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Characterization of several nano electro kinetic and plasma thrusters' models

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Electric propulsion systems of various types are among the technologies being developed to increase their efficiency in various space missions. Since work on it began in the 1960s, its use on board satellites, orbital platforms, and interplanetary probes has increased significantly later. In this article, we will review the advantages of electric propulsion. The most important types used in space propulsion in terms of composition and the mechanism of operation of each type. In our current work, several simple models of ion engines are designed and built without using a magnetic field or control grids while using atmospheric air as fuel. The other part of the work is to design and build an ion engine that uses argon gas as fuel. It operates in a gas atmosphere and can be used in a vacuum chamber as a simulation of outer space. This type of engine uses strong magnetic fields and grids to control the direction of electrons and ions inside the engine. High voltage is used to generate plasma inside the engine and low voltage to generate a potential difference on the control grids. There is also another type of space propulsion system known as the Nano electrokinetic thruster, which operates on the electro-osmosis flow concept. However, because of the difficulty in producing the required carbon nanotubes, it remains a theoretical thruster.

Keywords: Electric plasma; Electric thrusters; Electric propulsion systems.

1. INTRODUCTION

Though they produce far less thrust than their chemical counterparts, electric thrusters have some advantages for in-orbit propulsion since the propellant's energy is not affected [1]. At the moment, the most common space propulsion methods are electric propulsion thrusters and chemical rockets. mostly employed for spacecraft delivery from Earth to orbit. The thrust-to-mass ratio of chemical rockets is exceptionally high exceeding 2000 N/kg. Electric propulsion systems can only generate modest amounts of thrust but can achieve high exhaust velocities. These systems use electric fields to accelerate ions and future increases in velocity cannot be stopped by physical constraints [2]. By adding or subtracting electrons an ion thruster ionizes fuel to create ions. Most thrusters ionize propellant using electron bombardment which releases electrons from the propellant atom and produces a positively charged ion when a high-energy electron (negative charge) hits with a propellant atom (neutral charge). The gas generated has an overall electric charge of zero due to the equilibrium between positive ions and negative electrons. It denotes that the total charge of positively charged ions, negatively charged electrons, and neutral atoms is zero this is referred to as plasma [3-6]. Plasma has some of the properties of a gas, but it is affected by electric and magnetic fields [7]. For many space applications, Electric Propulsion (EP) has emerged as an economical and sensible technical option. Its greater commercial availability and the possibility it provides to carry out the same function as traditional chemical propulsion systems while lowering the percentage of the spacecraft's mass needed for that mission are two of the primary causes [8]. The EP has some technologies for moving satellites and spacecraft in space.

It is a known truth that ion propulsion is not novel. The idea for ion propulsion, a kind of electric propulsion, dates back to the early 1900s. Konstantin Tsiolkovsky authored a paper in 1911. He is also the first to present the idea publicly [9]. Goddard carried out experiments at Clark University from 1916 to 1917. The thrust demonstration used ionised air streams at atmospheric pressure, although it is advised for near-vacuum circumstances at high altitudes. Since the thrust generation is not too great, many individuals did not agree with the idea [10]. Hermann Oberth discussed his ideas in 1923 on the enormous mass savings of electric propulsion and its use in attitude control and spaceship propulsion [11]. The development of EP dates back to the 1960s [12] with the appearance and development of plasma sources capable of delivering substantial current. In 1964 the first ion engine demonstrations of EP occurred on the Space Electric Rocket Test (SERT-1) [13] spacecraft and with a Pulsed Plasma Thruster (PPT) on the Soviet Zond-2 satellite [14]. PPT essentially combine the benefit of consistently operating high power Magneto Plasma Dynamic Thrusters (MPDT) to reduce propellant mass through high specific impulse with variable low average electric power consumption and manageable heat generation, they are of particular interest for space exploration and exploitation [15]. Then new concepts have been made feasible by the rapid advancement of EP technology. Hundreds of EP thrusters have been created and deployed on space research probes and satellites. However, as seen by the recent advent of all electric communication satellites, the full potential of EP has started to materialize because of the increase in power available aboard spacecraft [12].

The experimental observation of the electrokinetic phenomenon dates back to the 19th century [16]. The electrokinetic principle could provide the basis for a new class of space propulsion engines based on the electroosmotic principle. Propulsion is achieved through the electroosmotic effect in nanochannels by converting the input electrical energy into total kinetic energy. Research in recent years has focused on the suitability of this method for pumping and displacing fluids on microscopic scales. Recent studies have shown that the electrokinetic effect can be used as a mechanism to efficiently convert mechanical work into electrical energy [17]. The electroosmotic phenomenon is one of the most technologically promising phenomena, where a fluid moves through a non-conductive micro- or nano-channel under an applied electric field. The efficiency can be further increased by applying surface modification [18] to the nanochannel walls, allowing hydrodynamic sliding at the walls to maximise efficiency [19]. Due to the difficulties in producing the required carbon nanotubes, experimental tests have not yet begun [16]. In this paper, we will review the different types of space electric propulsion engines used in different space missions, with a review of the characteristics of each type. In our current work, we designed and built several models of plasma engines, tested them, calculated the engine propulsion elements, and calculated their efficiency in the laboratory using energy measuring devices. Nanoengineers and plasma generation methods inside these engines are studied to obtain thrust from a large group of these engines. A wind speed meter of the type

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(UT363BT) is used to calculate the speed of the generated ions, and through it the thrust can be calculated.

2. FEATURES OF ELECTRIC PROPULSION THRUSTERS

The EPTs fuel systems operating have the following features [20]:
1) High specific impulse leading to a notable rise in the maximum mass of the spacecraft sent into orbit, including the mass and energy use of scientific instruments.
2) Capacity to reduce the fuel supply and make the required orbit adjustments to ease the strain on the guidance and stabilisation system's flywheel engines.
3) A larger supply of electricity to scientific instruments, since electric propulsion systems only require significant electrical energy for corrections, braking to enter the target orbit, and acceleration to put the spacecraft on the flight path to the destination planet, when scientific experiments are not being conducted.
4) A notable increase in the number of launch windows, which is crucial since an indicator of interplanetary travel in the Solar System is the presence of major launch date limitations.
5) Because EPSs are monofuel systems the gas flow scheme is much simplified because there is no requirement for gas pressurisation for the fuel delivery to electric thrusters.
6) EPSs improve the mission's environmental safety by using ecologically friendly fuel as a propellant.
7) High demand for electricity necessitates a larger solar panel area thus a rise in the spacecraft's total mass.
8) Low thrust, which results in a low thrust to weight ratio and, as a result, a lengthy EPS operating period and higher standards for the electric thrusters' service life.
9) In certain situations, a longer flight duration than chemical propulsion systems, which raises the mission's overall duration given the same amount of time for scientific observations.

3. CATEGORIES OF ELECTRIC THRUSTERS

The utilization of electric propulsion systems has several uses. Different propulsion systems are needed for the various missions, based on the spacecraft's circumstances and intended use. In order for technology to perform a wide range of space manoeuvres, it must overcome many operational hurdles [21,22].

Three criteria can be used to classify electric thruster technology [23] as shown in Figure 1:

a) Electrothermal propulsion: a nozzle is utilised to expand propellant, which is heated using electric energy.

b) Electrostatic propulsion: propellant ions are accelerated by the application of electric energy.

d) Electromagnetic propulsion: A propellant plasma can accelerate thanks to electromagnetic forces.

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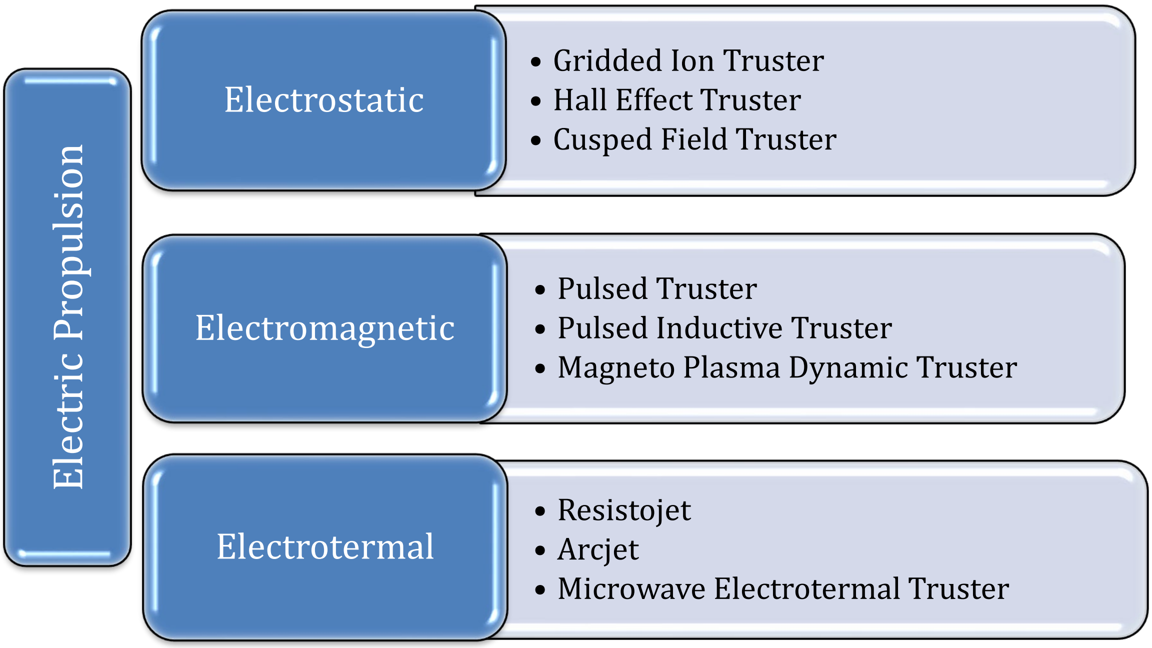

Figure 1 Classification of Electric Propulsion Systems.

3.1 Electrostatic

The charged ion's acceleration in the electrostatic field concatenates the thrust production. Typically the propellant's ionization and acceleration may be thought of as two distinct processes, resulting in a two-step process [24]. An important aspect for this type of thruster is the high availability of the propellant which results in a low price and makes these types of ion engines economically charming [25]. Based on the different electrostatic propulsion systems the thrusters are:

3.1.1 Gridded ion engine (GIE)

The ion thruster or gridded ion engine is a ripe electric propulsion technology whose evolution started in the 1960s [26-28] and has since then been used for commercial satellite propulsion [26-29]. GIE propulsion research is a rapidly evolving subject where new avenues such novel propellants are being explored [25, 30]. And new concepts, such as the Annular Ion Engine (AIE) are currently under development [31-34]. The primary characteristic of an ion thruster is the physical separation of the ion acceleration and propellant ionization processes from conventional electric thrusters. An ion thruster's neutralizer, power supply, grids, and ionisation chamber are its primary components. In terms of bulk and component count the power supply is the most crucial component. Their impact on the power plant's ultimate weight is significant [35]. The thruster's discharge chamber whose properties regulate losses and consequently thruster performance is where the ionisation process occurs. Depending on the ionisation technique used we may distinguish between different types of ion thrusters since it can function on a number of principles [35, 36]: namely electron bombardment (Kaufman thruster) [37, 38], Radio Frequency Thruster (RFT) waves [39, 40] or Electron Cyclotron Resonance Thruster (ECRT) [41]. Regardless of the kind of thruster being utilised ion acceleration is accomplished by harvesting ions from the discharge chamber using a multi-aperture grid arrangement called ion optics or ion engine grids [42,43]. As shown in Figure 2.

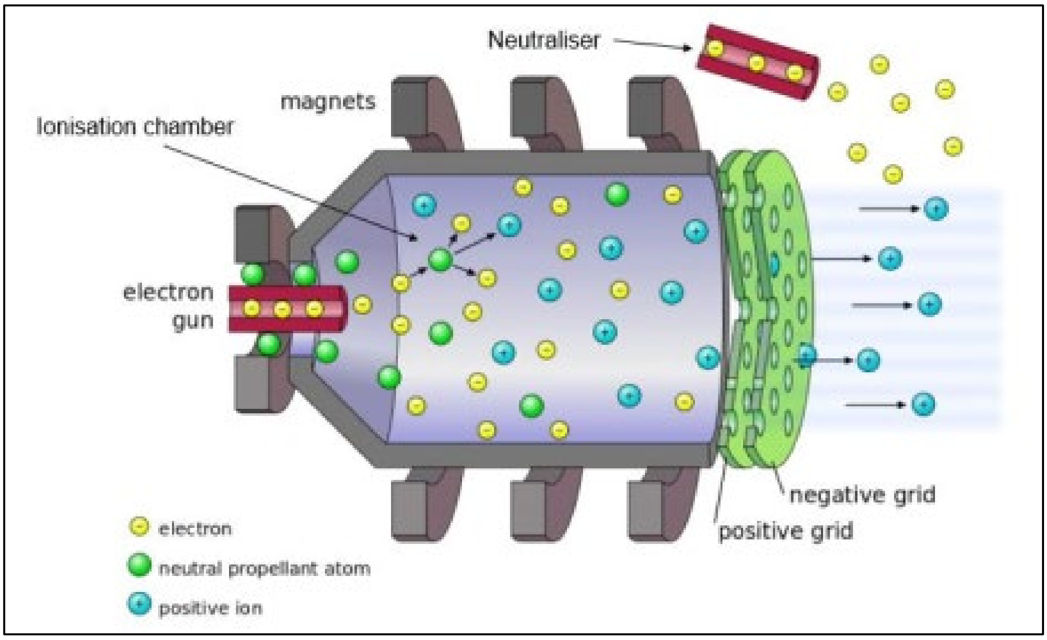

Figure 2 Electron bombardment ion thruster schematic [35].

The European Space Agency's (ESA) Gravity Field and Steady-State Ocean Circulation Explorer (GOCE), launched in 2009, provided evidence of the application of EP as a drag compensating method [44] as shown in Figure 3.

Figure 3 Tow ion engines which used on the EAS [28].

3.1.2 Hall effect thrusters (HET)

Hall Effect Thrusters stand out as one of the primary alternatives specifically employed for station keeping, orbital maintenance and disposal activities [45]. Xenon is the propellant employed in the bulk of these devices because of its wide cross section, low ionization energy and convenience of handling and storage [26,46].

The HETs are a form of stationary electric propulsion devices that use electric fields to accelerate ionized propellant to generate thrust [47]. Its efficiency and high specific impulse make it a desirable option for space applications such as far-space propulsion, orbit transfer, and station maintenance [48]. Simultaneously several thruster simulations with intricate modeling of the physics within the discharge channel and the HET plume have been created [49, 50]. In addition to particle deposition and sputtering, data on EP plume interactions with background particles may be used to analyze the plume's interaction with spacecraft [51, 52]. High-speed ions in the plasma plume have the potential to damage delicate spacecraft surfaces, and contamination products from the thruster may lower system performance as a whole [53, 54].

An electric (E) and magnetic (B) field are combined in the HETs a particular kind of electric propulsion. HETs are specifically distinguished by an annular channel with an internal anode, an exterior cathode, and a magnetic circuit that principally produces a radial magnetic field across the channel. An axial electric field is created when the cathode produces electrons which are outside of the motor and cause a potential drop. This is schematically depicted in Figure 4 along with a potential cathode location [55].

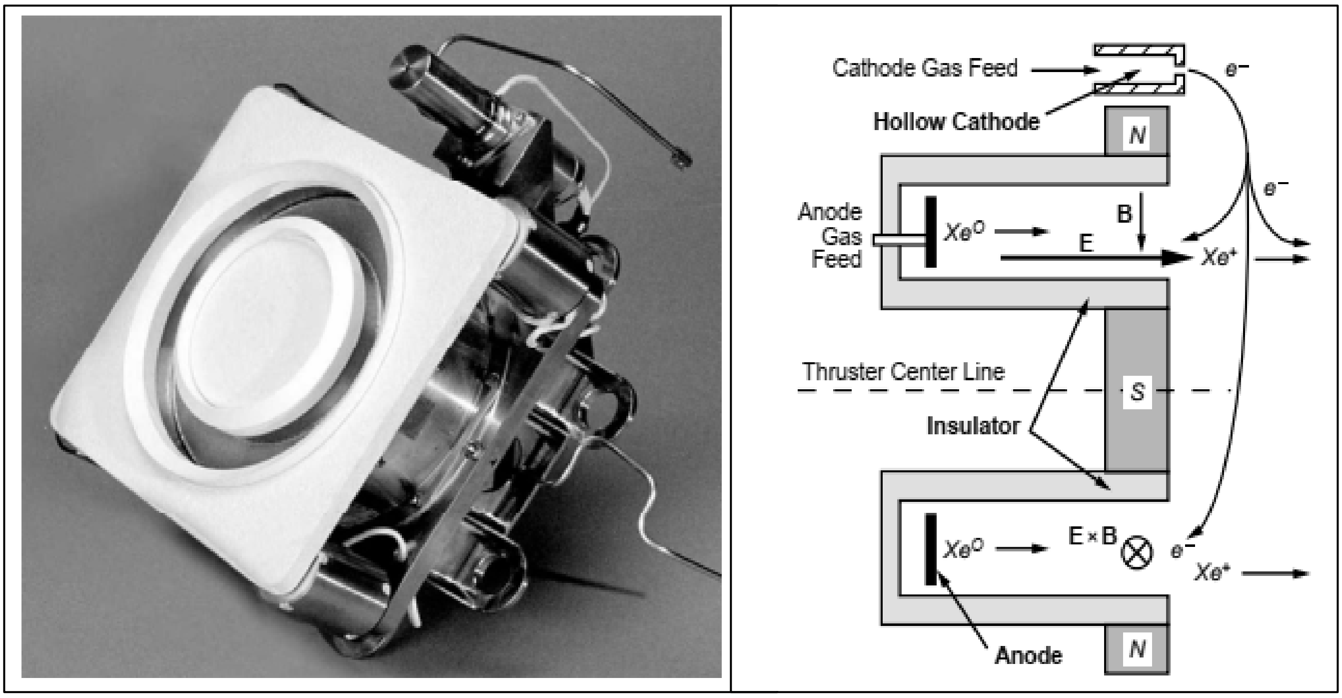

Figure 4 a) Photograph of a BPT-4000 Hall thruster manufactured by Aerojet. b) Schematic illustration of a Hall thruster showing the radial magnetic field and the accelerating electric field. [26]

3.1.3 Nano electrokinetic thrusters (NET)

This engine works on the basis of electroosmosis or electromagnetic flow, which is the flow of an electrolyte via a very narrow tube in the nanometer range. To create this flow, a voltage is given to both the cathode and anode at the tube's ends. This voltage accelerates and ejects the ions in the electrolyte held in a tank directly linked to the tube. This process converts electrical energy into kinetic energy. A single nano-propellant generates micronewtons of thrust; but, because of its small, it makes sense to organize a large number in an array to provide adequate push.

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Nano electrokinetic propulsors offer extremely high efficiency, specific impulse, exhaust velocity, and thrust-to-power ratio, making them appropriate for a wide range of uses. Because the propulsion system is made up of many nanopropellants, it is simple to create propellers of any size or thrust range. These features provide nanoelectrokinetic thrusters with excellent thrust control, making them suitable for a wide variety of spacecraft, from manoeuvring thrusters for small spacecraft such as satellites to the principal propulsion system for interplanetary or interstellar spacecraft. This system also does not require any additional heat or radiation shielding to protect the remainder of the spaceship; therefore it is comparatively lightweight in comparison to other systems.

The constraints of this sort of engine include the high cost of producing the requisite carbon nanotubes, as well as the high level of surface flaws in the manufactured carbon nanotubes, which affects efficiency and renders them unstable. This design also necessitates a high voltage in the 300 to 500 volt range, as well as a substantial storage tank for the needed liquid electrolyte, increasing the total weight of the system [16].

3.2 Electromagnetic propulsion
The electromagnetic propulsion system can be classified:

3.2.1 Pulsed plasma thruster (PPT)

Each pulsed plasma thruster system is a fully functional propulsion module with its own thruster, propellant, propellant supply and power processing. PPTs can precisely control spacecraft using impulse bits at a micro-Newton second (μN-s) resolution. The PPT utilises solid Teflon™ propellant and requires just analogue command/telemetry lines, 28V power input, and a mechanical hard point for attachment. Solid Teflon™ propellant avoids pressurised propellant safety regulations as well as the cost, mass, and reliability issues of propellant feed system components such as tanks, valves, and heaters. The PPT seen in Figure 5 functions when a capacitor is charged to several thousand volts by a Power Processing Unit (PPU) using power from the satellite bus. A pair of electrodes that have been charged by the capacitor are then supplied with teflon. Then a small amount of plasma is created between the electrodes by firing a spark plug igniter which is made up of a semiconductor encircled by another pair of electrodes. As a result, some Teflon can be absorbed and the capacitor can discharge. Then, thrust is produced by a combination of gas dynamic and electromagnetic forces, which accelerates the Teflon [56]. With propellant included, the envelope of a state-of-the-art PPT with two axis thrust capabilities is only about 5300 cm^3. Up to around 1.5 mN, a PPT may provide variable thrust based on firing frequency. Its particular impulse bear sec (Isp) of around 800–1200 makes it appealing for missions that call for higher V than cold gas systems can provide. It is also possible to change the lowest impulse bit from around 10 μN-s to over 800 μN-s by raising the voltage that is delivered to the energy storage capacitor. PPT systems have been designed for flight with a maximum torque of 15,000 N-s. [57]. On a good number of satellites certain PPT are formerly used as North-South station-keeping systems or as attitude control systems [58,59].

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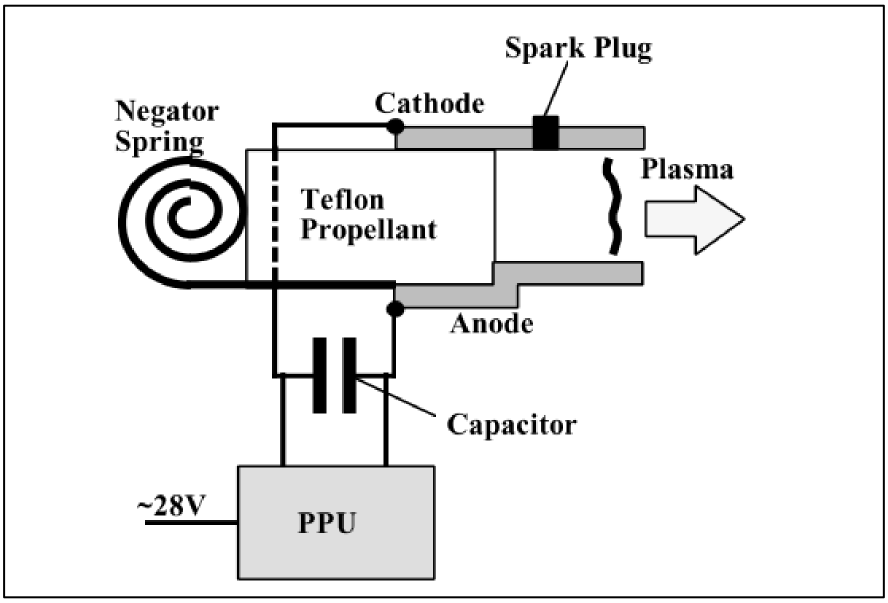

Figure 5 Major components of a Pulsed Plasma Thruster (PPT) [56,57].

3.2.2 Magneto plasma dynamic thruster (MPDT)

Magneto Plasma Dynamic Thruster is one type of the electromagnetic thrusters that is used in spacecraft engines. Due to their electrical thrusters' equivalent capability, these spacecraft are utilized for interplanetary space travel [60]. Despite having a much lower thrust density than other systems and a high exhaust particle velocity of 10^4 m/s, these thrusters are extremely dependable, have a long lifespan, and can fly for lengthy periods of time. MPDs require high electrical power and a low specific mass [61].

The MPDTs may use a mix of DC biased, RF power, and strong magnetic fields to accelerate semi-neutral gases (Xenon, Argon) to high exhaust velocities. The high operational current density of High Temperature Superconducting (HTS) coils at temperatures lower than their critical temperature (Tc) allows them to produce a strong magnetic field. It is possible to use the cold of outer space to cool these superconducting coils. Because 2nd Generation (2G) HTS coils are used in persistent mode, they may provide a large magnetic field with relatively little power consumption, which increases thrust. Thus there is a significant increase in specific impulse as a result of the coupling of the RF plasma and the HTS-based superconducting high magnetic field [26, 62]. The MPDT uses an externally produced magnetic field to accelerate plasma with high velocity using Lorentz force. The magnetic field can be created using either a permanent magnet or a copper-based electromagnet [63].

The development of a high-power density plasma thruster with a higher specific impulse and more thrust is required for human interplanetary space missions. The MPDT which comprises coaxial electrodes made up of a central cathode rod and an annular anode, has been created as one of the high enthalpy plasma thrusters with a high specific impulse [64]. The Lorentz force generated by the discharge current and self-induced magnetic field mostly accelerates plasma. An external magnetic field known as a magnetic nozzle has been used to boost performance even more. The presence of the external magnetic nozzle lowers heat loss onto the electrodes yielding improved efficiency [65-67]. Figure 6 shows the characteristics of the MPDT.

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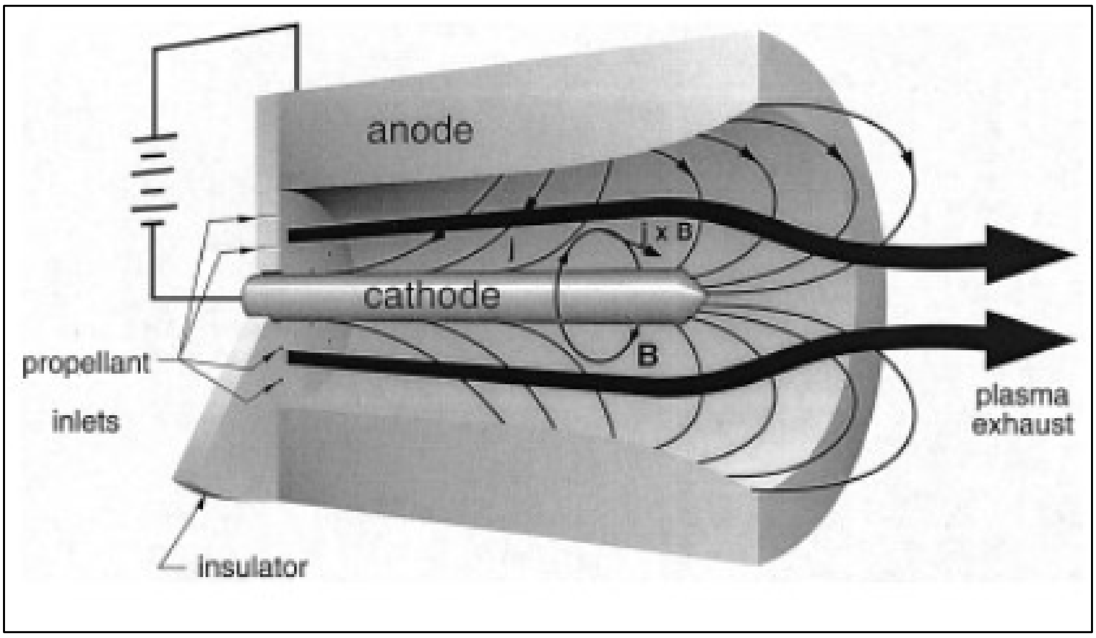

Figure 6 A schematic of a Magneto Plasma Dynamic Thruster (MPDT) [61,64].

3.3 Electrothermal thrusters

The gaseous propellant is heated electrically, and thrust is created by thermodynamic expansion of the propellant through a nozzle. These thrusters have a simple design however they cannot generate high propellant exhaust velocities. Traditional electrothermal thrusters are classified into two types: resistojet and arcjet [24,68].

3.3.1 Resistojet

The materials of the walls and/or heater coils in the resistojet subclass of devices inevitably limit the chamber temperature to about 3000◦K or less [69, 70]. As a result, even with equilibrated hydrogen the exhaust velocities are limited to 10,000 m/sec which is still two or three times faster than the fastest chemical rockets. Nowadays due to their overall system advantages biowaste gases like carbon dioxide and water vapor as well as lesser performance but easier to store propellants like hydrazine and ammonia are increasingly frequently used. The main practical issue facing resistojet technology, aside from frozen flow kinetics, is maintaining the integrity of the heater and non-conductor surfaces at the extremely high temperatures required by the concept all the while minimizing the radiative and viscous heat losses that further reduce thruster efficiency. Resistojets are especially appealing since they are easy to integrate with propellant storage and flow management systems that have been developed and are frequently utilized for hydrazine monopropellant thrusters. Their low operating voltage which eliminates the need for sophisticated power processing compared to other EP systems, is another benefit. For these reasons resistojets are among the first EP solutions to be employed for the NSSK of communication satellites in addition to the fact that spacecraft in GEO frequently have extra electrical power [68]. In ground testing, the University of Tokyo and JAXA's novel water-based resistojet named AQUARIUS, produced 4 mN of thrust at 70 s specific impulse using just 20 W of electricity [70].

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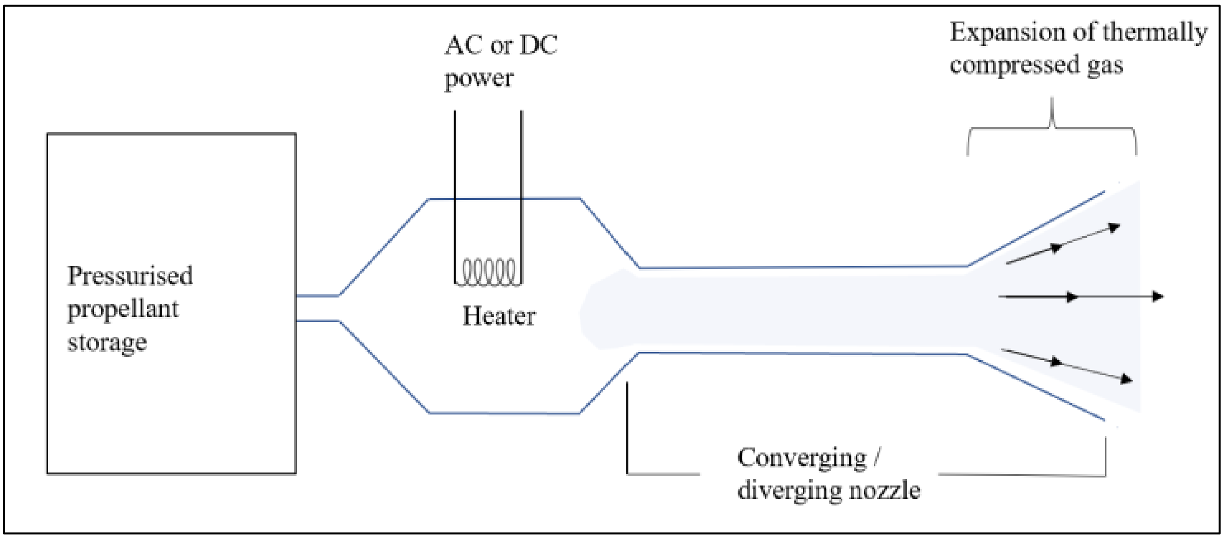

Figure 7 A resistojet thruster as a simplified schematic diagram [71].

3.3.2 Arcjet

The arcjet's propellant is dependent upon passing through an arc discharge. Propeller heats up in collisions with discharge particles, increasing exhaust velocity. By creating a continuous electric arc using two electrodes of opposing polarity at either end of a constricting tube, arcjet constant current warms the propellant, causing it to shoot out of a diverging nozzle at a high velocity [69] as shown in Figure 8. Anode affixed to a coaxial tube with a cathode rod at the end is often the initial component of the nozzle and nozzle constrictor. An insulator that can withstand high temperatures such aluminium oxide or boron nitride, is used to keep the electrodes apart [69]. Generally, a high voltage of 1000–4000 V is used to ignite the arc. After that it drops to either a high voltage operating mode of 80–160 V or a low voltage operating mode of 30–50 V. Four power levels are often available for arcjets ranging from extremely low 100–300 W to high 30–200 kW. Small satellites work well on the lower end of the power spectrum namely in the 100 W–1 kW range for arcjets [72].

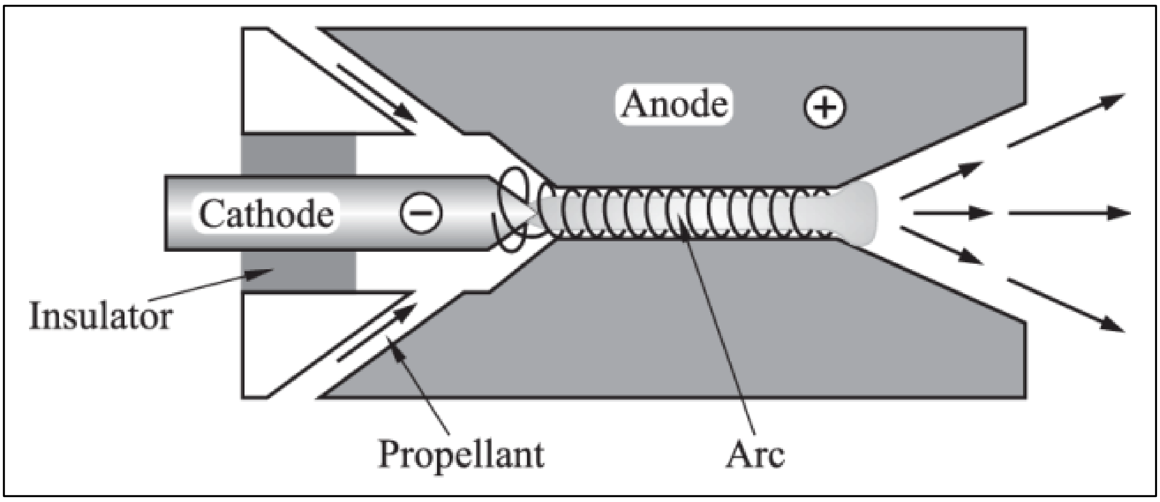

Figure 8 Arcjet thruster as a simplified schematic diagram [73].

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The specific impulse is often larger than that of a resistojet because the arc may produce temperatures that are much higher than those of a heating coil. Additionally arcjets like chemical thrusters typically have specific impulses that are two to three times higher than those of chemical rockets [74]. However, arcjets lose a lot of heat and are inefficient also usually demand very sophisticated PPUs for power processing. Aerojet may have a significant impact on satellite de-orbiting as well as station keeping. The ESA Clean Space project features them prominently [75]. Arcjets are especially well-suited to multi-mode propulsion systems where many propellants are shared throughout the propellant feed system which might be one explanation for this [76].

4. APPLICATIONS OF ELECTRIC PROPULSION

4.1 Ion propulsion systems

In order to explore the asteroids Vesta and Ceres, NASA's Dawn spacecraft used xenon ion propulsion, which allowed for effective trajectory corrections and longer mission durations.

4.2 Hall effect thrusters

They are often employed in long space missions and geostationary satellites for orbit maintenance and station-keeping. These thrusters retain a certain impulse value and a tolerable efficiency although they provide greater thrust levels than ion propulsion systems. For missions like satellite constellation deployment and orbital transfers that need precise manoeuvrability and modest force outputs Hall effect thrusters are a great suit. Greater force levels are provided by Hall effect thrusters in comparison to ion thrusters which makes them more suited for massive spaceship manoeuvres and quick orbit adjustments. Ion propulsion systems on the other hand are more favorable for missions requiring long-duration propulsion and having limited propellant mass since they usually attain greater specific impulse values and lower propellant consumption. A Hall effect thruster is used by ESA's SMART-1 mission to demonstrate the viability of ion propulsion for deep space missions.

4.3 Pulsed plasma thrusters

High thrust levels are produced by pulsed plasma thrusters relative to their mass, which makes them ideal for attitude control and tiny satellite missions. Compared to other plasma engines, PPT features simpler designs, making integration and construction into spacecraft easier. PPTs require more propellants to achieve the same Δv requirements as ion engines and Hall effect thrusters due to their lower specific impulse values. These thrusters' intermittent pulse activity can eventually cause electrode erosion and deterioration, which will shorten their operating life and dependability. The PPT are frequently utilised in CubeSats and other small satellite missions for attitude control and minor orbit modifications. Research is still being done to increase the pulsed plasma thrusters' dependability and efficiency. New propellant and electrode materials are also being investigated in order to increase the thrusters' operating lifespan and range of applications in space missions [77].

4.4 Electric thrusters in deep space

Similar to low-Earth orbit multiple-satellite systems like Starlink and OneWeb, electric propulsion thrusters are being used by a number of deep space projects. One of these is NASA's Psyche mission [78] a rare metal rich asteroid with a diameter of around 200 km that will be the subject of the probe's investigation. The spaceship is outfitted with massive 75 m^2 solar panels which can power Hall thrusters 500 million km away from the Sun. Launched in 2018 BepiColombo is a cooperative international mission between the Japan Aerospace Exploration Agency (JAXA) and the European Space Agency (ESA) [79]. It is now doing flybys to Mercury, which it will begin orbiting in 2025 and

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use two orbiters one built by JAXA and the other by ESA to conduct a thorough analysis. Four gridded ion thrusters, each with the capacity to use up to 4.5 kW of electricity from two 14 m solar panels, power the interplanetary journey. The spacecraft's Hall thrusters will propel the system into lunar orbit and have the ability to alter the station's orbit around the Moon. Its solar panels will provide electricity to the station's electronics. Testing in the vicinity of the Moon will establish whether Mars exploration might make use of such technology [80-83]. Table (1) displays some of the spacecraft equipped with ion engines. The thrusters' roles in their various missions are unknown however they might be used to manage attitude serve as the primary propulsion system for long space missions or raise orbit [35].

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Table 1 Application of electric thruster in spacecraft [35].

Spacecraft's name	Launch Date	Type of Drive	Comment
SERT 1	1964	Mercury Ion Engine	First ion engine in space
Program 661A	1964	Caesium ion engine	Suborbital, experimental test
SNAP-10A	1965	Caesium ion engine	Only nuclear reactor launched by the US
ATS-4	1968	Caesium ion engine	Experimental
ATS-5	1969	Caesium ion engine	Experimental
SERT 2	1970	Mercury ion engine	Experimental
ATS-6	1974	Caesium ion engine	Experimental
SCATHA (P78-2)	1979	Xenon ion source	First xenon ion flown
EURECA	1992-1993	RIT-10 ion engine	Radio frequency ion propulsion
ETS-6 (Kiku 6)	1994	XIPS	Experimental
PAS-5	1997	XIPS	First commercial satellite with ion propulsion system
Galaxy 8i	1997	XIPS	Bus based on HS-601HP
Astra 2A	1998	XIPS	Bus based on HS-601HP
Deep Space 1	1998–2001	NSTAR	Deep space mission
Satmex 5	1998	XIPS	Bus based on HS-601HP
PAS 6B (Intelsat 6B)	1998	XIPS	Bus based on HS-601HP
Astra 1H	1999	XIPS	Bus based on HS-601HP
DirecTV 1R	1999	XIPS	Bus based on HS-601HP
Galaxy 10R	2000	XIPS	Bus based on HS-601HP
Superbird 4	2000	XIPS	Bus based on HS-601HP
Galaxy 4R	2000	XIPS	
PAS 9 (Intelsat 9)	2000	XIPS	
PAS 10 (Intelsat 10)	2001	XIPS	Bus based on HS-601HP
Astra 2C	2001	XIPS	Bus based on HS-601HP
Artemis	2001	Radio-frequency ion thruster	Two RIT-10 thrusters
DirecTV 4S	2001	XIPS	Bus based on HS-601HP
AsiaSat 4	2003	XIPS	Bus based on HS-601HP
Hayabusa	2003	4 µ10 microwave ion thruster	
Galaxy 13 (Horizons 1)	2003	XIPS	Bus based on HS-601HP
MEASAT 3	2006	XIPS	Bus based on HS-601HP
Dawn	2007	NSTAR	Three ion engines
GOCE	2009	Two gridded ion thrusters	Precise thrust control
ABS-3A and Eutelsat 115WestB	2015	XIPS	First bus for orbit transfer
KaiTuo-1A (XinJiShu YanZheng-2)	2015	LHT-100	Experimental Satellite
ABS-2A	2016	XIPS-25	Satellite based on all-electric bus
Hispasat 36W-1	2017	SPT-100	Satellite based on OHB Luxor bus

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Eutelsat 172B	2017	SPT-140	Satellite based on bus Eurostar
AsiaSat-9	2017	SPT-100	Satellite based on Space Systems Loral
SES-14	2018	SPT-140	Satellite based on bus Eurostar Neo
NovaSAR	2018	QCT-200	Satellite based on SSTL-300 bus
UWE-4	2018	NanoFEEP	First IOD of orbit control on a picosatellite using electric propulsion
Yamal 601	2019	SPT-100	Satellite based on bus Ekspress-2000A
JCSAT-18	2019	XIPS	Boeing 702
Shijian-20	2019	LIPS-300	based on DFH-5 Bus
Hotbird 13F	2022	PPS5000	all-electric bus Eurostar Neo
MicroHETSat	2023	Sitael HT100	IOD for HT100
Ionozond	2024	APPT-95	AOCS

5. OUR PLASMA ENGINE DESIGN

In our current work, several simple models of ion engines are designed and built without using a magnetic field as shown in Figure 9 and the ion thrust is measured using a wind speed measuring device type Mini Anemometer UT363BT and from the results of the tests, the best models are selected.

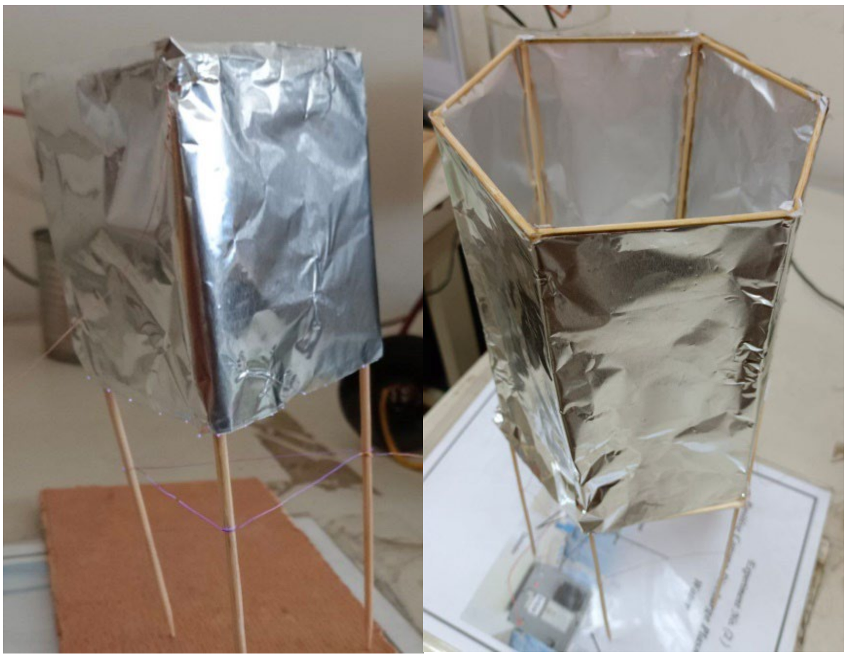

Figure 9 Some simple as our ion engines which used in laboratory.

While for the other part of our work, an ion engine is designed and built that uses argon gas as fuel due to its rapid ionization as it is one of the noble gases. It operates in the gaseous atmosphere inside the laboratory and can be used in a vacuum chamber as a simulation of outer space. The engine consists of a metal cylinder representing the cathode, open at one end and closed at the other end, with the closed side containing a small central tube for gas entry and representing the anode. The engine is surrounded by a coil to generate a strong magnetic field to direct the ions. The engine contains two grids, the first of which prevents electrons from escaping from the engine exhaust to be used to increase the ionization degree inside the engine, while the second is used to accelerate the ions towards the engine exhaust to increase thrust. A high voltage difference of up to 30 kilovolts is used between the cathode and the anode to generate plasma inside the metal cylinder. The grids are supplied with a low DC voltage to generate the bias voltage difference, as shown in Figure 10.

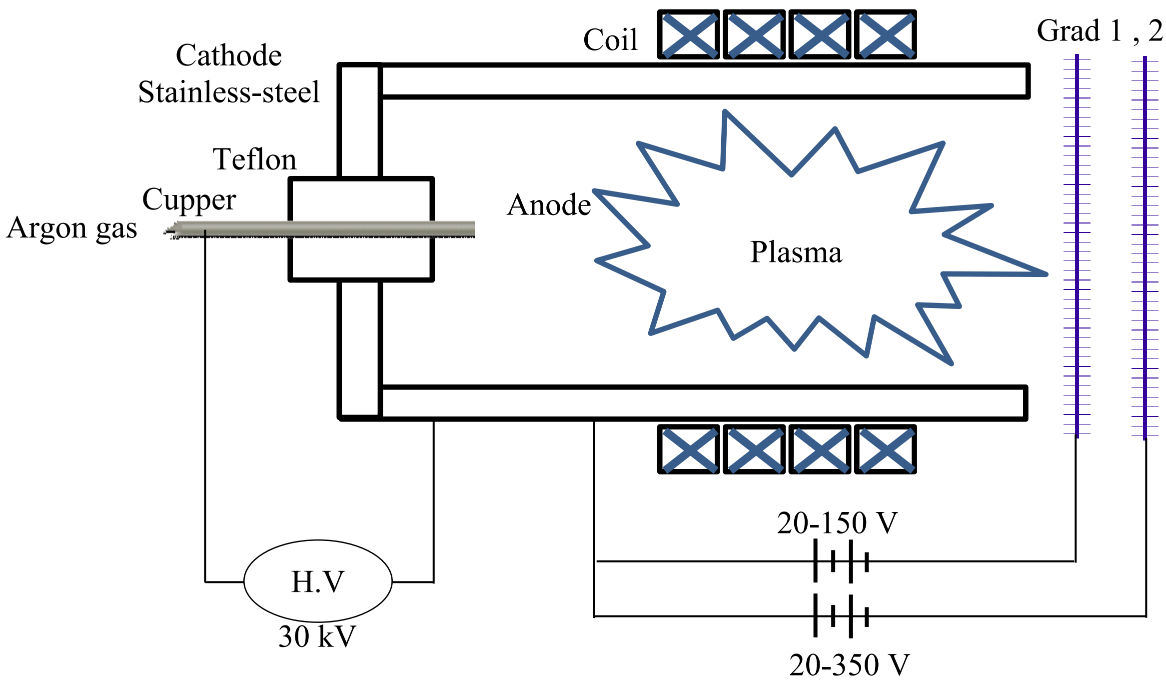

Figure 10 Schematic of the ion engine that we are working on designing.

6. CONCLUSIONS

In this review, we have provided an overview of the importance of using electric propulsion in various spacecraft and satellites due to their small size, strong design, and lack of need for large amounts of fuel, which means less weight in the space mission. The importance of engines with electrodes that do not directly contact the generated plasma is also highlighted, which causes corrosion of the metal of the engine as a result of direct ionic interaction. Electric propulsion systems also provide significant advantages in terms of efficiency, maneuverability, and mission life compared to traditional chemical propulsion systems. It is necessary to increase scientific efforts in research and development in such technologies to generate and manage space propulsion to ensure reliable and efficient operation and improve the lifespan and reliability of the systems, in addition to their integration with the rest of the satellite or spacecraft parts. There is also a need to reduce costs and increase the lifespan of space missions, which has economic feasibility. Among the engine models that were used in the first part of this work and which gave good results are the triangular engine model with a size of 54 cm^3 and the

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hexagonal model with a size of 650 cm^3. While for the second part, the tests and results have not been completed at the present time.

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