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Review

Unveiling the Future: A Survey of Electric Propulsion Systems and their Pivotal Role in Shaping the Next Frontier of Space Exploration

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Abstract: Electric propulsion represents the future of space travel, which is a promising technology for Earth-orbital and deep space missions, including potential applications in human Mars missions. The past decade has witnessed substantial progress in the conceptualization and experimentation of electric thrusters and their propellants, signaling a transformative era in space exploration. This review provides an overview of the comparison between electric and chemical propulsion, followed by a detailed examination of current research and development on various types of electric propulsion thrusters. The discussion encompasses the adoption of diverse technologies to enhance the scalability of these thrusters, presenting a comprehensive outlook on the future of space exploration.

Keywords: Electric Propulsion, Thrusters, Propellants, Space Exploration

Introduction

Electric propulsion systems have proven to be highly effective in various spacecraft applications, serving diverse purposes across the space industry. At their core, all-electric propulsion systems operate on the fundamental principle of converting electrical energy into kinetic energy to generate thrust. Through thrust, propellants are accelerated by the application of electric or magnetic power for optimum performance.

The high thrust generated in the electrical propulsion systems gave it have advantage over the traditional propulsion systems over the decade at a substantial increase in velocity. Chemical propellants, with their finite fuel supply, have caused missions to end prematurely for various spacecraft and satellites. For instance, the Kepler space telescope, launched in 2009, had its mission lifespan curtailed to nine years in deep space due to the exhaustion of its hydrazine propellant. The adoption of electric propulsion has addressed this limitation, markedly prolonging the operational life of satellites and spacecraft in space.

Electric thrusters outperform their chemical counterparts by showcasing efficiency levels that are six to ten times higher. This means they can generate more propulsion power per unit of fuel, contributing to enhanced overall performance and mission capabilities in space exploration. As a result, key sectors within the space industry, including earth science, human exploration, space sciences, and space development, have shown a keen interest in advancing electric propulsion technology.

The industrial application of electrical propulsion gained acceptability such as station keeping, interorbital transfers, long endurance missions, and interplanetary exploration. This article provides a survey on the variants of electric propulsion thrusters. It explores the thrusters currently in use and those still in the developmental stage, highlighting their limitations and research that pave the way for more extended and efficient space exploration.

Electric Thrusters

Resistojets

A resistojet is a type of thruster that operates on the principle of electrothermal propulsion. It generates thrust by passing propellant through an electric heater (or a heat exchanger chamber), where it becomes superheated and is then expelled through an expansion nozzle (Frisbee, 2003). Within this nozzle, the heating process causes the gas flow rate to decrease from a given upstream pressure, resulting in an increase in specific impulse (Martinez-Sanchez and Pollard, 1998). Consequently, a higher temperature in the working fluid indirectly translates to increased energy production relative to a specific impulse, thereby generating the necessary thrust. As outlined by Frisbee (2003), resistojets are suitable for propellant gases such as ammonia, biowastes, hydrazine, and hydrogen.

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Resistojets are the simplest form of electric propulsion (Fig. 1). However, they have limited challenges such as heat transfer from the resistance element to the propellant flow, radiation loss from the design assembly, limitations in sourcing high-temperature materials, and frozen flow losses (Frisbee, 2003). Weathersby (2021) explain that a strategy that is still in the conceptual stage for overcoming frozen flow and achieving effective heat transfer is to analyze them using various heat transfer techniques.

A heat exchanger is one of the heat transfer techniques with a streamlined fluid in which its fluid flow is said to be laminar flow by minimizing time contact. The fluid in contact with the heat exchanger is said to be heated which tends to loss it frozen in resistojet. An innovative design has been developed by Benchmark to enhance the mixing of the flow, ensuring that it forms vortex streams as it travels down the heat exchanger. This aids in spreading heat evenly throughout the flow, resulting in a 40% greater increase in specific impulse compared to laminar flow (Benchmark Space System, 2022).

Despite these challenges, there are other advantages, such as its ability to generate thrust within its minimal power requirements compared to other thrusters, a relatively compact body with low mass and relatively small impulse bits (Weathersby, 2021) All of these advantages make it an attractive choice for on-orbit missions, such as iridium low orbit constellation satellites and Intelsat V, as well as for attitude control and station-keeping on a wide variety of commercial satellites (Frisbee, 2003).

Amid the increasing focus on environmentally friendly and non-hazardous propellants, the exploration of micro-resistojets that replace inert gases with water or ice as propellants present a promising avenue for adoption in cube sats. The utilization of electro-thermal micro-thrusters with water as a propellant offers a specific impulse comparable to chemical systems while enabling higher thrust generation (Cervone *et al.*, 2017).

Arcjet

An arcjet is a type of electrothermal thruster that utilizes an electric arc to supply heat to the propellant through a constrictor and then expands the hot gas through a nozzle (Wollenhaupt *et al.*, 2018). The cylindrical symmetric geometry of an arcjet consists of a concentric upstream rod cathode, a downstream anode, a constrictor channel, a supersonic nozzle (which functions as an electric arc), and a propellant injector (Frisbee, 2003). Unlike the resistojet, which has limitations related to wall temperature, arcjets overcome this issue by internally depositing power in the form of an electric arc, (Fig. 2).

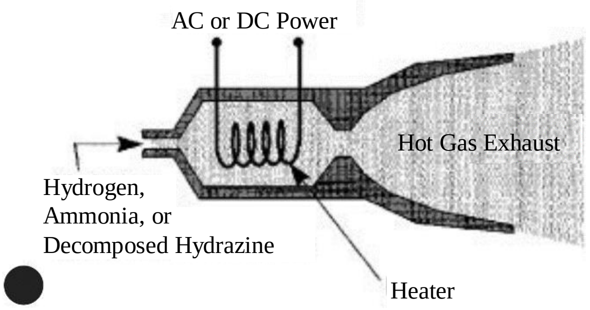

Fig. 1: The schematic diagram of a resistojet thruster (Martinez-Sanchez and Pollard, 1998)

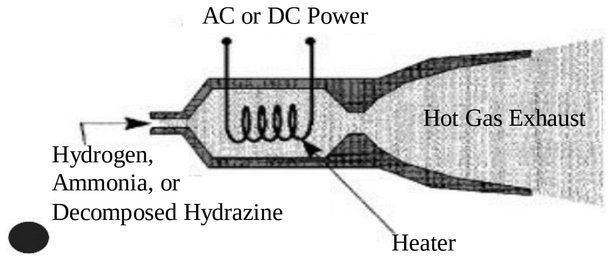

Fig. 2: The schematic diagram of an arcjet thruster (Martinez-Sanchez and Pollard, 1998)

Arcjets are susceptible to cathode erosion. In an experiment with a 100 kW arcjet thruster, a hollow cathode was explored as an alternative to the rod cathode and to limit erosion (William, 2002). The use of the hollow cathode resulted in achieving both high specific power and high specific impulse during low flow rate operation when compared to the rod cathode (Takahashi and Kinefuchi, 2023). There are several types of arcjets, configured based on their method of propellant heating, with the DC arcjet being the most highly developed. It offers the highest thrust-to-power ratio among all-electric propulsion thrusters, making it suitable for north-south station-keeping on commercial communication satellites such as Intelsat 8, AsiaSat, and Echostar.

The potential propellants of interest include Hydrazine (N_2H_4), Ammonia (NH_3), and hydrogen. Hydrogen offers a competitive advantage by achieving a specific impulse of over 1000 ISP compared to the other working gases. However, it suffers from low storage density and the cryogenic nature of the fuel. It is suitable for missions involving continuous thrusting, with tanks cooled by the evaporation of the feed. Martinez-Sanchez and Pollard (1998) reported that Ammonia readily dissociates in the arc into low molecular mass components, resulting in a high specific impulse.

Furthermore, in a study published by another author (Blinov *et al.*, 2020) employing ammonia as the working fluid in pulsed mode operations yielded a specific impulse, ranging from 230-340 s while consuming power in the range of 5-30 W. This makes it preferable for missions where cryogenic hydrogen tanks are impractical.

Hydrazine propellant, like ammonia, is used on a 1 kW medium arcjet thruster and stored in space in liquid form. It gives a viable choice for replacing chemical monopropellant thrusters while retaining some components of the propulsion system, such as tanks, valves, and filters. This approach is cost-effective when considering the overall expenses.

Hall Effect Thruster

Hall thrusters are gridless ion engines that produce thrust by electrostatically accelerating plasma ions out of an annular discharge chamber. The Hall Effect Thruster (HET) was initially developed by the United States and the Soviet Union. However, the USA had to pause its development due to prior limitations in achieving the same efficiency as gridded ion engines. The Soviet Union adopted the HET and made further improvements in efficiency and unique design concepts, which helped minimize energy loss to the discharge chamber, directly improving discharge efficiency. Hall effect thrusters are relatively well known for their great thrust-to-power ratio, high efficiency, typically ranging between 50 and 60%, and a relatively high specific impulse, ranging from 1000-3000 s (Dale *et al.*, 2020). These characteristics make them typically applicable for station-keeping, spacecraft maneuvering, and orbit transfer. There are two types of hall effect thrusters: The Stationary Plasma Thruster (SPT) and Thrusters with Anode Layer (TAL), which were developed by the Kurchatov institute and the central research Institute for Machine Building (TsNIIMASH).

The difference between SPT and TAL thrusters is that the acceleration region for SPT is located within the thruster, whereas TAL is positioned at the front of the thruster. The acceleration walls for SPT are made of ceramic, while TAL uses metallic materials such as stainless steel or molybdenum and they have narrower and shorter channels (Martinez-Sanchez and Pollard, 1998; Inamdar *et al.*, 2021).

There are various types of hall thrusters that have been developed in several laboratories and manufacturing companies around the globe (MIT OpenCourseWare, 2015) However, hall thrusters are designed based on their geometry, whether annular or cylindrical in shape. According to a source (Bapat *et al.*, 2022), annular thrusters are suitable for deep space missions, while cylindrical thrusters are applicable to satellite_station keeping due to their lower power consumption. Hall thrusters face limitations related to the erosion of their ceramic walls, which poses threats to the operational life of the thrusters, (Fig. 3).

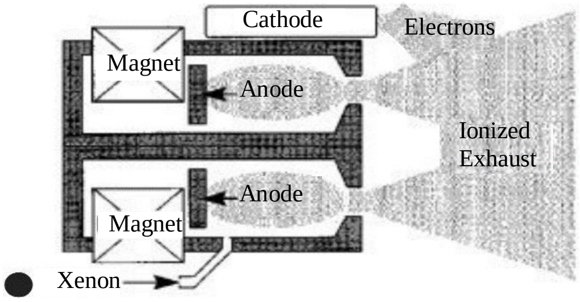

Fig. 3: The schematic diagram of a hall effect thruster (Martinez-Sanchez and Pollard, 1998)

Grimaud and Mazouffre (2017) investigated that low-sputtering materials like boron nitride and silica (Borosil) used as walls on hall thrusters are better substitutes for ceramics because their wall materials offer lower electron emission and reduced ion-wall interaction. Additionally, the concept of magnetic shielding has been proven to improve the thrust performance and lifespan of thrusters by reducing both the discharge chamber erosion and secondary electron emission. A distinctive advantage of hall thrusters, compared to gridded ion thrusters, is that they generate and accelerate ions within a quasi-neutral plasma environment, eliminating the limitations imposed by the child-Langmuir charge (space charge) saturated current on thrust density (Inamdar *et al.*, 2021). Among the various propellants used in hall thrusters, xenon has been highly recommended due to its potential to achieve a good thrust-to-power ratio coupled with a high specific impulse compared to chemical propellants. However, there are promising potential propellants in the form of different noble gases, molecular propellants, and condensable elements like krypton, iodine, zinc, and bismuth (Tirila *et al.*, 2023). By elevating the thruster current density, we can effectively enhance krypton's performance compared to xenon (Su *et al.*, 2023). SpaceX's Starlink constellation is a major user of hall thrusters.

Gridded Ion Engine

The Gridded ion engine, also known as an ion engine, falls under the category of electrostatic interactions, (Fig. 4). At high specific impulse, the overall efficiency is good, but it begins to degrade at lower exhaust speeds due to an increase in the effective energy expenditure for ionization the magnitude of total thrust varies depending on the size of the thrusters, ranging from micro thrusters yielding 10^-5 Newton to large modular arrays of thrusters capable of nearly 1 N (Jahn, 2006). Ion thrusters use Xenon as their propellant and types that have progressed beyond the experimentation stage include contact ion (Jahn, 2006) engines, microwave ion engines, plasma separator ion engines, Radio Frequency (RF) and microwave ion engines, radioisotope ion engines, and the dc electron bombardment engine (Frisbee, 2003). Despite its inherently low thrust level, the electron bombardment engine is the most researched. It was used for the transfer to the geosynchronous orbit of the first two all-electric communication satellites, ABS-3A and Eutelsat 115. The engine, known as XIPS-702 by Boeing, delivered 165 kN at 4.5 kW to reach its final orbit in 6-7 months (Frisbee, 2003). Next (evolutionary xenon thruster) engine developed by NASA offers the capability to handle increased thruster input power, all the while maintaining low voltages and ion current densities. This versatile engine is capable of producing thrust power within the range of 0.5-6.9 kW, providing a specific impulse of 4,192 sec (Fisher, 2020).

Pulsed Plasma Thruster

A pulsed plasma thruster is an electromagnetic device that generates thrust through the interaction of an arc passing from the anode to the cathode, aided by its self-induced magnetic field, with the goal of accelerating a quantity of fluorocarbon to achieve a high specific impulse ranging from 300-1400 sec (Mcguire and Myers, 1996).

The simplicity of Pulsed Plasma Thrusters (PPTs) in their structure makes them an attractive choice for miniature spacecraft applications (Fig. 5). They were initially utilized as an actuator for the altitude control system on the Soviet Zond 2 mission (Kazeev *et al*., 2009). The performance of PPTs is influenced by various factors, including electrode structure, propellant selection, energy discharge circuit, ignition method, propellant feeding system, and the number of thruster heads (Zhiwen *et al*., 2020). Different forms of propellants, such as gaseous, liquid, and solid, have been researched for use in PPTs. Among these, solid Polytetrafluoroethylene (PTFE) stands out as the most widely used propellant for PPTs. PTFE's advantages include its ability to function without the need for valves, injectors, or heaters, leading to improved performance and ease of storage. However, the use of PTFE at low-energy discharges in miniature satellites has the potential to cause carbon accumulation within the thruster walls. This accumulation eventually limits the operational lifespan and adds complexity to the mechanical propellant feeding system, especially for higher propellant masses. As an alternative, recent research (Ling *et al*., 2020) has introduced new propellants, such as sulfur, which do not lead to carbon decomposition.

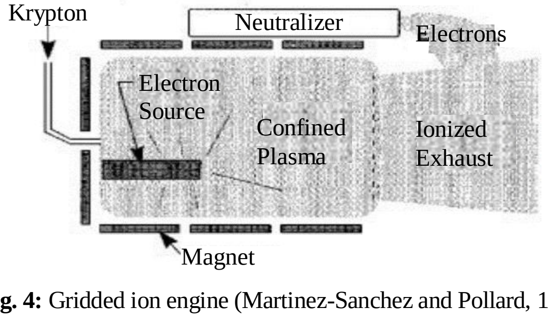

Fig. 4: Gridded ion engine (Martinez-Sanchez and Pollard, 1998)

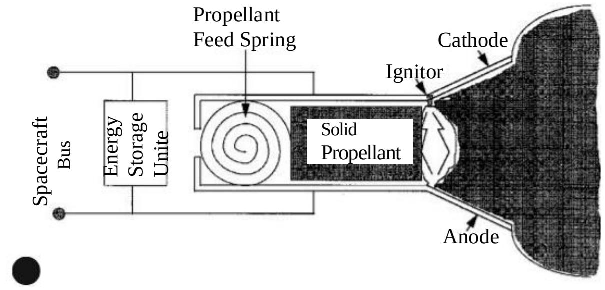

Fig. 5: Pulsed plasma thruster (Martinez-Sanchez and Pollard, 1998)

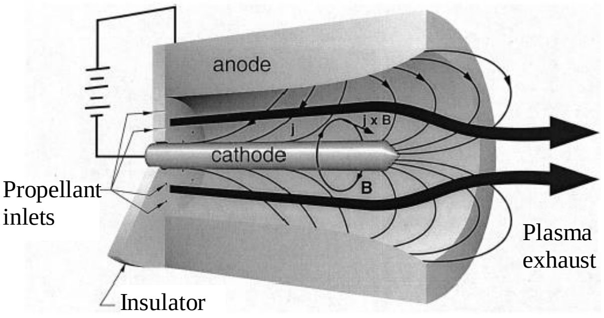

Fig. 6: Schematic of Magnetoplasmadynamics thruster (Lev, 2012)

Similarly, ethylene tetrafluoroethylene outperforms PTFE, offering a higher specific impulse, although it comes at the cost of a lower thrust-to-power ratio. This trade-off is particularly relevant in micro propulsion applications where specific performance is a key consideration.

Magnetoplasmadynamic Thruster

Magnetoplasmadynamic thrusters are leading candidates for future space missions as advanced electric propulsion systems are used in spacecraft. They offer a competitive advantage by providing high specific impulse, high thrust, and longer operational life (Zheng *et al*., 2021). The high specific impulse of MPD thrusters lies within the range of 2000-7000 s (Myers and Mantenieks, 1991), making it have the potential to significantly decrease the launch mass of spacecraft and also make them useful for performing maneuvers for interplanetary missions, such as heavy-lift Mars transfers. The major components of MPD thrusters include a central thoriated tungsten cathode, an annular anode, which constitutes the typical configuration of MPD thrusters (Myers and Mantenieks, 1991), and an insulator (Fig. 6). They harness the Lorentz force to transform electrical energy into kinetic energy of propellants along their axial direction (Peng *et al*., 2020). MPD thrusters are mainly categorized based on the generation of their magnetic fields. Thrusters that rely on self-generated magnetic fields are known as self-field MPD thrusters, while those utilizing externally generated axial magnetic fields are referred to as applied-field MPD thrusters. Applied field MPD thrusters operating at low-discharge current have received much attention in terms of research and development due to their higher magnetic fields for potential future low-earth orbit and deep space missions (Zheng *et al*., 2021; Balkenhohl *et al*., 2023). However, the erosion of the cathode has been identified as one of the limiting factors that affect the operational life of the thruster (Peng *et al*., 2020).

Other types of thrusters like hall thrusters are all characterized as plasma thrusters because the anode and cathode particles never get separated throughout the acceleration process, unlike the working principle of gridded ion thrusters (Zheng *et al*., 2021). Both the electric field and magnetic field influence the flow of plasma to provide thrust in MPD thrusters. Thus, the interaction between the electric field and the plasma plays a vital role in enhancing impulse and thrust. Several propellants have been experimented with in MPD thrusters; however, lithium and hydrogen offer a competitive advantage due to their low atomic mass and low ionization energies, making them desirable propellants for generating high specific impulse levels (Gilland and Johnston, 2003).

At lower power levels ranging from 0.5-5 MW, lithium is effective as a propellant due to its very low ionization energy, while hydrogen has demonstrated better efficiency in generating higher specific impulse for multimegawatts compared to noble gases, which have not achieved efficiencies exceeding 35%, even at megawatt power levels (Isp ≈ 2000). The primary difficulty faced by MPDs is that they exhibit subpar performance when operating at power levels below 100 kW (Dale *et al*., 2020).

Helicon Plasma Thruster

The development of Helicon Plasma Thrusters (HPT) is still in the developmental phase and has not yet been adopted for spacecraft missions. Nevertheless, there is considerable interest in the study of HPT due to their lack of dependence on neutralizers and the absence of electrodes that make direct contact with the plasma (Takahashi *et al*., 2020). The several components of the Helicon Thruster (HPT) include the discharge chamber, an antenna, a propellant line, and a direct current magnetic source (Williams, 2013). Helicon waves are electromagnetic waves with right-handed circular polarization and are emitted by a radiofrequency antenna, resulting in the ionization of the gas (Ferreira *et al*., 2015).

Helicon sources, generated by helicon thrusters, are responsible for creating and accelerating ions. Helicon thrusters operate using two different techniques: One that simultaneously creates and accelerates ions and another that separates ionization and ion acceleration (Takahashi *et al*., 2020). The absence of electrodes in the plasma region mitigates the erosion effect on the thruster walls, which can degrade the thruster's lifespan (Fig. 7). This characteristic makes it a favorable choice for low-budget satellites (Lemmer, 2017).

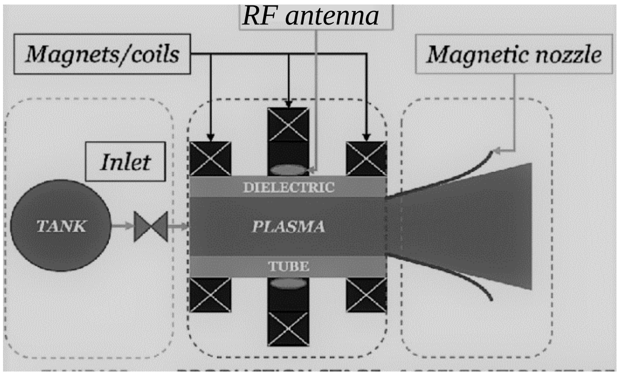

Fig. 7: Helicon plasma thruster schematic (Majorana *et al*., 2021)

The dynamics of plasma production in the source cavity determine the extent of its performance. The primary drawback of HPTs is their poor efficiency when converting Radio Frequency (RF) power to thrust power, typically less than 30% (Di Fede *et al*., 2023). The power requirement for HPT is a combination of Radio Frequency (RF) power for plasma production and Direct Current (DC) for generating a static magnetic field (Takahashi *et al*., 2020). This combination results has greater ionization efficiencies, high plasma density, and comparatively low plasma temperatures (Thakur *et al*., 2015). Other types of helicon thrusters, such as double-layer thrusters and high-power thrusters, operate at low densities and may use multiple magnetic coils (Batishchev, 2009). HPT has gained attention due to its lack of dependence on neutralizers and its avoidance of electrodes that come in contact with the plasma.

Conclusion

In general, the competitive advantage of electric propulsion over chemical-powered thrusters has emerged as a game-changing technology in diverse applications such as space exploration, interorbital travel, and energy efficiency over the last few decades. In this article, we have explored the key findings and trends in the research and development of various electric propulsion thruster variants, emphasizing their significance in improving efficiency, extending operational lifespan, offering greater versatility in propellant choices, and enhancing maneuverability in space. While challenges and knowledge gaps persist, the future of electric propulsion is undeniably promising. Moving forward, researchers should continue to push the boundaries of this technology, exploring new materials, designs, and applications. The possibilities in this field are boundless and the journey toward a more electrifying future is just beginning.

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Author's Contributions

Jinadu Abdulbaqi: Supervised the validation of the entire written process of the article and provided final approval of the article version to be submitted.

Okikijesu Omolona Olajide: Contributed to the written, research, and data validation of the article.

Ayodeji Tunde Akangbe: Contributed to the planned of the research drafted and reviewed the article.

Ethics

This manuscript is an original work and all sources have been appropriately cited. The research conducted adheres to ethical standards and any potential conflicts of interest have been disclosed. No part of this study has been submitted elsewhere for publication. I confirm that all co-authors have reviewed and approved the final version of the manuscript.

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