Proceedings of the 2nd International Conference on Computing Innovation and Applied Physics (CONF-CIAP 2023)
DOI: 10.54254/2753-8818/5/20230309

Analysis on the working mode of electric propulsion system

Xiangyu An[1]

[1]Qingdao HONGWEN school, Qingdao, Shandong, China

Mr_Annnn2005@yeah.net

Abstract. At present, the electromagnetic propulsion technology and the electrostatic propulsion technology are more mature than before. With the increase of available power on the spacecraft, the performance can be better improved. This paper mainly reviews the electric propulsion technology for long-term space travel. It can be concluded that, compared to traditional chemical rocket systems, electric propulsion systems are more suitable for long-term space missions and have the ability to transport relatively heavy objects in space.

Keywords: electric propulsion system, vasimar, ion engine, hall engine.

1. Introduction

Compared to chemical rockets, electric thrusters generally consume much less propellant, mainly due to their higher jet velocity [1]. In other words, electric thrusters can be limited by limited electrical power, but because of their high specific impulse, they can provide propellant for a longer period of time [2]. As a widely used technology mature in development, the electric propulsion is now being applied to the operation of spacecrafts (starting with a successful demonstration by NASA) for keeping the station, raising the orbit, or as the main propulsion [3]. In the future, it has been calculated that the most advanced electric propulsion may reach 100 km/s (62 miles/s). This is enough to send a spacecraft to the outer space in the solar system, but still not suitable for interplanetary travel [1]. Electric rockets with an external power source (which could be transmitted by a laser on a photovoltaic panel) have the theoretical possibility of interstellar flight [4]. However, because of the low thrust of electric propulsion, they do not have the ability to launch from Earth. Except for the low thrust, electric spacecraft are well suited to transportation in space, as chemical rockets can usually only transport a few percent of their own mass to their destination, but electric spacecraft can achieve transporting more than 60 percent of their initial mass. According to the comparison of the electronic engine and chemical engine mentioned above, this paper focuses on the electronic engine. The author first introduces and explains three engines made according to electromagnetic propulsion technology and electrostatic propulsion technology. Then, the most ideal variable specific impulse electromagnetic rocket for long-term space travel is introduced. This paper helps people understand the potential of electric propulsion technology and its importance for long-term space travel.

© 2023 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

2. Electrical Propulsion (EP) System

2.1. Specific Impulse and Thrust

Specific impulse (Isp) can measure the efficiency of a reaction mass engine producing thrust. The specific impulse is exactly proportional to the effective exhaust velocity when the reaction mass only contains the fuel carried in an engine. The mass of propellant can be used with more efficiency if the propulsion system has higher Isp. For rockets, it means that less propellant is required for a given delta-v [5], so that the vehicle attached to the engine can gain altitude and speed more efficiently. According to the rocket thrust equation F(thrust)=MC, M is the mass flow rate, and C is jet velocity. The electrical propulsion has great C, but is smaller in M compared with the chemical propulsion system. And also because F is proportional to 2P/C, if C increases, F will decrease. This means that the higher the impulse, the lower the thrust force.

2.2. Ion Propulsion System

Konstantin Tsiolkovsky was the first person who made a public presentation of the idea of ion propulsion system [6]. This technology was suitable to be used in near-vacuum conditions at high altitudes. The thrust was demonstrated under atmospheric pressure with ionised air currents.

2.2.1. Ion thruster. The ion propulsion principle is based on an engine driven by the acceleration of ions by electrostatic forces, which are positive ions obtained by ionising neutral gases. As shown in Fig. 1, it is basically constructed by filling the engine shell with propellant and the inside of the discharge chamber with an electron gun (for ionisation effect), which moves the ions towards the other side of the tank due to the voltage, or so there are usually two layers of electric screens on the other side. The inner layer is negatively charged and the outer layer is positively charged. So when the ions pass through these two layers of the screen (which comprise a strong voltage inside the screen), they are pushed out at a very high speed. To prevent electrical interaction between the thrusters and the temporarily stored electrons, when they pass through the electrostatic grid they are neutralised by the neutraliser in the ion cloud and therefore become neutral again. In contrast to electromagnetic thrusters, they will accelerate all matter with the Lorentz force and the electric field is not in the direction of acceleration [7]. Ion thrusters can only work in space because of the high specific impulse characteristics, so the thrust provided is very small, which means that they cannot work when there is significant air resistance, so when a rocket is launched from Earth to the initial orbit a chemical rocket is needed to achieve this.

Since the beginning of the development of grid electrostatic ion thrusters in the 1960s [8], they have been used for commercial satellite propulsion [9,10] and scientific tasks. Their main characteristic is the physical separation of the propellant ionisation process from the ion acceleration process [11]. During ionisation, single outgoing valence electrons from the ionised atoms can be accelerated by passing through the hot cathode and later through the potential difference of the anode. As the positive ions pass through these two porous grids (the inner side is called the screen grid and the outer side is called the accelerating grid), the potential difference (a strong voltage) is used to generate thrust. To prevent the spacecraft from accumulating charge due to the positive ions emitted by the ion thrusters, they also attract the ion beam by placing a cathode near the engine to make it neutral or emitted after it has been emitted [12].

Figure 1. The Ion engine.

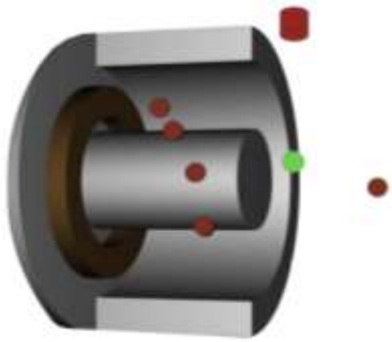

Figure 2. The Hall engine.

2.2.2. Hall thruster. One of the basic operating principles of the Hall thruster (as seen in Fig. 2) is to accelerate ions into a high speed so as to better compress the charge density. Instead of attracting a grid, the electron plasma from the open end of the Hall thruster attracts a negative charge. The electrons are confined through the use of a radial magnetic field of 100-300 G (0.01-0.03 T) according to the data search, where the combination of the radial magnetic field and the axial electric field causes the drift of electrons in azimuth because of the electrons emitted at the open end, thus creating a Hall current.

The xenon gas is generally known as the most suitable propellant, which is supplied through the internal anode with a number of small holes and acts as a gas distributor. The neutral xenon atoms are ionised by the high-energy electrons emitted with the open end when they diffuse into the channels of the propellant. The high-energy electrons move towards the anode and collide with the neutral xenon atoms in the channels. Most xenon atoms are ionised to a net charge of +1, while some are +2. Then, the xenon ions are accelerated by the electric field between the anode and the cathode. According to the data for a discharge voltage of 300 V, a velocity of about 15 km/s (9.3 mps) is reached by the ions at a Isp of 1,500 seconds (15 kN-s/kg). On departure, the electrons will be pulled in by the ions with the same number, thus neutralising the electrical properties of the thruster.

The energy efficiency of the thruster is limited since approximately 20-30% of the electron current does not generate thrust, and the rest of the current is in the ions. However the thruster has a very high mass use efficiency (90%) because most of the electrons stay in the thruster for a long time, so that almost all the xenon propellant an be ionised.

Like all kinds of electric propulsion, the thrust is influenced by the power, efficiency, and Isp available. The Hall thruster uses the thrust in a very small amount compared to that of chemical rockets. However, it operates at a high Isp, typical of electric propulsion. One of the advantages for the Hall thruster is that the ion generation and acceleration occurs in a quasi-neutral plasma. Therefore, the thrust density will not be limited by the space charge saturation current. Different from the grid ion thruster, this allows smaller thrusters. Additionally, these thrusters can apply more types of propellants (oxygen) provided to the anode, which is counted as another advantage, although at the cathode, it is best to choose something that is easily ionised.

2.3. Eletromagnet Engine

The mode of operation for an eletromagnetic gun is similar to that of a rail gun. Most of the PPTs use a solid material as the propellant. The first stage of PPT operation is to cause the ablation and sublimation of the fuel through the arcing of the fuel. This causes the resulting gas to become a plasma, leading to a cloud of charged gas. The plasma is propelled between two charged plates (anode and cathode) at a low speed because of the force of ablation [13]. The fuel completes the circuit between two plates when the plasma is charged, thus allowing a current to flow through the plasma. This electron flow creates a powerful electromagnetic field, and then the field will exert a Lorentz force on the plasma, thereby pushing plasma out of the PPT exhaust by accelerating it into a high speed. This is because of the time required between charging of the pole plates and each arc. This is why it is called pulsed and the pulse frequency is usually very high, so that instability of the thrust force is usually not a concern. The PPT, on the other hand, can run continuously for a long time, thus producing a large final velocity, although the thrust remains small.

2.4. Variable Specific Impulse Mangnetoplasma Rocket (VASIMR)

The VASIMR (as shown in Fig. 3) is an electrothermal magnetoplasma thruster. In this type of engine, all of the ways described above for engines are used to accelerate the plasma. Then, the radio waves are used to ionise and heat the inert propellant to finally produce a jet of plasma and generate thrust.

As a neutral gas (usually xenon or argon), the propellant is first injected into a hollow cylinder with an electromagnet on its surface. The electromagnetic radiation from the helical RF antenna heats the propellant into a plasma [1], and finally produces the plasma composed of ions and free electrons. Known as the ion cyclotron heating (ICH) for the second RF antenna, the plasma is spirally accelerated backwards by the Lorentz force generated by the electromagnetic field [14]. Microwaves are then used and further heated to over 1,000,000 degrees Celsius, approximately 173 times higher than the surface temperature of the Sun [15]. The ionised plasma is then guided through an electromagnet that acts as a rocket motor nozzle and exits the motor to generate thrust at speeds of up to 50,000 metres per second [16]. By varying the energy of the electromagnetic radiation and the content of the plasma, the VASIMR is theoretically able to be operated at a condition of low thrust and high Isp exhaust, or, on the contrary, high thrust and low Isp exhaust [16].

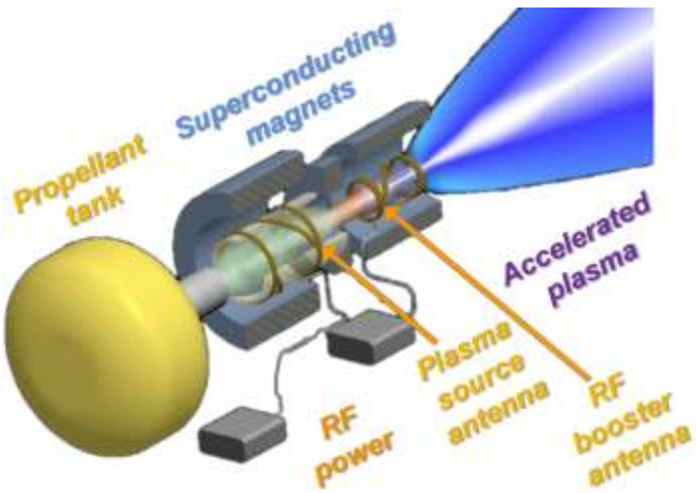

Figure 3. The VASIMAR structure.

3. Conclusion

To conclude, propellant mass economy is a main strength of the EP system, particularly for the tasks with a large velocity increment. While the main disadvantages include its need of complex external power sources as well as the low thrust density level. In addition, the electric propulsion also has better accuracy and variability of thrust. What is more, its capability of restarting and the long operating time, are fully uesd in the outer space travel. It even allows a task that cannot be completed by using the chemical propulsion. The missions of sending heavy cargo to other planets, or sending unmanned probes beyond the solar system, or the journeys to asteroids, giant exoplanets and their moons are all suitable for EP.system.

There is no doubt that in the near future, the number and types of efficient electric propulsion systems will increase dramatically while a number of problems and challenges will still remain to be solved. The longevity and stability of equipment have to be guaranteed for far more than they have been achieved to date by ground-based test facilities. To accomplish this, more research need to be conducted in the field of new materials, as well as improved or modified architecture and plasma confinement. Energy is another essential issue. While the efficiency of solar panels will certainly increase, safe controlled fusion is the key to accelerating the process of making deep space exploration possible.

References

[1] Choueiri E Y 2009 New Dawn of Electric Rocket *Scientific American* 300(2) pp 58–65 doi:10.1038/scientificamerican0209-58
[2] Electric Versus Chemical Propulsion *Electric Spacecraft Propulsion* ESA Retrieved 17 February 2007
[3] Lev D, Myers R M, Lemmer K M, Kolbeck J, Koizumi H and Polzin K 2019 The technological and commercial expansion of electric propulsion *Acta Astronautica* 159 pp 213–227 Bibcode:2019AcAau.159.213L
[4] Geoffrey A L 1994 Laser-powered Interstellar Probe Presented at the Conference on Practical Robotic Interstellar Flight (NY University: New York NY)
[5] Lee H 2013 New F-1B rocket engine upgrades Apollo-era design with 1.8M lbs of thrust *Ars Technica*
[6] Science@NASA 2010 Ion Propulsion--50 Years in the Making *Science Mission Directorate* (nasa.gov) https://science.nasa.gov/science-news/science-at-nasa/1999/prop06apr99_2/
[7] Jahn R G and Choueiri E Y 2003 Electric Propulsion (PDF) *Encyclopedia of Physical Science and Technology* Vol. 5 (3rd ed.) Academic Press pp 125–141 ISBN 978-0122274107
[8] Mazouffre 2016 Electric propulsion for satellites and spacecraft: Established technologies and novel approaches *Plasma Sources Science and Technology* 25(3) doi:10.1088/0963-0252/25/3/033002. Retrieved 29 July 2021.
[9] XIPS (xenon-ion propulsion system) www.daviddarling.info Retrieved 10 April 2016.
[10] Sovey J S, Rawlin V K and Patterson M J 2001 Ion Propulsion Development Projects in U. S.: Space Electric Rocket Test 1 to Deep Space 1 *Journal of Propulsion and Power* Vol. 17 No.3 pp 517-526
[11] Sangregorio M and Xie K 2017 Ion engine grids: Function, main parameters, issues, configurations, geometries, materials and fabrication methods *Chinese Journal of Aeronautics* doi:10.1016/j.cja.2018.06.005 Retrieved 29 July 2021
[12] Hall-Effect Stationary Plasma Thrusters Electric *Propulsion for Inter-Orbital Vehicles* Archived from the original on 2013-07-17 Retrieved 2014-06-16
[13] NASA Glenn Research Center PPT *National Aeronautics & Space Administration (NASA)* Retrieved 5 July 2013
[14] Alessandra N 2008 VASIMR Prefeasibility Analysis *Advanced Propulsion Systems and Technologies* Today to 2020: 335.
[15] Beth D 2004 Star Power *Air & Space* Smithsonian Retrieved February 7 2014
[16] Tim W G et al 2005 Principal VASIMR Results and Present Objectives (PDF) *Space Technology and Applications International Forum* Vol. 746 pp 976–982 Bibcode:2005AIPC..746..976G doi:10.1063/1.1867222