimal thrust. The future may incorporate these types of systems more in long travels and far explorations but the use of these for quick changes in orbit or for lower orbit propulsion is thought to be unfeasible [13].

Electric Propulsion Thrusters:

ResisoJets: As illustrated above, resistojets operate by passing the gaseous propellant around an electrical heater (whichcould be the inside of tubes heated radiatively from the outside), then using a conventional nozzle to generatethrust. The heating reduces the gas flow rate from a given upstream pressure through a given nozzle area,thus leading to the familiar increase in specific impulse [14, 15].

ArcJets: Just like resistojets, arcjets are electrothermal devices where the wall temperature limitation of the resistojets overcome by internal deposition of power in the form of an electric arc, typically between a concentric upstream rod cathode and a downstream anode that also serves as the supersonic nozzle [19]. The flow structure at the throat is extremely nonuniform, with the arc core at temperatures of 10,000–20,000K, and the buffer layer near the wall at no more than 2000 K. Because of this there is practically no flow through the arc core, which can be thought of as an effective fluid plug; this reduces the flow, without reducing the pressure integral, and leads to the high specific impulse [24, 25].

Hall Thrusters: Gas (usually xenon) is injected through the anode into an annular space and is ionized by counter flowing electrons, which are part of the current injected through an external hollow cathode (the rest neutralizes the ion beam). The ions accelerate under the electrostatic field impressed by the negative cathode and are only weakly deflected by the imposed radial magnetic field. The electrons, however, are strongly magnetized, and are forced to execute an azimuthal drift (Hall current), while slowly diffusing axially across the field toward the anode (from where the power supply pumps them to the cathode) [16].

Ion Engines: In gridded electrostatic ion accelerators, ions are produced in a separate, magnetically confined ionizationchamber, usually by a dc discharge (could be done by radio-frequency power(RITs)[16] or tuned electroncyclotron resonance (ECR ionizer)[16]. One side of the chamber is covered by a double grid structure, withspacing of the order of 0.5 to 1 mm, across which the ion acceleration voltage is applied.Ions that wanderinto the thin sheath covering the inner (screen) grid fall through and are extracted and accelerated, the ionoptics geometry being designed to avoid impact on the accelerating outer grid [23].Electrons are absent in the grid gap, which limits theextracted current below that level for which repulsionby ions in that gap would keep new ions from entering (space charge limit). The electric field at the innersurface of the accelerator grid is strong, and its pull on the grid transmits the thrust to the structure[17].

Pulsed Plasma Thrusters:A capacitor is charged from the primary power supply and applies 1– 2 kV across the exposed Teflon face;a spark plug initiates the discharge, which may be shaped by additional pluse-forming circuitry, and thecombination of thermal flux, particle bombardment, and surface reactions, depolymerizes, evaporates, andmostly ionizes a small amount of material (1.5 mg/J). The instantaneous current is in the tens of kA, andthe self-induced magnetic field is high enough to create a magnetic pressure comparable to the gas kineticpressure in the thin ionized layer; the combination of both pressure gradients accelerates the slug of gas tospeeds up to the vicinity of the critical Alfven velocity, at which the kinetic energy equals the ionizationenergy [18].

Field-Effect Electrostatic Propulsion (FEEP): The high field is created at the tip of a two-dimensional capillary feed channel (depth1 mm) withsharp lips, by an extractor electrode placed 0.5– 1 mm in front of it. Neutralization is done by a field-effectmicrotip array, which can emit ’1 mA/mm2 with a bias of the order of 100 V. This would be an excessivevoltage for traditional electrostatic thrusters, but FEEP requires a primary voltage in excess of about 6000V to initiate ion extraction, making the relative neutralization loss negligible [19].

Colloidal Ion Thrusters: The principle is analogous to that in FEEP, except that a nonmetallic liquid is used, and submicron-sizedcharged droplets are extracted rather than individual ions [14].

Magneto-Plasmic Thrusters: The self-field magnetoplasmadynamic (MPD) thruster creates an azimuthal B field, and a corresponding magnetic pressure, by passing a strong radial current between concentric electrodes (the samebasic principle as in PPT discharges, but with a different geometry) [26]. The thrust is proportional to magneticpressure, hence to I^2 (I being the current), and because the thrust power is $F^2/2m.C$, the back emf (usefulpart of the voltage) scales as $I^3/m.C$. This means that at low currents ohmic and near-electrode voltagelosses will dominate, and the efficiency will be low (although, as with PPTs, some recovery of the ohmicallydissipated power may be possible) [27].

V. Analysis and Comparison

Although it may seem like the work of fiction, Electric propulsion systems have been in use since the 1960’s and are being used for major missions in today’s world. Longer, cheaper and simpler make this class of futuristic propulsion systems perfect for many types of missions [28, 29, 30].While conventional chemical propulsion systems can lift huge spacecrafts with sufficient thrust, the engineering of the system is complex, making it quite prone to major issues and hence dangerous. Instead, electric propulsion systems require very little mass for acceleration of the spacecraft, the propellant can be discharged with almost 20 times the speed as plasma, making it overall incredibly mass efficient and the use of electric power boosts it's propulsive performance. It provides flexibility in locating mechanism compartments and even designs with minimal or absolutely no moving parts, piping, valves, etcetera [31, 32]. It offers significant advantages, enabling interplanetary missions previously thought unfeasible by other propulsion systems for propellant, mass and impulsive thrust efficiency requirements. Other advantages include reduced pollution and increased operational efficiency-especially at low speed.

There are two general types of propulsion systems- primary propulsion systems, which perform functions like orbit transfer, and the secondary propulsion systems, which perform functions like orbital attitude and control, reaching the desired position after initial injection from the launcher, maintaining the satellite in the required position during its operational time, graveyard injection at satellites end of life, precise course correction during interplanetary missions deceleration of satellite to swing into an orbit of a planet or a moon. The tasks for secondary propulsion depend on mission and propulsion requirements [28, 33].The overall electric propulsion systems are categorized as Electrothermal, Electrostatic, and Electromagnetic based on how the propellant is accelerated.

Multiple countries and their companies are focusing on developing and launching electric thruster systems for various missions bringing novel designs and approaches to drastically advance this field. Some of the companies which have been developing EP systems include NASA, Maxar Electric Propulsion, Rafael, MELCO, Airbus, Boeing, SITAEL, Ad Astra, Accion systems, Busek Co. Inc., Safran SA,ThalesAlenia Space, Northrop Grumman Corporation, Apollo Fusion IRS, JAXA, ISA, ESA, ISRO, Phase Four, Exotrail, Eutelsat, and many, many more. New tests with iodine electric system which marked a historic launch by ThrustMe in 2020 was also news realizing the upcoming interest in EP systems for smaller satellites like CubeSats [34, 35].

Hall thrusters prove to be significantly better than chemical propulsion, but their reliability decreases overtime as compared to gridded ion thrusters [36]. Hall thrusters have been seen to exhibit minor anomalies on orbit at the early stages and gridded ion thrusters show wear out failures. A reliability growth program and better ground testing and acceptance steps could possibly solve these issues [28, 36]. EP anomalies evidently arise from space environment or difference in thruster cycle dependencies.In recent years, the number of geostationary satellites with EP systems has increased from 5 to 15 on average. The market growth of EP is predicted to be at a CAGR of 14% and the 100% EP system spacecrafts are said to be in key trend for the next few years. The incorporation and wide use of 3-D printing technology for the system drives and components is predicted to be an important part to cater to the ever-growing need of compactness, simplicity and sophistication of the system.Solar electric propulsion systems seem to be going well with the mission needs today but not all power needs are aptly satisfied with just solar power. For better performance and for large scale missions in the future, nuclear power unit must be developed with reliable characteristics [37]. Hybrid EP systems are in tremendous research and development stages after the burst of EP since 2018-19. A lot of the hybrid systems in design processes are predicted to spearhead the futuristic EP systems and bring quicker progression such as the High Efficiency Multistage Plasma Thruster, Field-Emission Electric Propulsion thruster, Electrospray thrusters, Variable Specific Impulse Magneto-plasma Rocket are concepts that with better testing and research could outdo all present propulsion systems and many more concepts are still underway[28, 38]. As of yet, the QinetiQ T6 ion thrusters are the most powerful propulsion system in space.

VI. Recent Development and Technologies in Electric Propulsion

Recent developments [39,40, 41] have been directed to increasing use of CubeSats and tailoring electric thruster systems to suit their power, thrust and payload needs. The Cylindrical Hall Thrusters are considered a promising system as they discard the central cylindrical part making it simple and reliable, and some Hall Thrusters feature a wall-less configuration-the plasma discharge is shifted outside the channel reducing erosion at the walls and hence increasing efficiency [41]. Furthermore, to reduce industrial costs, hybrid configurations can be used.Significant research and developments for Hall and Ion thrusters and other plasma sources have been made in performance and modelling of thermionic hollow cathodes, in the case of low current hollow cathodes, HHCs (heater-less hollow cathodes) have been of interest in the recent years.Apart from traditional plasma-based electric thruster systems, some incredibly futuristic but marvelous recent theories of propulsion are laser, electric and magnetic beam-sail propulsion systems [42]. In the laser propulsion system, the proposed concepts include the laser-pushed Lightsail with or without photon recycling and the laser energized rockets-laser thermal rocket, ablative laser propulsion, pulsed plasma propulsion (lightcraft developed by LeikMyrabo and Frank Mead) and CW plasma propulsion [43]. The magnetic sail or the magsail and the electric sail both can work just from solar wind and can be considered solar sails. These techniques of micro propulsion have been going through tremendous research over the past few years. The thrust to weight ratio can be significantly greater as compared to conventional electric propulsion systems, as they include physically disconnecting the power generation unit and the spacecraft, making it overall compact and with higher efficiency [44].

A comparatively new approach in development of electric propulsion systems is the use of nanomaterials, they are proposed to have multiple uses in the thrusters such as, surface healing, ultra-nanocrystalline diamonds or graphene erosible as a substitute for the easily ceramic wall, graphene nanotubes for channel wear resistance, nanocrystalline graphite and carbon nanotubes grown in clusters for a potentially efficient substitute for cathodes [39]. Self-healing which is essentially just surface healing of the chassis, which is significantly important for next generation thrusters, either selective deposition of patching material or electric field induced reconstruction have been demonstrated to be viable methods for healing of damaged surface[39, 40].

Since 2019, some major launches including electric thruster systems are: AOBA-VELOX-IV(pulsed plasma thruster-PTFE), Xiaoxiang-103(electrospray thruster), Starlink L0 & 1-1 to 1-60 & 2-1 to 2-60 & 3-1 to 3-60 (all Hall Effect thrusters-Krypton), Yamal 601(Hall Effect thruster-Xenon), ShiJian 20 and JCSAT-18/Kacific-1 (both Ion Engines-Xenon), Eutelsat KONNECT(XPS-Xenon), GSAT-20(Hall Effect thruster-Xenon), SES-17(Hall Effect thruster-Xenon).Upcoming planned missions including electric thruster systems are: Hotbird 13G and 13F(Hall Effect thruster-Xenon) in 2021, ASTER(Hall Effect thruster-Xenon) in 2021, ETS-9(Hall Effect thruster-Xenon) after 2021, Ionozond(Ionosfere 1&2)(Pulsed Plasma thruster-PTFE) after 2023 and the Soyuz-Sat-O(Pulsed Plasma thruster-PTFE)(date of launch unconfirmed) [45, 46, 47].

VII. Limitations

Electric thrusters operate with very small flows, so they drive the spacecraft very gently in contrast to chemical systems [48]. As a consequence, electric propulsion cannot be used when high acceleration is needed.The electric propulsion system's Power Processor Unit transforms raw power into the specific form needed by the thrusters, and it's typically one of the most complex and difficult EP components. As a result, the Power Processing Unit can be many times the thruster's weight. The tendency of the hydrazine to create nonvolatile deposits at the hot inlet to the catalytic chamber is one of the major problems presented by these resistojets [48].If the plume intersects the antenna pattern in hall thrusters, deep current fluctuations at a few tens of kHz, combined with a variety of higher frequency (but less deep) plasma fluctuations, can cause communications interference problems. Erosion of the ceramic is the key limiting factor in thruster lifetime.The EP thrusters have a short lifespan of a few hundred hours. It is determined by the erosion and evaporation of the cathode material in the arc area caused by ion bombardment, especially during discharge ignition [49].Ion thrusters are large, bulky EP devices with a complex power processing unit capable of delivering high voltages and controlling multiple components. Since the beam divergence angle is poor (less than 10 degrees), interactions with spacecraft components such as solar panels are restricted [50].Future missions, such as deep-space exploration, would have a power requirement that clearly scales with distance due to their low thrust range (0.1 to around 100 mN) and vacuum requirement. This amount of power cannot be produced exclusively by solar-electric conversion [51].Interaction of the plasma plume or any of its components with spacecraft components (e.g: solar arrays, electronic subsystems) will compromise the spacecraft's function and lifespan [51].The discharge chambers are prone to sputtering and spalling as a result of the ion bombardment.

VIII. Future Scope

Over the years, EP has received positive feedback and has been successfully deployed on a variety of commercial and military satellites. Regardless, there is a surge in interest in EP systems right now [49]. However, the application of EP to scientific Earth and solar system robotic mission’s lags behind that of commercial satellites. There are signs that the gap between the two may be closing. This is reflected in a number of recent science missions conducted by three different agencies, all of which have used or plan to use EP. There is, of course, a financial consideration to be made [52]. In a competitive environment, the mission that does not use a "new" propulsion system would have an advantage. A task has been established by NASA's In-Space Propulsion Technology project to begin addressing this challenge. Without a doubt, the number and variety of effective EP systems will skyrocket in the near future. The situation is slightly different when it comes to ambitious EP-based space missions with large velocity increments. Several issues and challenges remain, despite the fact that high-power high thrust devices such as MPD thrusters, HTs, and the VASIMR engine have already been developed and investigated [49]. Despite the fact that solar panels' efficiency will undoubtedly improve, nuclear energy remains the only option for deep space exploration. As a result, compact high-power nuclear fission reactors will have to be deployed in space, posing both a technological and political challenge. It is, however, the cost of expanding the boundaries of human knowledge [49]. Satellites with electric propulsion are being used by an increasing number of companies to extend the operational life of satellites and reduce launch and operation costs. This results in cost savings that can be passed on to the public. Ion propulsion will be used primarily by NASA for main propulsion on long missions that would be difficult or impossible to complete with other types of propulsion [53].

Thrusters are being improved to allow them to operate at higher power levels, faster speeds, and for longer periods of time. NASA is developing PPU and PMS technologies that will allow them to build lighter, more compact systems while also increasing reliability.High-powered thrusters will be developed as new power sources become available, allowing for greater speed and thrust. Supporting technologies like carbon-based ion optics and ECR discharges could greatly extend the operational life of ion thrusters, allowing for longer missions or high-power IPS operation. Humanity will be able to explore the farthest reaches of our solar system, thanks to these technologies [49, 52].

IX. Conclusion

In this paper, we have reviewed the vital role of advancement of the electric propulsion systems in space exploration as it has been observed that it is now around 5 decades since the initialization of electric propulsion as one of the substantial and efficient future in-space propulsion system. For more full-fledged EP devices, we pointed out the challenges as being the consideration of different thrust requirements, EP thruster’s life span, facility effects and long-duration testing while some recent developments suggest that there are possible practical situations for using EP devices of which the solutions were brought by numerical and experimental facility effect investigation, new power processing/sources systems and data driven techniques. In terms of growth of practical applications and real time space missions, the electric propulsion technology has come a far now and has to go a far way because of the benefits it potentially brings to the table which probably no other propulsion technique can possibly do. In coming times, we will see the challenges turning into effective applications in real world while we will be looking at some advanced level challenges then to rise to the peak of efficiency of electric propulsion systems.

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