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Some Advances in Electric Rocket Propulsion for Space Exploration

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Abstract.

This article examines some of the current challenges facing electric propulsion designers to improve space exploration efficiency. The paper discusses various types of electric motors, such as ion, plasma engines, and compares their performance characteristics. The importance of using electric engines for interplanetary missions and reducing the costs of space exploration is noted. The problems and limitations of electric motors are also described, and new technologies that can solve these problems are noted. The use of nanotechnology to develop lightweight, high-performance propulsion materials could contribute to the longevity of plasma thrusters. As a result, it is concluded that electric propulsion systems have a large reserve in the field of advancing space missions.

Key words: spaceships; electric rocket engines; ion, plasma engines; multistage plasma engines, magneto-plasma dynamic engines; nanocomposite engine coatings.

1. Introduction and Brief History

Since the idea of using a rocket to launch a satellite into Earth orbit, first proposed by Konstantin Tsiolkovsky in 1903, the technologies used to design rocket engines have undergone significant changes. Currently, the newest technology used in creating rocket engines is ion engine, which uses the fourth state of matter, i.e. plasma. The idea of electric propulsion for spacecraft was proposed by Konstantin Tsiolkovsky in 1911 [1]: “Perhaps in time we will be able to use electricity to create high-speed particles ejected from a rocket device” [2]. This possibility was previously mentioned by Robert Goddard in his notebook of 1906 [3]. He later invented the first electric motor in 1917, a diagram of Goddard's invention is shown in Fig.1. Konstantin Tsiolkovsky and Robert Goddard were two theorists who were the first to work independently on the fundamentals of rocketry, and they were far ahead of their time in spaceflight [4].

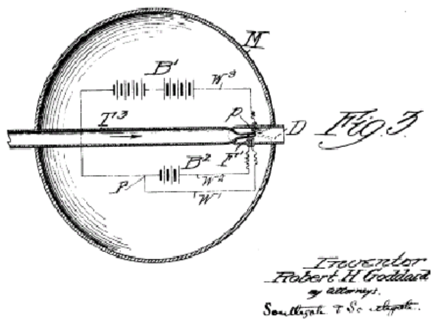


Figure 1: Goddard's first invention with an electric motor in 1917, US Patent No. 1363037 [3]

This theory was again proposed by Hermann Oberth in a 1923 paper [5]. A few years later, Soviet designer V.P. Glushko built the first electric motor in 1929-1933 (electrothermal version), and tested it on a bench. During this period, he worked at the USSR Gas Dynamics Laboratory [6]. Subsequently, in July 1964, the first SERT-1 (Space Electric Rocket Test) ion propulsion systems were demonstrated in space on NASA's Space Rocket Test missions [7], successfully proving that the technology worked in space as predicted.

In November 1964, the Soviet space station Zond-2 was launched from the Baikonur Cosmodrome with a corrective pulsed plasma engine, which was successfully tested in space [8]. In December 1971, the Soviet spacecraft Meteor was launched with a corrective ion-plasma engine SPD-60 [9].

Throughout the 1980s and 1990s, electric motors continued to evolve, with new types of motors being developed and tested. In 1989, NASA launched Deep Space 1, which used ion propulsion to successfully visit Asteroid Braille and Comet Borrell. In the 2000s and beyond, electric propulsion became an increasingly important technology for space exploration. Ion and Hall thrusters are now widely used for a wide range of missions, including communications satellites, scientific probes, and deep space missions [10].

New types of electric propulsion, such as the Variable Specific Impulse Magneto plasma Rocket (VASIMR), enable faster and more efficient space travel. From the first ideas proposed by K. Tsiolkovsky and R. Goddard, until today, when various types of electric motors have been invented and tested, they remain a priority for future flights. Today, electric propulsion systems are an integral part of many space missions, from scientific probes to commercial satellites. As technology advances, electric propulsion systems are expected to become even more efficient and powerful. Table 1 presents a list of missions performed from 1964 to 2019, indicating the electric engines used [7].

Table 1: List of electric propulsion missions [7]

Mission	Objective	Country	Launch	Orbit	Thruster	Propellant	Thrust (mN)	Isp(s)	Purpose
SERT-I	Technology Test	US	1964	Sub-orb	Ion	Hg	28	4900	EP test
Zond-2	Exploration	USSR	1964	Interplanetary exploration of Mars	PPT	Teflon	2	410	EP test
Meteor 1-10	Meteorology	USSR	1971	LEO	Hall	Xe	20	800	Orbit Control
Intelsat V 2	Communication	US	1980	GSO	Resistojet	Hydrazine	0,45	300	Stationary Keeping
Telstar 401	Communication	US	1993	GSO	Arcjet(MR-508)	Hydrazine	250	500	Stationary Keeping
Deep Space 1	Technology Test	US	1998	Interplanet	Ion(NSTAR)	Xe	20-90	3100	EP test
Artemis	Communication	Europe and Japan	2001	GSO	ION	Xe		3370	EP test and Orbit raising
Smart-1	Technology Test	Europe	2003	Moon	Hall	Xe	67	1540	Main Propulsion
Hayabusa-2	Exploration	Japan	2014	Interplanet	ECR ION(4 μ 10)	Xe	10	3000	Main Propulsion
LISA Pathfinder	Technology Test	Europe	2015	L1	Colloid	Cs	0.0001-0.15	240	Orbit and attitude Control
BepiColombo	Exploration	Europ,Japan	2018	Interplanet (Mercury)	Ion(4 T6)	Xe	145	4000	Main Propulsion
Uwe-4	Technology Test , Nano Sat	Germanay, Russia	2019	LEO	FEEP	Ga	0,001	Several thousand	Orbit Control

The purpose of this work is to consider modern problems facing developers of electric rocket engines, with the aim of analyzing and determining the possibilities of their future development for the purpose of effective space exploration. The work may be useful for assessing the current state of development of this industry in the world, and determining priority directions for the development of domestic mechanical engineering in the field of space rocketry.

Modern scientific publications, research articles, reviews of domestic and foreign scientists on this topic were used as source material for this study. Processing of research materials was carried out using methods of collecting, analyzing, comparing and synthesizing information about the prospects for future development.

2. The need to use an electric motor

Considering that rockets with chemical fuel have a simpler design and greater reliability, the question arises: why are difficult-to-use electric rocket engines needed? The most important factor in spaceflight is the cost of building and launching a spacecraft. To reduce the cost of space flights per kilogram of cargo, two main factors are considered, the first is a reduction in the total number of launches, the second is a reduction in the cost of each individual launch [11].

Solid propellant and liquid propellant rocket engines have very high thrust and are used in the first stage of launch due to their relatively low specific impulse, they are more efficient for achieving orbital speed and placing cargo in Earth's orbit. In contrast, most deep space missions require low thrust but higher specific impulse thrust to effectively control the attitude and position of the spacecraft. Also, interplanetary missions often require significantly greater propulsion capacity than the launch vehicle can provide. For these missions there is a choice of a combination of chemical or electric propulsion. Chemical rocket engines typically use liquid or solid fuel for propulsion. The main limitation of chemical rockets is that the energy of the gas leaving the rocket is precisely determined by the chemical energy and the fuel consumption [12]. Therefore, for long-duration space flights we need more fuel, more powerful pumps and therefore a larger rocket, which will require greater costs.

However, with electric motors the situation is completely different. The operating principle of electric rocket engines is based on electrical energy. Electricity can be generated by solar panels or a portable on-board nuclear power plant, which requires much less initial mass, and this electric motor can run continuously for hours. For this reason, electric traction has a higher stability, therefore, this system is several times more efficient and reliable than chemical engines. Electric fuel can also replace chemical fuel in Earth orbit for research, which significantly affects the mass ratio of the launch vehicle and, as a result, reduces launch costs. For this reason, the need to use such fuel for long-distance space missions may be more justified. This type of fuel is suitable even for interplanetary flights without human participation, in automatic mode, therefore, interplanetary space flights for deep space exploration can be more confidently planned [13], [14].

3. Expanding the use of electric propulsion in spaceflight

The use and development of electric propulsion technology in space missions is increasingly expanding, and its capabilities and benefits continue to grow. John Brophy, in a paper published in 2022 [15], based on his 40 years of experience in electric propulsion at NASA's Jet Propulsion Laboratory, describes how the expansion of electric propulsion can be used in a wide range of commercial and government launches. He also mentions that the use of electric propulsion in space missions is seen in applications ranging from small satellites in low Earth orbit to deep space probes. He also believes that over time, electric propulsion will permeate all aspects of exploration and exploitation of space technology.

We also note some articles that explore the problem of operating electric rocket engines for various purposes. Work [4] is devoted to the development of plasma rocket engines based on thermonuclear fusion. The proposed concept has some advantages for the future use of electric rocket engines in deep space exploration. Despite some risks, rocket engines powered by nuclear and thermonuclear fuel are more appropriate to use for deep space exploration, where solar energy will be poorly available.

An overview of the developments of the Energia rocket and space corporation is given in [16], which describes the stages of creating a magnetoplasmodynamic engine with a working fluid made of lithium, with an electrical power of 500–600 kW. Magnetoplasmodynamic engines have the highest thrust density (the ratio of thrust to the maximum cross-sectional area of the engine) and are highly efficient [17]. The performance characteristics of this engine in terms of power still remain relevant.

The book [18] presents the results of research on the creation of Hall and ion plasma engines, which are used as part of spacecraft for various purposes. The work describes the designs and characteristics of these engines based on experimental studies. The tasks of using electric propulsion engines to adjust the position of spacecraft are described in article [19]. A classification of modern electric jet engines, especially electrothermal, electrostatic, pulsed and magnetoplasmodynamic engines, has been carried out. Their technical characteristics are systematized: thrust, specific impulse, power consumption and efficiency. Issues of their further effective use for the purposes of correcting the orbits of spacecraft are noted.

Articles [20], [21] are devoted to the use of a laser rocket engine for the purposes of near space exploration. Engines of this type can not only be cost-effective in operation, they can also be used to launch a small spacecraft and solve the current problem of destroying space debris [22]. The stages of development of laser-based rocket engine concepts are noted [23], domestic and foreign research in this area, and prospects for experimental application are presented [24].

One of the important factors for the use of electric motors in satellites and spacecraft is that they consume much less fuel than chemical rocket engines. This allows spacecraft to travel longer distances and for longer periods of time [25]. These installations also provide more precise control of the trajectory and direction of the spacecraft, which is very important for maintaining the satellite in a given orbit or preventing collisions with other space objects. The advantages of electric motors make it possible to use satellites and spacecraft to change orbits and even return to Earth. It should also be noted that they produce much less waste than chemical rocket fuels and do not pollute outer space.

4. Types of Electric Motors

Figure 2 shows the main categories of modern electric rocket engines [25]. They can be divided into two categories: the first is ion and plasma engines, and the second is non-ion engines. In turn, ion and plasma engines can be divided into various types of electric engines.

Three main groups of ion and plasma engines are used today: electrostatic, electromagnetic and electrothermal engines [25]. They are currently used in various types of satellites and spacecraft. Another category is non-ionic motors: electromagnetic drive or Canna drive, quantum vacuum drive, electrodynamic tethers and photonic drives. However, these types of engines have not yet been fully researched and tested in practice.

Electric propulsion uses electricity and magnetism to accelerate spacecraft or satellites. Let's look at some types of electric motors: An electrostatic motor works by accelerating ions using an electric field and allowing those ions to pass through a grid (Figure 3). The ions are then neutralized by the flow of electrons to prevent charge buildup on the spacecraft. This method provides very low thrust, but compensates for the lack of thrust by delivering very high specific impulses, around 3000-5000 seconds. Specific impulse is a measure of the fuel efficiency of a rocket engine, and a higher specific impulse allows a spacecraft to use less fuel and achieve higher speeds. Electrostatic propulsion is now more commonly used for orbital transfer and stabilization.

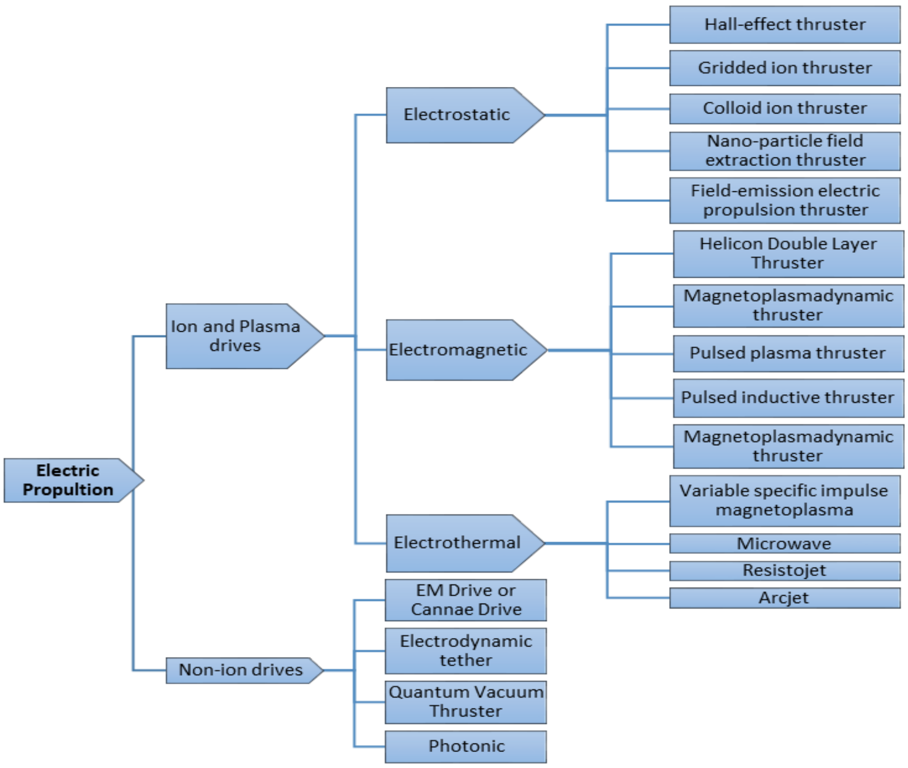
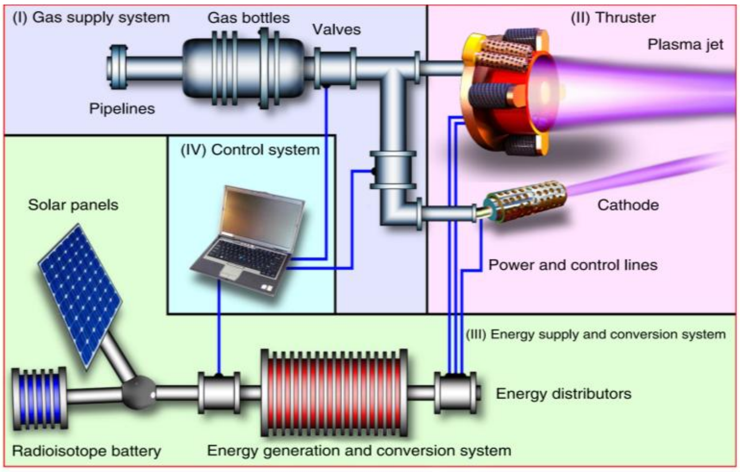


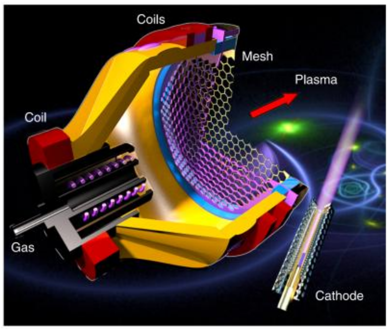
Figure 2: Classification scheme of different types of electric motors [25]

An electrothermal engine works by using electrical energy to transfer heat to the fuel and increase its efficiency and specific impulse. This is done by heating the element through which the fuel passes, this type of propulsion system can be used with both monopropellant and dual-fuel rockets. Although these engines increase specific impulse compared to chemical engines, the resulting specific impulse usually does not exceed 1000 seconds [27]. This makes electrothermal propulsion less efficient than electrostatic or electromagnetic propulsion.

An electromagnetic engine uses plasma as fuel; when it is heated to a temperature of more than 5000 degrees Kelvin and a magnetic field is applied, the conducting plasma is accelerated under the influence of the Lorentz force [2828]. This method provides higher efficiency than electrostatic motion because the particles are accelerated without becoming fully ionized. Electromagnetic thrust can produce thrust 100 times greater than electrostatic thrust. However, it is used less frequently than the electrostatic motor due to the higher complexity of its production and maintenance.

You can also note non-ionic engines, which include photonic engines, electrodynamic cables, and unconventional methods of propulsion. Photon engines produce all of their thrust using photons, allowing them to neither carry nor eject any propellant. Non-traditional types of electric motors, such as quantum vacuum plasma motors, electromagnetic motors and Cannae motors, are mostly theoretical and require experimental confirmation. These types of engines may become popular in the future, but are not currently in use [27].





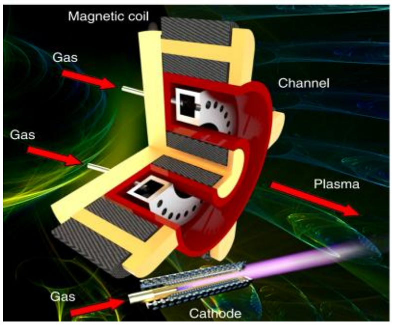


Figure 3: Diagram of the two main types of electric motors [28]

5. Main characteristics, advantages and disadvantages

Table 2 shows the characteristics of some of the main engine types, each with its own unique characteristics. Some of these systems are very effective and efficient, despite the complexity of their designs. These engines are designed for specific missions, and depending on their performance, they must run continuously for weeks or months in order for the spacecraft to reach the required speed. The required energy for these electric motors must be provided by solar panels or nuclear energy. Increasing power from solar panels would require adding more panels and increasing the volume of the spacecraft. This also makes him more vulnerable when colliding with other objects, this must be taken into account when choosing the type of mission.

Jet engines are classified as electrothermal and provide propulsion by heating a liquid. These engines are more often used to launch satellites into orbit, control them, and deorbit. Their specific impact is small and ranges from 150 to 850 seconds. Reactive arc jets also belong to the group of electrothermal systems. They are engines in which an electric arc is created in a flow of fuel, which is usually hydrazine or ammonia. Their specific impulse ranges from 130 to 2200 seconds and they have high thrust. These engines are used to support stations in orbit and can replace single-propellant rockets.

Grid ion thruster is a common design for ion thrusters, a highly efficient, low-thrust method of spacecraft propulsion that is powered by electrodes. The high voltage network accelerates the ions using electrostatic forces and has lower energy losses compared to other motors. These electrostatic ion thrusters can achieve a specific impulse of 1500-10000 seconds, which is longer than other types of thrusters.

Another series of thrusters included in the group of electrostatic thrusters are Hall effect thrusters, which are a type of ion thruster in which plasma is accelerated by an electric field. Their specific impulse typically ranges from 600 to 3000 seconds. Plasma pulse engines, which are part of the electromagnetic group, are considered the simplest form of electric spacecraft engine, and were already the first to be used for space flight. These engines are very powerful compared to other electric spacecraft engines, and have a simple design. They also benefit from an increase in specific output from 1400 to 2700 pulses. Pulsed plasma engines require high power to operate optimally. Another electric motor is the magnetoplasmodynamic motor, which belongs to the electromagnetic group; their disadvantage is the need for high power [7], [29].

Table 2: Characteristics of some main types of engines [7]

Table:	Resisojet	Arcjet	GIE	HET/HEMPT	PPT	MPDTE/ECR
Type	Electrothermal	Electrothermal	Electrostatic	Electrostatic	Electromagnetic	Electromagnetic
Achievable Thrust (mN)	0.5-6000	50-6800	0.01-750	0.01-2000	0.05-10	0.001-2000
ISP(s)	150-850	130-2200	1500-10000	600-3000	1400-2700	200-3200
Efficiency ηe (%)	30-110	25-60	30-90	20-70	5-30	20-70
Thrust-to-Power ratio (mN/KW)	450-700	150-600	20-250	150-300	50-200	150-500
Operation time	Month	Month	Years	Month	Years	Weeks
Propellants	NH3,hydrazine, H2,xe,and N2	NH3,hydrazine, H2,and N2	xe,Kr,Ar Bi, I2,and H2O	xe,Kr,Ar and I2	PTFE	xe,H2,Ar and Li
Benefit	Low level of complexity	High Thrust	High Isp and high Efficiency	High Power-to-Thrsut-ratio	Simple device and Solid propellant	High Isp and high Thrust density
Drawback	Very Low Isp	Low Efficiency	Low Thrust Density and Complex PPU	High beam divergence and channel erosion	Low Efficiency	Low lifetime and requirement

One of the factors that makes electric engines superior to their chemical counterparts is their efficiency in the space environment. This determines their primary use for interplanetary and interstellar flights. Also an important factor is lower fuel consumption, which allows the engine to move at higher speeds over longer distances [30].

Another problem with using chemical rocket fuels is their noise level and environmental pollution. Their release into space increases the amount of space debris and can cause many problems in the future. The use of electric propulsion with smaller volume and more precise control can reduce the amount of space pollution [7], [22]. Another advantage of them is their actual use for adjusting the orbit of spacecraft. With the increasing number of satellites in space, it will be very important to monitor and determine the exact position of the satellites because in case of an error, the satellites or spacecraft may collide with each other or other objects [7].

The disadvantages of electric engines include the fact that they do not have the ability to send spacecraft into space or launch objects into Earth orbit [31]. Also, some varieties require high production costs. The complexity of their manufacture is much greater than that of other engines, requiring a long time for design, assembly and testing. Another disadvantage is that long-term use in space makes them very vulnerable; plasma and ions can cause erosion of the working surface for a long time over long distances. The use of radiation-sensitive electrical parts may result in motor failure during a long flight, which could result in the failure of the entire space mission.

6. Prospects for the development of electric motors

The development of electric propulsion systems requires careful consideration of appropriate design, parts and materials, as well as the use of new technologies to improve efficiency. Let's consider these problems for two types of engines: electrothermal and electrostatic. An electrothermal engine uses heat generated by electricity to create thrust, while an electrostatic engine uses electric fields to ionize and accelerate fuel. One of the factors contributing to the development of electric propulsion is the need for greater power reduction, as well as the creation of new resources for energy production.

The use of nanomaterials and high-performance equipment can improve the efficiency of electric motors. Lightweight carbon composites can reduce erosion and vulnerability and extend the life of electric motors. Higher power, improved plasma enclosure techniques, and optimized electrode geometries can be used to improve efficiency. Increased efficiency could lead to higher impact as well as lower energy consumption, which is critical for space exploration.

One of the main limitations of the electric propulsion is its limited drift, which makes it unsuitable for certain missions such as planetary landing or sending spacecraft from earth to space. To increase electric propulsion, several parallel drives can be used: multi-stage, hybrid propulsion systems. They can be developed by combining different types of electric motors with other types of motors: chemical or nuclear. The development of hybrid powertrains is particularly promising as it offers the potential to improve efficiency and reduce fuel consumption.

7. Potential applications of nanotechnology in the development of electric motors

The introduction of nanotechnology in space propulsion can lead to the revival of interplanetary missions using spacecraft and small unmanned systems. The use of nanotechnology can make a constructive contribution to the development of space technology. The use of lightweight materials with unique mechanical and electrical properties, such as carbon nanotubes, graphene and nanocomposites, can help produce electric motors with new properties. The use of nanomaterials will solve many problems and disadvantages that previously existed in the design of electric motors [28].

One of the important factors when creating electric motors is miniaturization and lightweighting. We can use lighter materials and have higher efficiency and improved design. Nanomaterials can provide the strength-to-weight ratio, thermal stability, and radiation resistance that are critical when operating in outer space. One of the problems that make electric motors vulnerable is the effect of plasma, which is where the electric motor experiences corrosion, changes in electrical characteristics, and removal of the surface layers of the drive. The use of nanomaterials in the design of a power plant can prevent destructive effects, increase performance, and increase service life (Fig. 4).

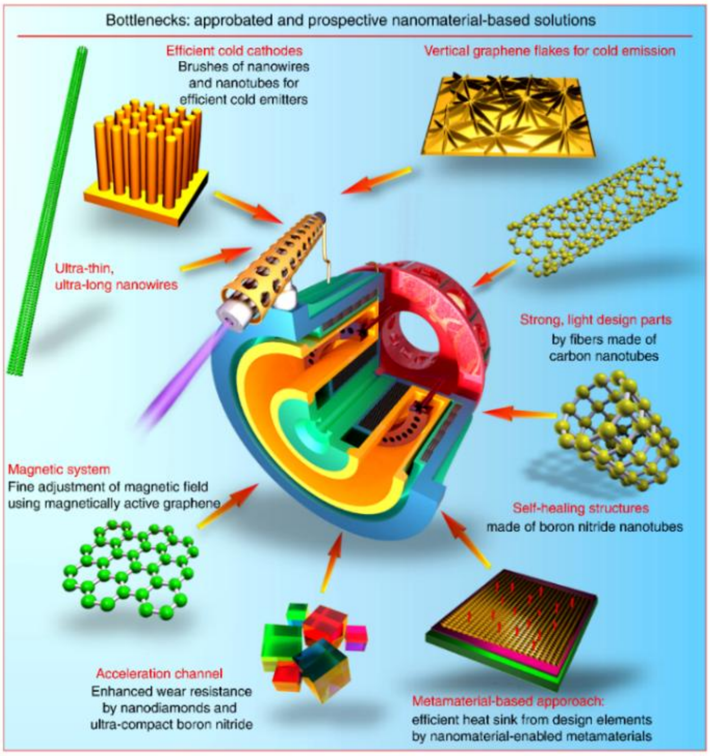


Figure 4. Application of nanomaterials in the production of electric motors [28]

Also, as an ideal alternative to conventional thermionic or hollow cathodes, one can consider the use of parts based on carbon nanotubes, which have extraordinary field emission properties [32]. The use of nanotechnology can also lead to the development of new propulsion systems such as nano-electrospray motors and nanofluidic motors that use nanoscale properties to control propulsion. Overall, the potential applications of nanotechnology in the development of electric propulsion systems are wide and varied. From lightweight, high-performance materials to new propulsion systems, nanotechnology has the potential to transform space exploration. As researchers continue to explore the possibilities of nanotechnology, we can expect new advances in electric motors in the coming years.

8. The future of electric motors

Meanwhile, more advanced electric propulsion system concepts are gaining more credence for future space missions. Today, electric propulsion is the focus of much research in space centers around the world, with many projects being developed that are looking for interesting alternatives for transporting people into deep space [33]. Such alternatives include some technologies such as solar sail, fusion, plasma and nuclear propulsion for long-distance missions [34].

The next generation of engines must be designed to take full advantage of electric and chemical engines. Electric motors have evolved over the years, and research is now being conducted to improve their performance and efficiency. It is difficult to predict which types of electric motors may be developed in the future. The use of nanotechnology can lead to significant improvements in the performance, efficiency and durability of electric propulsion systems. However, more research and development is needed to understand the benefits of nanotechnology in this field to create compact and efficient spacecraft. Another problem still remains increasing the efficiency of electric drives based on the development of new energy sources [35]. It can also be noted that the future of electric motors is associated with research, computer modeling of plasma jet formation processes and the development of more efficient systems [36].

9. Conclusion

In conclusion, I would like to note that electric engines are a promising technology for space exploration, certainly in the future, in connection with the expansion of interplanetary and interstellar flights. They have higher efficiency, lower fuel consumption and precise control. However, they also have some limitations in terms of maximum thrust, power, and production complexity. Despite these limitations, ongoing research and development in electric motors is likely to lead to significant improvements and innovations in the future. Electric propulsion is the best candidate for powering spacecraft in deep space. The use of nanotechnology can lead to significant improvements in their performance, efficiency and durability. The search and development of new energy sources, such as solar panels and batteries, can significantly increase the efficiency of electric propulsion systems. Taking into account the development of reusable spacecraft, it can be expected that electric propulsion will be very effective for future space missions, creating new opportunities for space exploration and interplanetary space flights.

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