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Review Article

A Comprehensive Review of Atmosphere-Breathing Electric Propulsion Systems

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To develop the satellites for a low-Earth-orbit environment, atmosphere-breathing electric propulsion (ABEP) systems have become more attractive to researchers in the past decade. The system can use atmospheric molecules as the propellant to provide thrust compensation, which can extend the lifetime of spacecraft (S/C). This comprehensive review reviews the efforts of previous researchers to develop concepts for ABEP systems. Different kinds of space propulsion system are analysed to determine the suitable propulsion for atmosphere-breathing S/C. Further discussion about ABEP systems shows the characteristic of different thrusters. The main performance of the ABEP system of previous studies is summarized, which provides further research avenues in the future. Results show great potential for thrust compensation from atmospheric molecules. However, the current studies show various limitations and are difficult to apply to space. The development of ABEP needs to solve some problems, such as the intake efficiency, ionization power, and electrode corrosion.

1. Introduction

After over 50 years of space exploration, space orbit resources show their significant position in the national economy and defense construction [1]. Through observation of the Earth, the satellite has a wide application prospect in weather forecast, ocean monitoring, agricultural monitoring, electronic communication, positioning navigation, remote sensing, and other fields [2]. At the same time, considering that the number of satellites in space orbit is becoming increasingly saturated, lower Earth altitude orbit (lower than 250 km) has become a new choice for satellites to expand the operation range and improve the mission capability.

Lower-orbit S/C can significantly reduce the cost of launch, effectively improving the resolution of the instrument to obtain higher Earth observation accuracy. However, due to the particularity and complexity of the low-orbit environment, the long-term residence of low-orbit S/C is faced with lots of difficulties. The development of low-orbit S/C is seriously restricted by the problems of short life of satellites and expensive fuel supply. If we can make full use of the thin atmosphere in the low-orbit environment as the propellant for the propulsion system to maintain the orbit speed of the S/C, we can greatly reduce the weight of the propellant carried and extend the lifetime of the S/C. Therefore, as a new technology of low-orbit S/C, atmosphere-breathing electric propulsion technology will meet the supply demand, so as to greatly reduce the cost and prolong the lifetime of S/C, which has a great economic benefit.

Therefore, the study of atmosphere-breathing electric propulsion (ABEP) has the following advantages [3]: (1) Launch cost is low. The launch altitude of low-Earth-orbit (LEO) satellite is lower, so the launch cost is obviously lower. (2) Resource allocation is reasonable. The number of high-orbit S/C is becoming saturated, so the development of low-orbit S/C can effectively use space resources. (3) There is a good reconnaissance conditions. As the low orbit is close to the Earth's ground, the requirement to monitor equipment is reduced. Under the same conditions, the ground target can be observed more clearly and accurately in low orbit. (4) The service lifetime is longer. Instead of traditional propellants, using atmospheric molecules can remove the capacity limitation of carrying propellants. (5) It can be destroyed automatically. Due to the existence of the thin atmospheric

resistance, when the thruster does not work, the S/C will deorbit due to the air resistance after the mission and fall into the atmosphere for breakup to avoid becoming space debris. (6) Aerodynamic is applied [4, 5]. Such systems may be benefitting from the potential use of aerodynamic payloads and forces in general for maneuvers in between satellites and as a hybrid use with ABEP. Aerodynamic stabilization and pointing manoeuvres were shown to be feasible on LEO using aerodynamic surfaces.

Compared with other orbits in the vacuum environment, the drag of atmospheric molecules must be considered in the design of flight mission when the S/C is flying in a low-Earth-orbit environment (lower than 250 km). The number of gas particles increases with the decrease of orbital altitude. In the low-orbital environment, due to the increase of atmospheric density, the S/C is bound to be subject to the resistance of atmospheric molecules, and additional power is needed to compensate for the resistance of the S/C. Considering the characteristics of the space environment in the low orbit, the rarefied gas can be used as the working medium of the electric propulsion engine to compensate for the resistance and adjust the flight altitude. Rarefied gas resistance compensation can be completed without carrying fuel, which is a promising way for the efficient work of the S/C in the low orbit [6].

This comprehensive review examines the efforts of previous researchers to develop concepts for the ABEP system, estimate the performance of these systems, and understand the physics involved. The manuscript is organized into four distinct sections. The following section introduces the fundamentals of space propulsion system and summarizes the main characteristics of different propulsion systems. Section 3 reviews the seminal work of different teams of the ABEP system. More recent studies are presented, which demonstrate the renewed interest in ABEP with a particular focus on the design of the inlet to attain high performance on the ABEP system. The final section proposes avenues for continued research given the results of the research conducted thus far.

2. General Situation of Space Propulsion

This section first introduces the different propulsion systems available and theoretically feasible for S/C and explains their working principles. Compared with each propulsion system, their advantages and disadvantages are analysed. Combined with the working characteristic of ABEP, the suitable thruster for ABEP is selected.

2.1. Chemical and Nuclear Propulsion. Chemical propulsion includes solid and liquid fuel, and it uses the combustion of reactants to raise the temperature of gas products and accelerates the ejection through the nozzle, thus converting heat energy into kinetic energy to generate thrust [7]. This technology can provide a high level of thrust, but it also consumes a lot of propellants. In the case of liquid propellants, complex subsystems need to be designed.

The nuclear propulsion system uses a nuclear reaction to heat the propellant and accelerate its ejection through the nozzle. Cassibry et al. [8] summarized the more than 50-year history of fusion propulsion research for deep space exploration, which suggests that magnetoinertial fusion can provide the most economical approach rapid interplanetary trip times. Borowski et al. [9, 10] summarized NASA's research for over one year, which examined the feasibility of the fission propulsion system in the exploration of human extraterrestrial space. NASA designed a "two mode" thermonuclear rocket, bimodal nuclear thermal rocket (BNTR), to propel the vehicle to Callisto [11]. The fission reactor system uses high-temperature uranium dioxide (UO_2) in tungsten (W) metal matrix cermet fuel and advanced Brayton power conversion technology to generate electricity [12]. In this scheme, the full-automatic freight and oil tank trucks start first, and the track and ground resources are deployed in advance before the crew gets on the Piloted Callisto Transfer Vehicle (PCTV) driven by artificial gravity. The BNTR thruster is shown in Figure 1.

2.2. Electric Propulsion. According to the different acceleration strategies, the electric propulsion system mainly includes the following three categories:

2.2.1. Electrothermal. For the electrothermal thruster, the electric power is used to heat up the propellant which expands through a nozzle. Common propellants include hydrogen, xenon, hydrazine (N_2H_4), ammonia (NH_3), and other anaerobic propellants. There are Resistojet and Arcjet under the electrothermal subcategory. For Resistojet, the temperature of the propellant is increased with an arc discharge. For Arcjet, it uses a combination of a heat exchanger connected to a resistive heater element to heat up the propellant. According to the research of Wollenhaupt et al. [13], Arcjet requires a power between 0.3 and 100 kW generating thrust between 200 and 7000 mN with a higher I_{sp} between 200 and 2000 s. For instance, an Arcjet thruster developed by the University of Stuttgart [14, 15] uses hydrazine and ammonia as propellants with a thrust of 100-500 mN. In addition, the energy sources of the electrothermal thruster include solar energy, laser, and microwave thermal energy, which are transmitted and concentrated in the heat exchanger or propellant itself, so as to heat it and spray it out. The Arcjet thruster is shown in Figure 2.

2.2.2. Electrostatic. For electrostatic thruster, the electric power is used to ionize the propellant and the electrostatic field is used to accelerate the propellant. The main type includes field emission electric propulsion (FEEP), ion thruster, and Hall-effect thruster (HET).

FEEP thrusters extract atoms and ions directly from the metal surface exposed to a vacuum by the electric field and accelerate them. The propellant that produces thrust is usually liquid metal. Using indium as the liquid metal ion source, Tajmar [17, 18] developed a special in-FEEP thruster. The thruster is a micropulse device for a thrust of 1-100 μN, which has low thrust noise and high resolution. The in-FEEP thruster is shown in Figure 3.

Ion propulsion and Hall-effect propulsion are currently relatively successful thrusters, which have been tested and

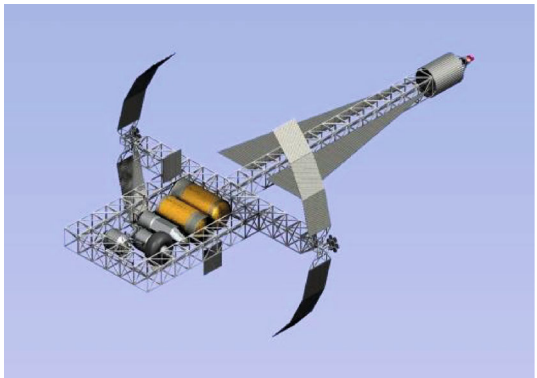


Figure 1: BNTR thruster [12].

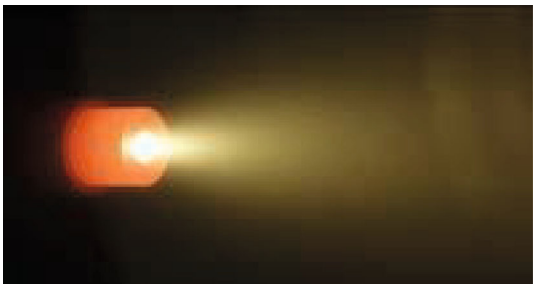


Figure 2: TALOS Arcjet thruster in the University of Stuttgart (NH_3) [16].

applied in various space missions. They all extract ions from plasma by the electrostatic field and then accelerate to produce thrust. Among them, the characteristics of ion thruster are small thrust and high specific impulse. In 2012, a xenon ion propulsion (XIP-20) thruster was used in the "Shijian 9" satellite and it was successfully launched by Taiyuan Satellite Launch Centre [19]. After that, the main performance indexes of 40 mN/3000 s xenon ion electric propulsion system were introduced by the Lanzhou Institute of Space Technology Physics [20]. The "Shijian 9" satellite is shown in Figure 4.

HET needs more power than the ion thruster, so it shows higher thrust density. In 2004, NASA [21] carried out special research on HET. This research focused on improving the technical preparation level of high-power HET, developing medium power/medium specific impulse HET, demonstrating the operation of high power/high specific impulse Hall thruster, and solving the basic technical challenges of the new concept of HET. Based on the existing NASA-457M Hall thruster, this team redesigned a 50 kW Hall thruster (NASA-457M V2), which eliminated the defects of anode installation, electrical isolation, concentricity, and thermomechanical interference. The NASA's HET is shown in Figure 5.

2.2.3. Electromagnetic. For electromagnetic propulsion, the electric power is used to ionize the propellant and the electromagnetic field is used to accelerate the propellant. It mainly includes pulsed plasma thruster (PPT), magnetoplasma dynamic (MPD), and inductively plasma generators (IPG).

PPT usually uses polytetrafluoroethylene (PTFE) as the propellant, which causes the propellant to ablate and sublimate through surface discharge. The generated heat ionizes the generated gas into plasma and generates charged clouds. Due to the force of ablation, the plasma flows between the anode and the cathode completing the circuit. The current flows through the plasma to generate a strong magnetic field, which exerts Lorentz's force on the plasma, accelerating the plasma and expelling it out of the PPT. A team from Tokyo University studied a liquid propellant pulsed plasma thruster (LP-PPT) [22], which improved the situation that solid propellant needed to undergo ablation and thus improved the performance of the propellant. The LP-PPT is shown in Figure 6.

In MPD, when the magnetic and electric fields are applied by a power supply in the AF-MPD (applied-field) or generated by a SF-MPD (self-field), the gaseous fuel is converted into plasma and sent into the acceleration chamber. The ionized particles here are driven by Lorentz's force, which is the result of the interaction between the current flowing in the plasma and the magnetic field in the chamber. NASA's research results show that [23] the MPD thrusters have a specific impulse of between 2,000 and 7,000 seconds at an efficiency of nearly 40%, and it can operate continuously at a power level over 500 kW. Subsequent studies have found that the steady-state applied-field magnetoplasma dynamic (AF-MPD) thrusters feature a combination of high exhaust velocity, high thrust density, and power scalability, making them relevant for interplanetary missions. The ESA-IRS has developed a new 100 kW gas-fed steady-state AF-MPD SX3 thruster [24]. The experimental results show that the discharge characteristics and performance of the thruster can reach the arc power level of 115 kW, and the thrust efficiency is more than 40%. The AF-MPD SX3 thruster is shown in Figure 7.

In IPG, the particles of ionized gas are usually in a tube made of quartz, through a coil of high-frequency current that is not in direct contact with the flow. The plasma is accelerated and ejected by Lorentz's force created by the interaction of the plasma current and the magnetic field generated to produce thrust. IPG is electrodeless, which means that the life and contamination problems associated with electrode corrosion will be eliminated. The modular IPG was developed and tested in the space research institute of the University of Stuttgart. The IPG6-B is shown in Figure 8.

2.3. Summary of Space Propulsion System. The performance of a typical space propulsion system is shown in Table 1.

As shown in Table 1, the chemical propulsion system is not suitable for small S/C due to its characteristics of high cost, large weight, limited operation time, and lower specific impulse.

Nuclear propulsion is not yet in space, and it is unlikely to be used in small S/C, mainly because of the risk of explosions during lift-off and the potential for radioactive products to spread on Earth. Such applications have yet to be resolved, so public opinion is still against the technology.

As shown in Table 2, electric propulsion systems usually have a higher specific impulse, which means that they use propellants in a very efficient manner. The required power can be extended to small S/Cs and their components. In

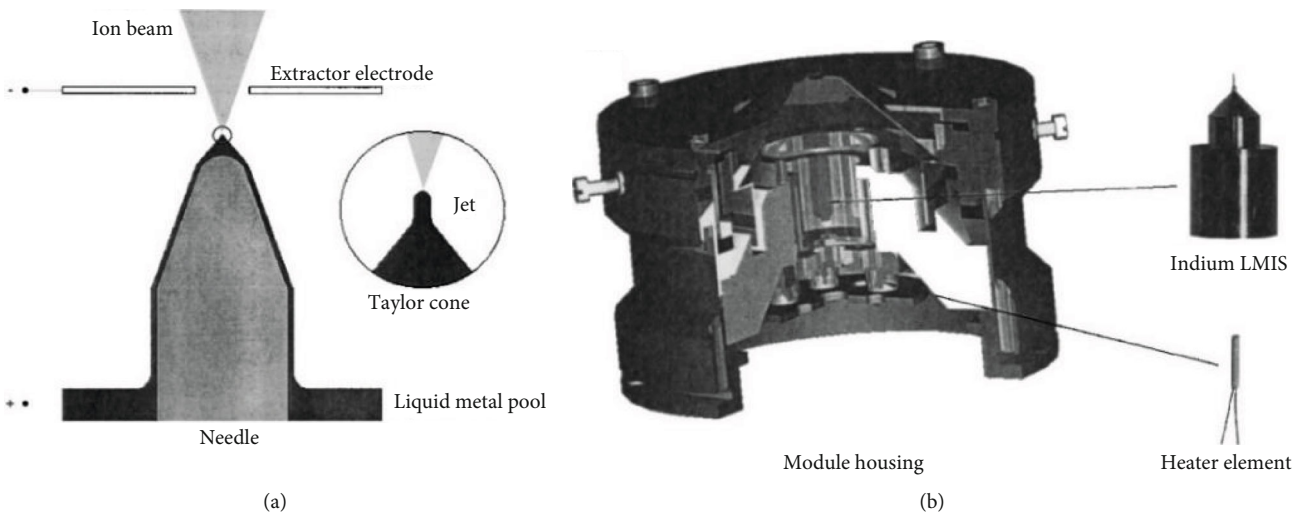


Figure 3: In-FEEP thruster: (a) in-FEEP principle; (b) in-FEEP thruster consisting of indium LMIS, heater element, and module housing [18].

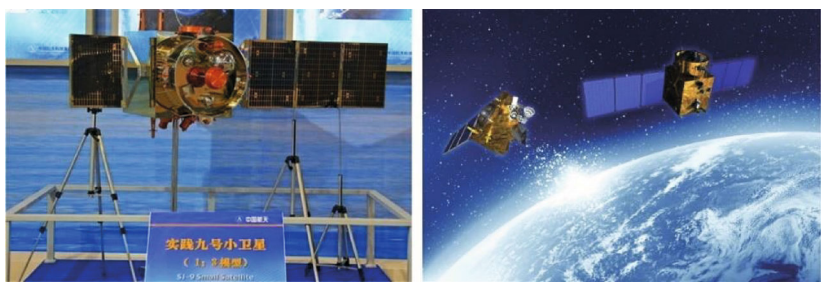


Figure 4: Xenon ion propulsion "Shijian 9" satellite [19].

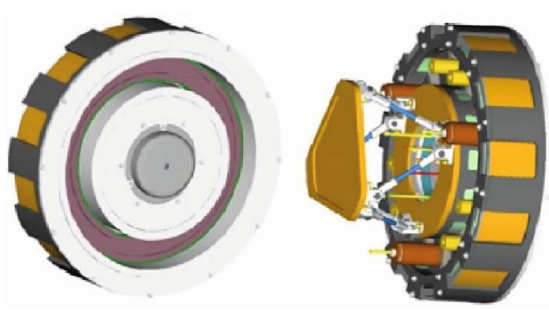


Figure 5: NASA's Hall-effect thruster: a solid model rendering of NASA-457M V2 [21].

addition, its complexity is lower than that of chemical and nuclear propulsion systems. Therefore, the electric propulsion system is selected as the main research object of ABEP.

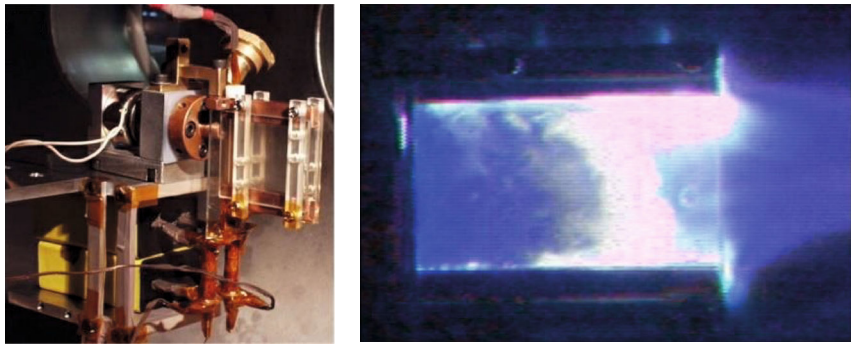
3. Atmosphere-Breathing Electric Propulsion

The traditional electric propulsion system cannot guarantee the long-time low-orbit operation of the S/C [31]. Due to the constraints of propellant storage and thrust compensation, the flight time usually does not exceed 2 years. ABEP is a technology that uses a thin atmosphere as a propellant in low orbit without the need to carry any onboard propellant. And this system is generally composed of an inlet and an electric thruster. In addition, the technology can be applied to planets with atmospheres, such as Mars [32], which allows S/C to perform longer missions at a new atmospheric altitude and is important for scientific research as well as military and civilian monitoring services.

3.1. Air Intake of the ABEP System for LEO. The functions of the intake are of collecting the air while keeping its velocity, compressing it, and driving it into the thruster.

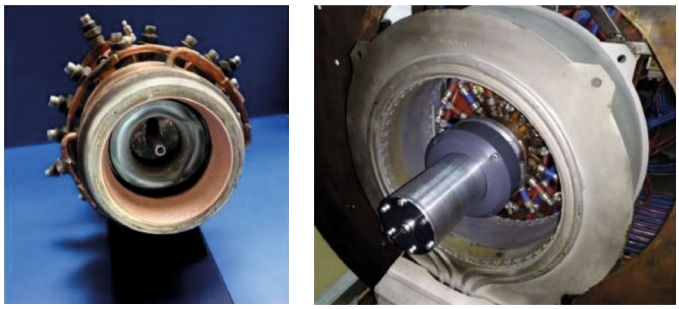
In 2003, the Japan Aerospace Exploration Agency (JAXA) [33, 34] designed air intake for the ABEP system. The air intake shows a honeycomb parallel straight pipeline, and the parallel gas flow has less collision with the intake wall. Thus, it has a high intake efficiency. In 2012, its study [35] showed that the intake design was sufficiently compressed to provide a pressure of 0.5 Pa to ignite the plasma inside the ECR at the orbital altitude of 200 km. The air intake of JAXA is shown in Figure 9.

In 2007, the European Space Agency (ESA) [31] carried out a feasibility analysis of the air-breathing electric propulsion (RAM-EP) system. The proposed concept includes a collection system to capture thin airflow and a gridded ion engine (GIE) to generate the required thrust. The intake is



(a) (b)

Figure 6: LP-PPT of Tokyo University: (a) picture of a parallel plate LP-PPT; (b) streak photograph of parallel plate LP-PPT firing [22].



(a) (b)

Figure 7: AF-MPD SX3 thruster: (a) SX3 thruster after test campaign without SX coil (BN3); (b) mounted SX3 thruster and SX coil assembly [24].

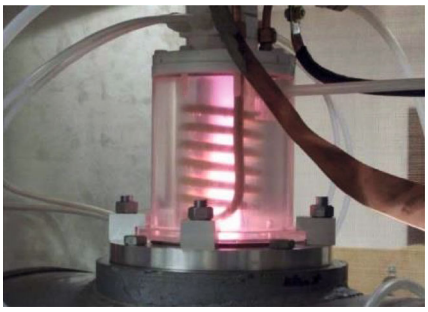


Figure 8: IPG6-B in the University of Stuttgart [25].

positioned in the axial direction of the S/C and presents a honeycomb shape, which can directly provide the required mass flow rate (MFR) to the thruster's inlet at a certain pressure. The feasibility analysis shows that the RAM-EP concept has great potential for low altitude and long lifetime missions in the range of 200 to 250 km altitude. However, the results of the study are based on the prediction of thruster performance for a given gas mixture using available theoretical models. In order to verify the performance prediction, the thruster of the nitrogen-oxygen mixture still needs to be tested and verified. The collector concept is shown in Figure 10.

In 2015, the Lanzhou Institute of Space Technology Physics [36] designed and analysed an air-intake device for atmosphere-breathing electric propulsion. The team carried out a feasibility analysis of the air-breathing electric propulsion system [37] and designed a vacuum intake device with an inlet diameter of 500 mm, which was used to collect space gas as the propellant of the air-breathing electric thruster. It is composed of a multihole plate, a large turbine, a small turbine molecular pump, and a miniature scroll pump in series. The intake device is shown in Figure 11.

In 2015, the team conducted design research on the air intake of the atmosphere-breathing electric propulsion system [38]. Compared with the research of JAXA and BUSEK, it is found that, ideally, the inflow should be as high as possible and the backflow as low as possible in an air intake. It is recommended to use a grid instead of a honeycomb structure at the front of the air intake to form a higher performance air intake.

In 2016, the team studied the transmission probability of rarefied flows in low Earth orbit [39]. The results show that the collection efficiency (collected part of the flow into the air inlet) can be improved by implementing small ducts at the front of the intake. The principle is a molecular trap that allows most of the fast inflow passing through while reducing backflow.

In 2018, Jackson and Marshall [40] tested three different shapes of intake for their effectiveness in capturing incoming particles: a pyramidal shape, a conical shape, and a parabolic

Table 1: Performance of space propulsion systems [26] p.11.

Space propulsion		Specific impulse (s)	Max. Δv (km/s)*	Max. thrust (N)
Chemical	Solid [7]	250~310	5.7~7.1	10^7
	Liquid [7]	300~500	6.9~11.5	10^7
Nuclear	Fission [9, 10]	500~800	11.5~20.7	10^6
	Fusion [8, 27]	10,000~100,000	23~2,300	10^5
Electric	Electrothermal [13]	150~1,200	3.5~27.6	10^1
	Electrostatic [16–20]	1,200~10,000	27.6~230	3×10^{-1}
	Electromagnetic [28]	700~5,000	16.1~115	10^2
Propellantless	Photon Rocket [29]	3×10^7	Unlimited	10^{-4}

*Δv (velocity difference) assuming S/C consists of 90% propellant.

Table 2: Performance of electric propulsion systems [26] p.76.

Electric propulsion		Propellant	Power (kW)	Specific impulse (s)	Efficiency (%)	Thrust (mN)
Electrothermal	Resistojet [30]	N_2H_4, NH_3	0.5~1.5	300	80	100~500
	Arcjet [13]	N_2H_4, NH_3	0.3~100	500~2k	35	200~7000
Electrostatic	FEEP [17, 18]	In, Cs	0.01~0.15	8k~12k	30-90	0.001~1
	Ion [20]	Xe	0.5~2.5	3k	60-80	100~200
	Hall [21]	Xe, Kr, Ar	1.5~5	1.5k~2k	50	80~200
	PPT [22]	PTFE, Ar	0.001~0.2	1k	5	1~100
Electromagnetic	MPD [23]	NH_3, H, Li	1~4000	2k~5k	25	1~200N
	IPG [25]	N_2, O_2	0.5~3.5	—	46	—

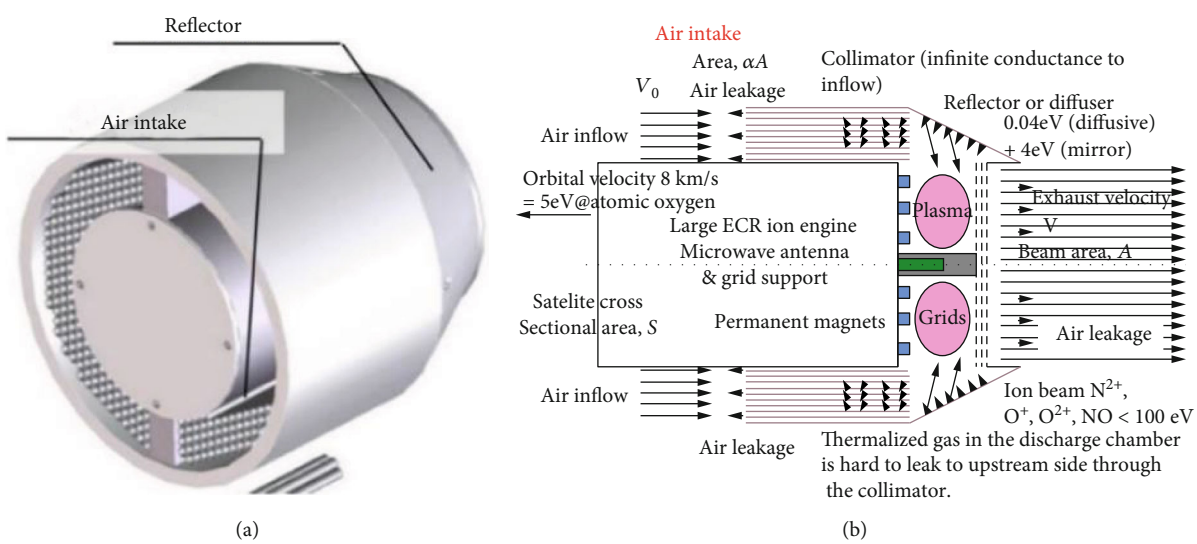


Figure 9: Air intake of JAXA: (a) air intake; (b) operation principle of ABIE (without a neutralizer) [33].

shape. The results show that, under the ideal scenario of specular reflection, the parabolic shape outperforms the other two shapes due to the optics of a parabola and all particles will reflect toward the focus of the parabola. The test shapes are shown in Figure 12.

3.2. Electric Thruster for the ABEP System. The main electric thruster types for the ABEP system are electrothermal, electrostatic, and electromagnetic. For electrothermal thrusters, common propellants include N_2H_4 and NH_3. In the application background of ABEP, the high-temperature oxygen-containing environment may corrode the nozzles, resistors, and other components, so the electrothermal thrusters are not suitable for atmosphere-breathing electric propulsion [41].

3.2.1. Electrostatic Thrusters. Electrostatic thrusters have the most extensive research on the concept of ABEP, including IE and HET.

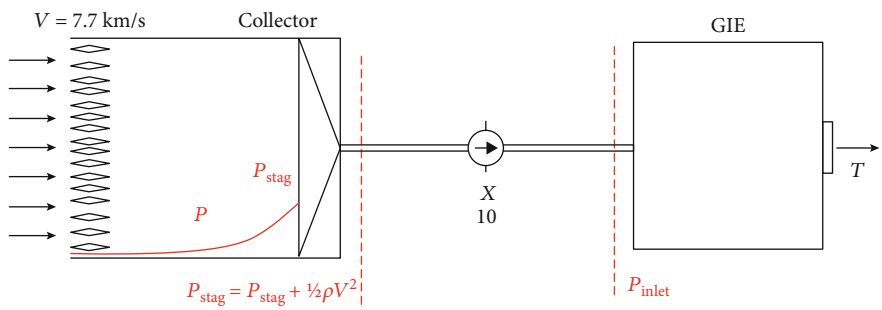


Figure 10: Schematic diagram showing the collector concept (ESA) [31].

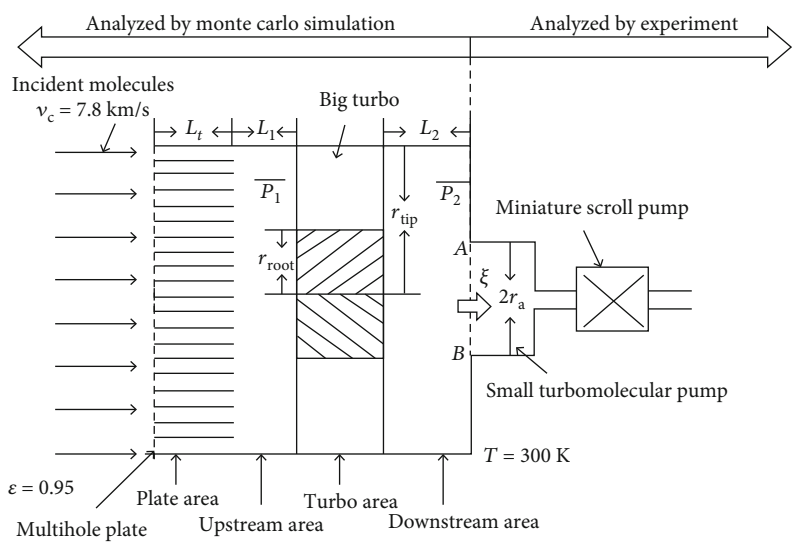


Figure 11: Schematic diagram of a vacuum air-intake device [36].

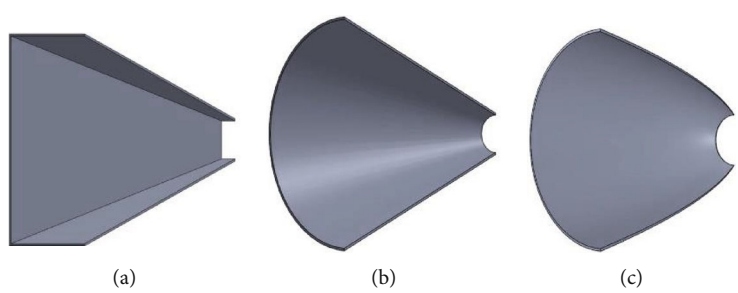
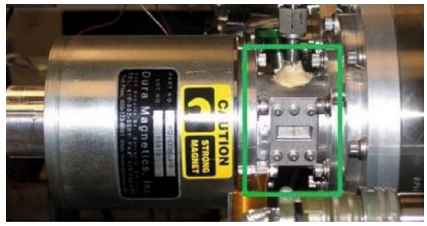


Figure 12: Cross-sections of the test inlet shapes: (a) pyramidal inlet, (b) conical inlet, and (c) parabolic inlet [40].

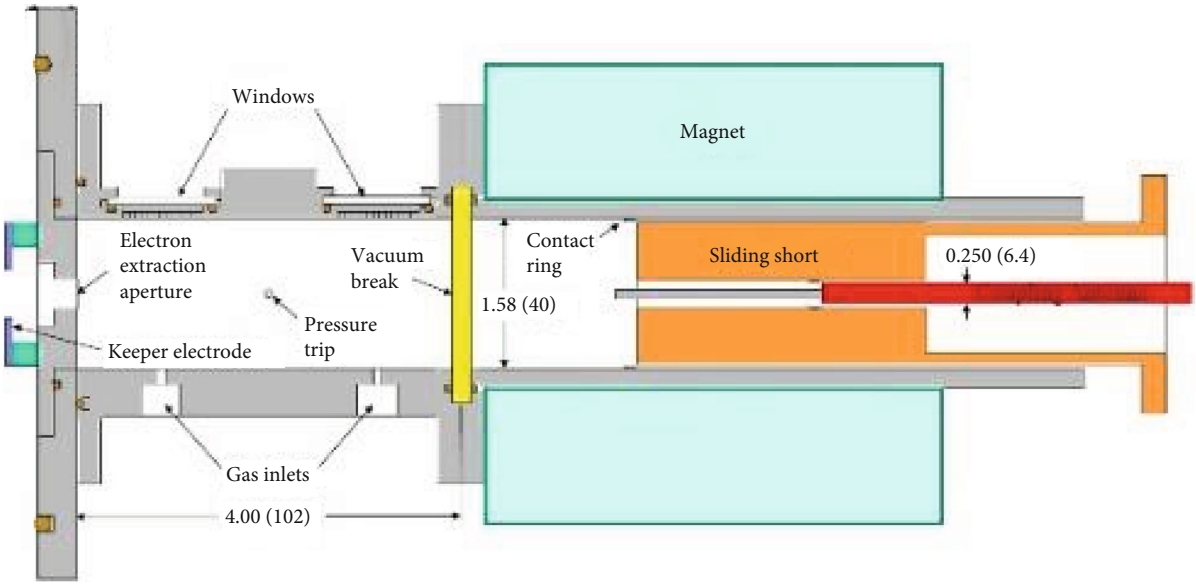
In 2003, JAXA [33, 34] first proposed the concept of the air-breathing ion engine (ABIE), which consists of air intake, discharge chamber, grids, and neutralizer. In this system, the thin atmosphere around the S/C is used as the propellant for the electron cyclotron resonance (ECR).

In 2010, Diamant [42, 43] designed a 2-stage cylindrical Hall thruster for air-breathing electric propulsion. This study suggests that, on a S/C at an altitude of about 200 km, a 2-stage cylindrical Hall thruster can be used to absorb the propellant from the atmosphere to compensate for drag. The first stage is an electron cyclotron resonance ionization stage, and the second stage is a cylindrical Hall thruster. It is shown that when the compression ratio of 500 is assumed to be achieved, a pressure of 0.01 Pa can be provided to the thruster. Compared with other cylindrical Hall thrusters, the results of this work are favorable in terms of plume ion energy and divergence, but the thrust efficiency is lower. This study also includes the effects of changes in anode position, magnetic field topography, and cathode type (e.g., microwave cathode), but did not address the use of the thin atmosphere. The 2-stage ABCHT is shown in Figure 13.

In 2010, Cifali et al. [44] carried out two test campaigns on Snecma's PPS1350-TSD Hall thrusts and RIT-10 ion engine to determine the performance characteristics with



(a)



(b)

Figure 13: A 2 stage ABCHT: (a) ABCHT mounted to a vacuum chamber; (b) section view of cavity, dimensions in inches (mm) [43].

nitrogen and oxygen as propellants. The test results show that the performance of both thrusters is obviously decreased with the propellant Xe, especially due to the low ionization efficiency of atmospheric propellants. However, a long time of ignition test indicates that both devices are basically able to work continuously and steadily with such propellants. Furthermore, the measured performance is in the range of RAM-EP applications. HET is preferred when a low power/-thrust ratio is required, and RIT is more appropriate when a low thrust level (less than 10mN) is required. The HET and RIT tests are shown in Figure 14.

In 2012, Pekker and Keidar [45] presented a model of air-breathing Hall-effect thruster. A new working method of air-breathing thruster is presented in which the inlet air is fully ionized without preliminary compression. It shows that, in the case of 90-95 km orbit, the model can give 9.1-22 mN thrust depending on the strength of magnetic field intensity. The estimation results show that the beam receiver on the spacecraft is not expected to generate a drag force larger than the thrust. However, this research considers a highly simplified thruster model of the plasma-wall interaction inside the thruster chamber, and the Monte Carlo method should be used for more accurate simulation. The concept of ABHT is shown in Figure 15.

In 2012, BUSEK [32] developed a Martian Air-Breathing Hall-Effect Thrust (MABHET) applied to S/C in the low orbit of Mars. It is also applied for corresponding patent [46]. This system uses atmospheric gases as propellants, eliminating the need to launch and carry propellants from the ground. The thrust of a power peak ratio for an unmodified Hall thruster (designed to operate with xenon) has been measured, with a Mars-like gas mixture, to be around 30 mN/kW with a low peak of 19 mN/kW with an efficiency of about 22-25%. The MABHET of BUSEK is shown in Figure 16.

In 2012, Garrigues [47] carried out a computational study on Hall-effect thrusters using the atmosphere as the propellant. The possibility of using atmospheric gas as a propellant for S/C in the Earth ionosphere is analysed by using the simple analytic scaling laws and the two-dimensional hybrid model of the Hall-effect thruster. Compared to xenon propellants, the length of the ionization layer increases due to a less favorable ionization cross-section in the atmosphere. As a result, the channel geometry and magnetic field strength employed by xenon are no longer suitable for low-mass propellants. The analysis and calculation show that the decrease of the magnetic field and the increase of channel length are beneficial to the ionization of atmospheric gas. The calculation also shows that the mass flow rate of the propellant is about 3 mg/s. For O and N, 20 mN of thrust must be generated to compensate for the resistance at an altitude of 250 km.

In 2013, Tagawa et al. [48] carried out an experimental study on the air-breathing ion engine (ABIE) by using a laser detonation beam source. The basic performance of ABIE using upper atmospheric gases as a propellant was studied.

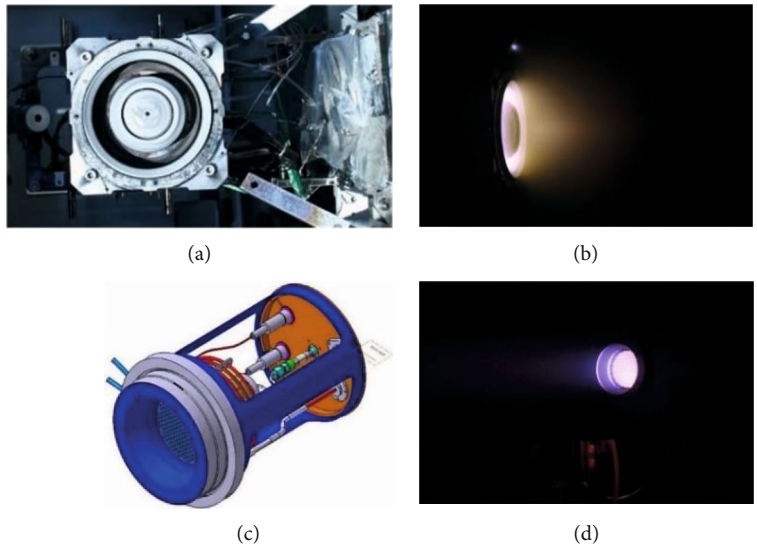


Figure 14: Two tests on HET and RIT: (a) the PPS1350-TSD; (b) HET operating with N_2/O_2 mixture; (c) 3D-CAD view of RIT-10EBB ion thruster; (d) RIT-10 thruster running with N_2 [44].

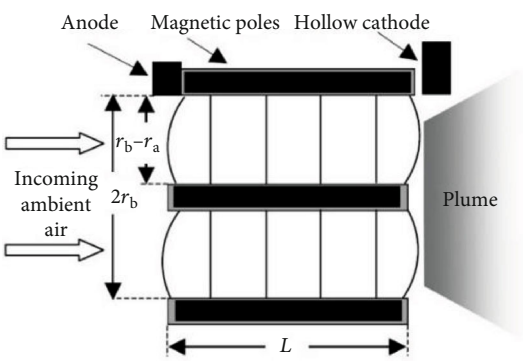


Figure 15: Schematic of atmosphere-breathing Hall thruster (not to scale) [45].

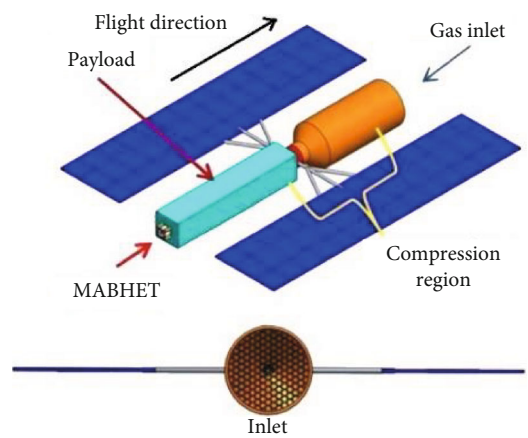
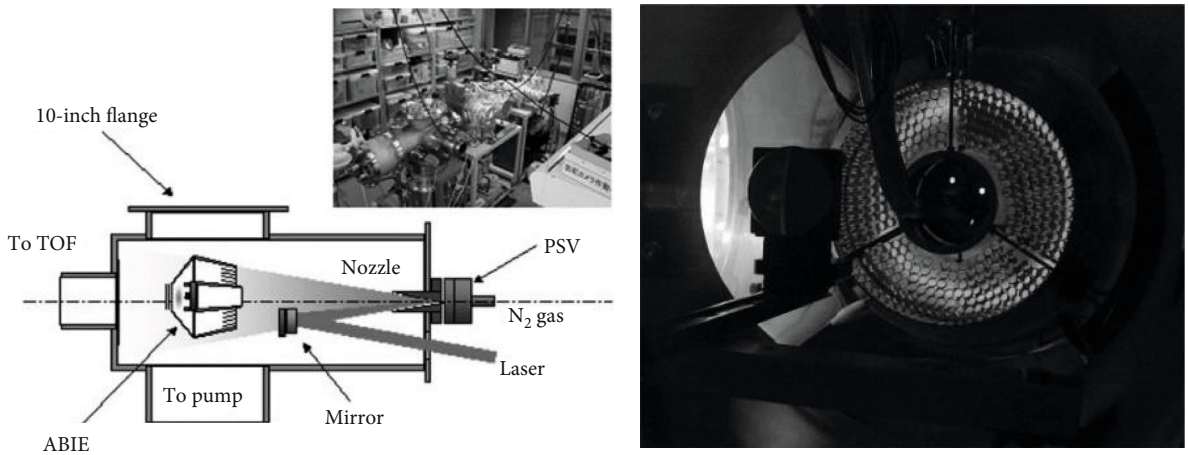


Figure 16: Conceptual MABHET of BUSEK [32].

The low-Earth-orbit environment of 140-200 km was simulated by a laser detonation beam source, and the basic performance of ABIE was studied by using a hyperthermal N_2 beam. It was proposed that in an ABIE, hyperthermal N_2 molecules were thermally heated by scattering on the reflecting surface. The efficiency of the collimator was experimentally investigated, and it was found that the collimator could maintain the N_2 pressure inside the ABIE. The ion beam current of 16 mA at an acceleration voltage of 200 V provided a thrust of 0.13 mN for the hyperthermal N_2 and atomic oxygen beams. It was also found that the maximum ion beam was limited by the space charge effect. The experimental results strongly illustrated the composite action of oxygen molecules in an ABIE. The ABIE concept is shown in Figure 17.

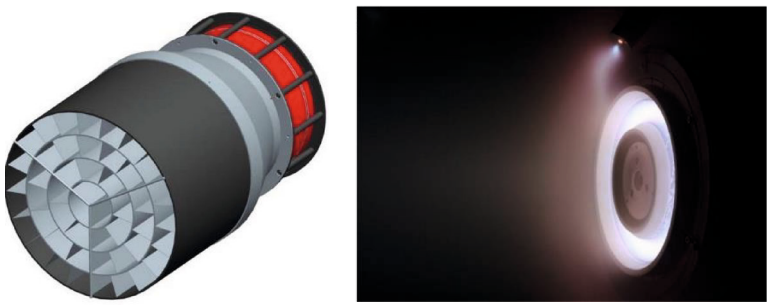
In 2017, Andreussi et al. [49] developed and tested the air-breathing Hall-effect thruster concept at SITAEL. This system consists of a passive air intake/collector assembly and an air-breathing double-stage Hall-effect thruster (RAM-HET). The former collects atmospheric molecules and directs them to the thruster, while the latter enhances the ionization of the incoming flow by plasma confinement in the first stage and electrostatic acceleration in the second stage. This test shows that the system can generate 6 mN thrust when the airflow generated by the particle flow generator (simulating the atmospheric flow characteristics corresponding to the altitude of 200 km) and the airflow collected at the system inlet are run. However, this system is currently unable to provide positive thrust due to the measurement of resistance of 26 ± 1 mN. Andreussi's RAM-HET is shown in Figure 18.

In 2018, Jackson and Marshall [40] studied an atmosphere-breathing ion thruster. This study mainly designed the inlet of the system, studied the capture efficiency of particles and the ionization efficiency of atmospheric particles, and then analysed the thrust force. The results show that ionization efficiency is crucial to the thruster's ability to overcome low-Earth-orbit resistance. If the combined efficiency of the inlet and ionization is greater than or equal to



(a) (b)

Figure 17: ABIE concept: (a) schematics and a photograph of the laser detonation atomic beam source; (b) photograph of oxygen plasma observed from the front side of the ABIE [48].



(a) (b)

Figure 18: Andreussi's RAM-HET: (a) view of the intake/collector assembly reduced scale mode; (b) HT5k firing with $1.27N_2+O_2$ mixture [49].

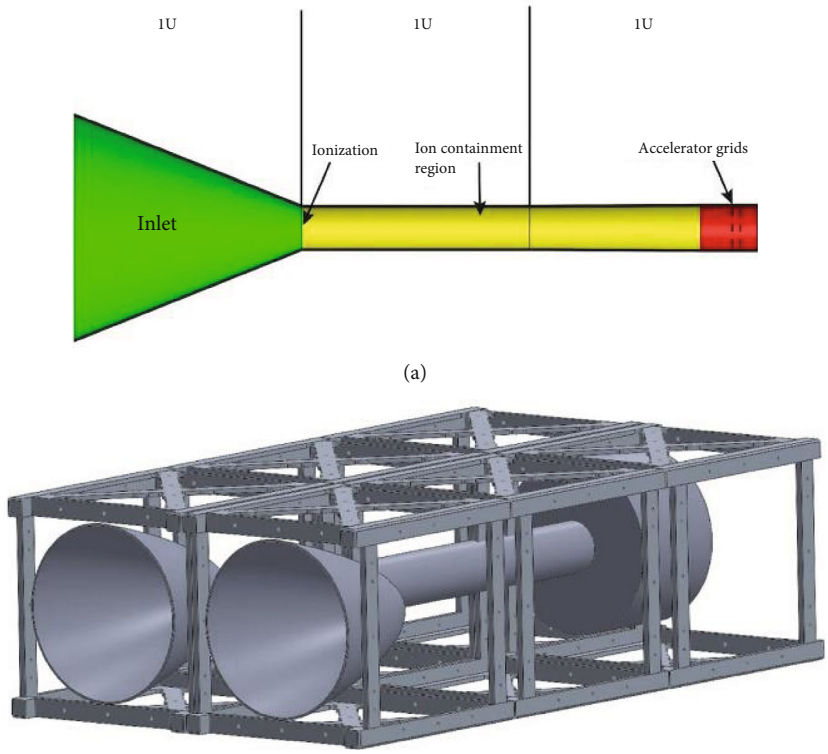
9%, the 3 U version of the system can only compensate for the resistance of approximately 300 km. If the combined efficiency of the inlet and ionization is maintained at approximately 5% or more, 6 U, 12 U, and 27 U system configurations can compensate for the resistance of 200 km. When the ionization efficiency is 50%, the resistance of the 6 U system of 200 km matches the intake efficiency of 10%, and the performance will be greatly improved. Jackson's ABIT is shown in Figure 19.

3.2.2. Electromagnetic Thrusters. Researches about electromagnetic thrusters for the ABEP concept are rarely less, including PPT, MPD, and IPG.

In 2013, Greig et al. [50] studied an atmospheric plasma thruster (APT). Using direct force measurements and particle image velocimetry, an unparallel angular actuator with an exposed electrode and a closed electrode was investigated. It was shown that the induced force increased nonlinearly by increasing the included angle. In addition, the direction of the upstream component of the ion wind was varied by changing the electrode angle. Changing the angle between the electrodes can change the strength of the electric field near the plasma driver, which in turn changes the response. Then, using the experimental results, a concept of atmospheric plasma thrust was designed as a dielectric barrier discharge plasma actuator. The APT products are shown in Figure 20.

In 2013, Shabshelowitz [51] studied the radio-frequency plasma technology for the ABEP system in his doctoral thesis. According to the requirements of the system, two novel thrusters were tested in the laboratory. The first thruster used only radio frequency and magnetic fields to generate thrust. The second was a two-stage thruster using a radio-frequency ionization level to improve the propellant utilization efficiency of traditional thruster. Measurements of thruster performance were presented against the background of atmosphere breathing, as well as plasma probe exhaust measurements to characterize the major loss mechanisms. The results showed that the air-breathing S/C was feasible under the condition of the existing technology. The RF-ABEP is shown in Figure 21.

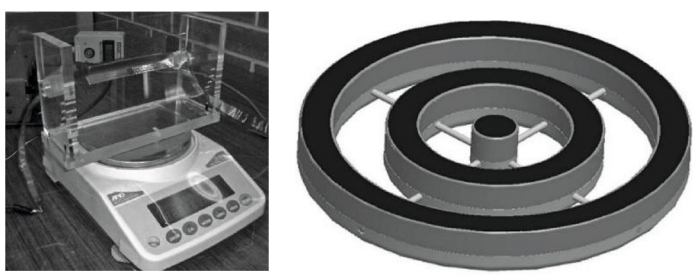
In 2014, Johnson et al. [52] studied a pulsed plasma thruster (PPT) for atmospheric operation. Coaxial PPTs with different sizes of electrodes were tested under the background pressure of 10-40 Torr. The resulting specific thrust was defined as the impulse measured on the thrust stand



(a)

(b)

Figure 19: Jackson's ABIT: (a) representations of the cross-section of the proposed system; (b) mockup of the 6 U sized thruster system [40].



(a) (b)

Figure 20: APT products: (a) experimental rig and balance; (b) computer model of plasma thruster prototype [50].

normalized by the capacitor energy, which was proportional to the background pressure and discharge chamber volume, and inversely proportional to the capacitor energy. Current and voltage measurements showed no difference in the discharge between atmospheric and vacuum operations, while high-speed camera imaging showed that the acceleration mechanism of atmospheric operations was entirely electrothermal, compared to the mixed thermal and magnetic acceleration under vacuum pressure. To demonstrate that atmosphere-breathing PPT was a viable concept, the device was launched from a high-altitude burst balloon at an altitude of 31.9 km. Johnson's AB-PPT is shown in Figure 22.

In 2017, Göksel and Mashek [53] demonstrated that the first critical test of the future air-breathing magnetoplasma propulsion system (MPP) had been successfully completed. In this regard, it was also the first time that a pinching dense plasma focus discharge could be ignited at one atmosphere and driven using a very fast nanosecond electrostatic excitation in pulse mode to induce a self-organizing plasma channel for propelling the master discharge ignition. According to the capacitor voltage (200-600 v), the energy input in one atmosphere varied from 52 to 320 J/pulse, corresponding to the pulse potential of 1.2-8.0 mNs. This new pulsed plasma propulsion system, driven by 1000 pulses per second, already had the thrust area ratio (50-150 kn/m^2) of a modern jet engine. Göksel's AB-MPP is shown in Figure 23.

In 2013, the University of Tokyo and the University of Stuttgart jointly conducted research on the air-breathing electric thruster [41, 54]. Preliminary studies have shown that the propellant flow required for electrostatic propulsion of the near-Earth altitude exceeds the possible mass intake, and that electrode corrosion due to oxygen flow may limit

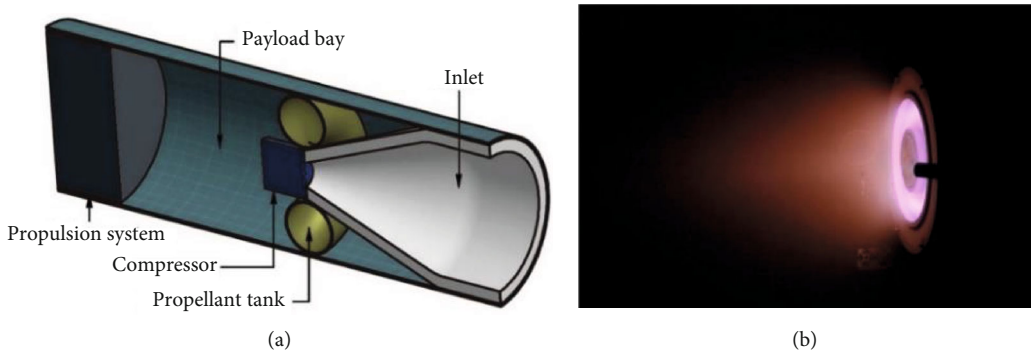


Figure 21: RF-ABEP: (a) cross-section of a notional atmosphere-breathing spacecraft; (b) single-stage Helicon Hall Thruster (HHT) operation with nitrogen propellants [51].

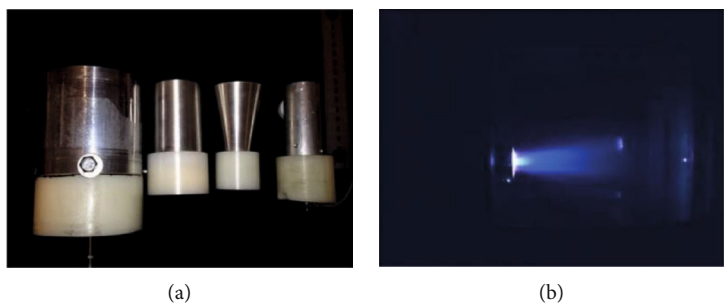


Figure 22: Johnson's AB-PPT: (a) the four PPTs tested with different diameters; (b) 62 J plume images at 50 μTorr, 0-40 μs after igniter discharge [52].

the life of the propulsion system. However, pulsed plasma thrusters (PPT) can operate successfully with low mass intake and relatively low power. This makes it an interesting candidate for low-orbit air-breathing applications. The analysis of this atmosphere-breathing PPT system shows that in the altitude range of 150-250 km, a thrust power ratio of 30 mN/kW and a specific impulse of 5000 s are at least partially feasible for the resistance compensation. In addition, in order to avoid electrode ablation, induction heating electrothermal plasma generator technology is also discussed to obtain a possible propulsion system that can handle gaseous propellants without adverse side effects. Current technology can be used to generate a thrust of about 4.4 mM per 1 mg/s mass flow, which is sufficient to compensate for the drag of small satellites at the altitude of 150-250 km.

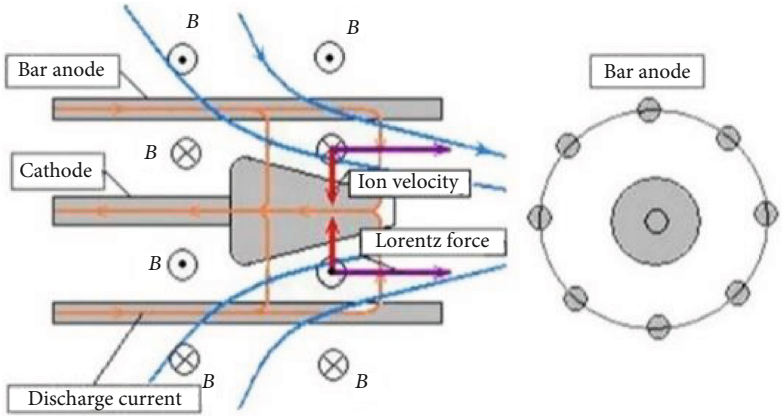
The coaxial air-fed pulsed plasma thruster was further developed by the cooperative team in 2018 [55]. Potential design improvements in electrode geometry and propellant injection were derived from the experimental results of the early air-fed PPT prototype and applied to the design of the next generation of coaxial air-fed PPT. This latest study examines the effectiveness of design changes on performance and electrode corrosion, which will be a strong indicator of lifetime assessment. The results show that the electrode ablation degree of air-fed PPT is higher than that of a typical gas-fed thruster. The VIPER concept is shown in Figure 24.

Starting from 2013, a team in the University of Stuttgart developed and tested a new design of an inductively driven plasma generator (IPG) [25]. This new IPG makes it possible to produce a nonpolar high enthalpy plasma and gives the initial characterization results of air plasma. It is shown that the mass-specific enthalpies of air plasma are more than 10 MJ/kg.

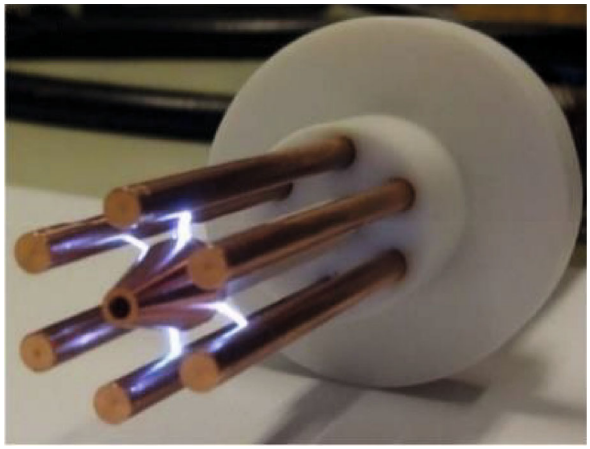
In 2017, the team conducted a performance evaluation of a novel inductive atmosphere-breathing EP system [56]. The facility uses IPG6-S, a small-scale IPG with an input power of up to 3.5 kW. The device allows for more reliable test conditions. The operation and performance of IPG6-S were tested for the first time. IPG6-S is a test bed for the development of an induced plasma thruster (IPT) for ABEP application.

In 2018, the team analysed the electrodeless plasma source enhancement by an externally applied magnetic field for an induced plasma thruster (IPT) [57, 58]. The plasma resistance and density characteristics of magnetized and unmagnetized plasma source were studied for different frequencies, input power, magnetic field intensity, pressure, temperature, plasma density profile, discharge channel, and antenna sizes. In 2019, the team also carried out experimental tests on the system [56–58] and carried out detailed design and verification of the IPT system. The IPT system is shown in Figure 25.

In 2020, this team deals in particular with the design and implementation of a novel antenna called the birdcage antenna [59]. It can be employed for helicon-wave-based plasma sources in fusion research. It uses antenna resonance for the additional acceleration of both ions and electrons via $E \times B$ forces. Correspondingly, the system benefits not only from the electrodeless design enabling a maximum variability of both composition and density but also from the quasineutral plasma jet such that a neutralizer is not needed.

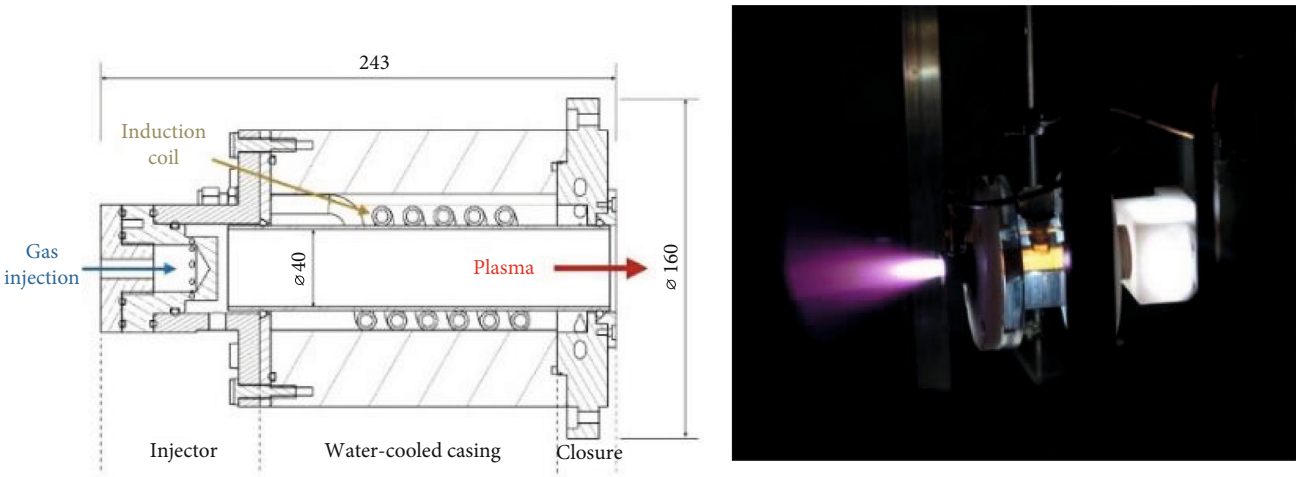


(a)



(b)

Figure 23: Göksel's AB-MPP: (a) physical principle of magnetoplasma compressors (MPC); (b) photos of transient atmospheric nanosecond pulse discharges for internal MPC excitation [53].



(a) (b)

Figure 24: Variable Inlet feeding atmosphere-breathing PPT for Electrode eRo-sion measurements (VIPER): (a) schematic of VIPER in radial-injection configuration; (b) VIPER in operation [55].

In 2019, the Beijing Institute of Spacecraft Environment Engineering [61, 62] carried out a concept study of air-breathing helicon thruster (ABHT) used in ultra-low-orbit flight. A contractive-shaped air inlet channel compacts well directly with an electrodeless helicon wave discharge tube. A predischarge sheath is set up in the rear port of the

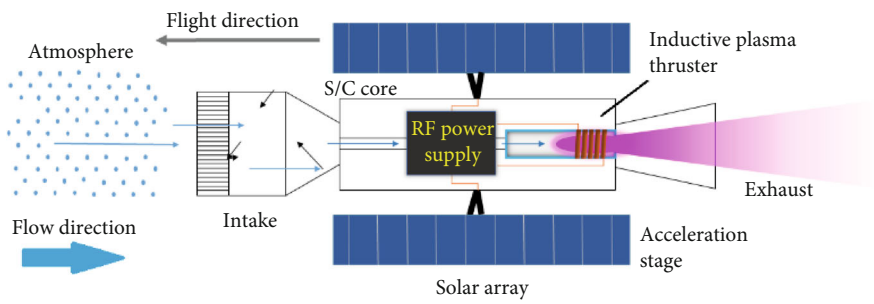


Figure 25: Inductive plasma thruster (IPT) system in the University of Stuttgart [60].

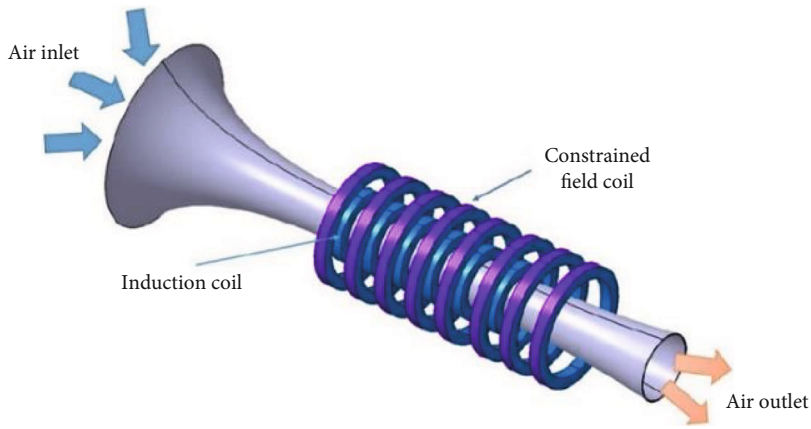


Figure 26: Concept of air-breathing helicon thruster [61].

channel, with the upward leakage of the plasma generated in the discharge tube by helicon waves. The existence of a pre-discharge sheath in the rear port of the channel makes the air density disturbance propagating downstream of the channel with the velocity of the ion-acoustic speed. Almost all molecules in the inlet go into the contractive-shaped channel, and then the tube, and are discharged and accelerated backward by the helicon plasma thruster at a larger directional velocity; propulsion is thus generated enough to maintain the long-term operation of an ultra-low-orbit satellite. The ABHT concept is shown in Figure 26.

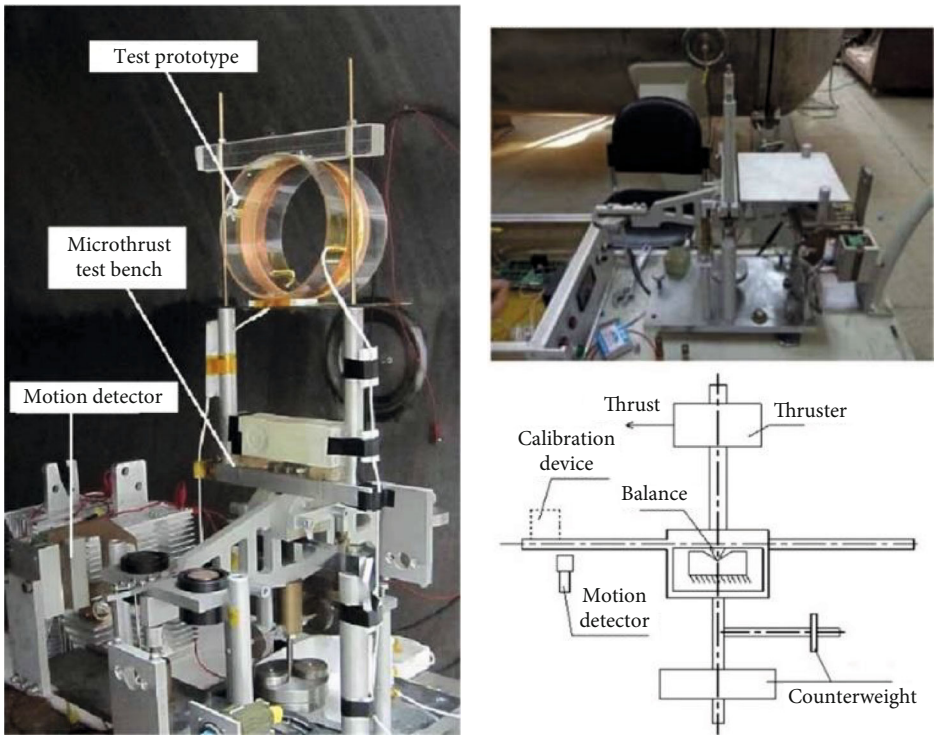
3.2.3. Other Technologies for the ABEP System. Electrohydrodynamic (EHD) propulsion is also a type of ABEP system that has been studied. It generates induced ion wind and thrust through the corona discharge device.

In 2003, NASA studied the thrust performance of EHD propulsion under low pressure and pure nitrogen gas environment [63]. The influence of different emitters on the thrust performance was also considered [64]. Preliminary experiments indicate that the observed thrust is equal to that of the ion wind. Different types of high voltage electrodes, including wire, knife edge, and needle array, were tested. A needle array was found to be the most optimal. However, the experiment results [24] showed that the suitable thrust per unit power only can be reached at low values of thrust. Based on this, it was concluded that the use of corona discharge in propulsion seemed impractical.

In 2005, Zhao and Adamiak [65] studied the flow of EHD gas in an electrostatic levitation device. Based on boundary, finite element method, and characteristic method, an electric field prediction algorithm is used. FLUENT software was used to calculate the airflow, and the detailed distribution of different parameters was given. The research results confirm the feasibility of the concept of the electrostatic levitating unit.

In 2006, Martins and Pinheiro [66] simulated EHD corona flows in nitrogen with asymmetric capacitors. The simulation results show that the main thrust on the physical origin of the force that acts on a capacitor is electrostatic, not hydrodynamic. However, this force mechanism still depends on the availability of surrounding ionization-sensitive particles in order to be able to function.

In 2013, Masuyama and Barrett [67] studied that the thrust power ratio of EHD propulsion to judge the efficiency. It is believed that the thrust power ratio of EHD propulsion is usually in the order of tens of N/kW, while the thrust power ratio of current aeroengines is only a few N/kW, so EHD propulsion should be a relatively efficient propulsion scheme. Due to the low energy conversion efficiency of EHD propulsion at higher air pressure (usually less than 1%), it is considered unsuitable as a main propulsion device [68]. Dielectric barrier discharge (DBD) is an unbalanced gas discharge with an insulating medium inserted into the discharge space. It is a technology that can generate a large volume and high energy density of low-temperature plasma under atmospheric



(a) (b)

Figure 27: Chen's prototype and test bench: (a) test prototype; (b) test bench of microthrust [69].

pressure. In 2016, Chen [69] introduced an air-breathing electric propulsion technology for near-space vehicles. This technique uses the single dielectric barrier discharge (SDBD) as the plasma source, which can ionize the atmosphere to produce plasma and generate thrust in a wide range of atmospheric pressure. The test results show that the thrust force of 10^2-10^3 μN can be generated when the atmospheric pressure is 10-90 kPa, and the thrust force is related to the power of the driving voltage. Chen's products are shown in Figure 27.

In 2017, Erofeev et al. [70] designed an accumulator for air-breathing ramjet electric propulsion (ABREP) system. As shown in Figure 28, the inlet channel is intended for receiving the incoming atmospheric particle flow and it should prevent particles leaving the accumulator under free molecular motion. The accumulator is a chamber for flow deceleration. Its main function is to "maxwellize" (or thermalize) particles of the incoming gas flow. The accumulator can make it possible to maintain the gas density needed for the operation of the ramjet thruster in the ionization region in the thrust unit.

3.3. Discussion about the ABEP System. According to the previous studies, it can be found that the types of atmosphere-breathing electric propulsion mainly include pulsed plasma thruster (PPT), magnetoplasma dynamic (MPD) thruster, ion engine (IE), and Hall-effect thruster (HET). As shown in Table 3, a comparative analysis of different ABEP products/concepts is listed, which is in terms of mass, frontal area, altitude, lifetime, thrust, power density, efficiency, and so on.

The mass of the ABEP device is basically less than 1000 kg, which directly determines the launch cost. The cross-sectional area of the intake device is about 0.2 m^2, which determines the atmospheric absorption capacity of the device. The work altitude of S/C is generally lower than 250 km, which determines the resistance compensation required by the thruster. The system is potentially interesting for low altitude and long lifetime missions, which is lower than 250 km and in the range of 3~8years. The power density is about 10~59 mN/kW, which can produce effective thrust. In the previous studies, MPD, PPT, IE, and HET have been considered.

For electrothermal thrusters, common propellants are usually oxygen-free and the high-temperature oxygen-containing environment may corrode the nozzles, resistors, and other components in particular for Arcjets, so a new electrode technology needs to be developed. Arcjets with an advanced electrode technology could be relevant for the high-power regime. In addition, Resistojets are flexible but too low I_{sp}. Therefore, the electrothermal thrusters are not suitable for atmosphere-breathing electric propulsion currently [41].

For MPD, the corrosion of the electrode system is one of the most important problems in the product application. Future atmosphere-breathing MPD needs 10^3 ignitions per second [53]. Therefore, alternative materials for amorphous metals and special alloys with different porosity and surface structure will be studied in the future. In addition, the necessary mass flow rates for thruster might be too high for the ABEP application [41].

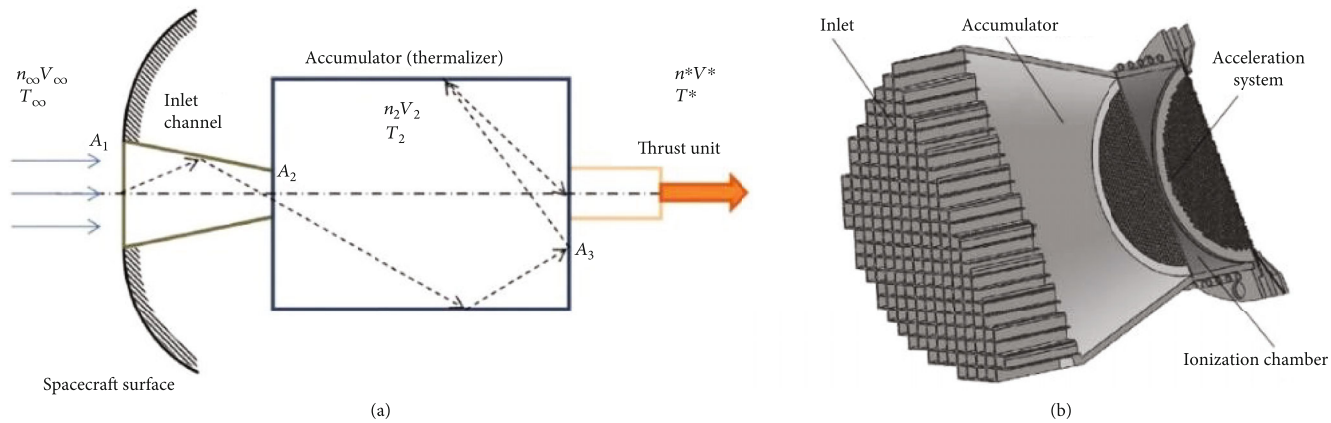


Figure 28: Erofeev's ABREP: (a) principal block-diagram of ABREP thruster; (b) 3D model of ABREP thruster [70].

Compared to MPD, the power requirement for PPT is lower (a few watts of power). Choueiri's research [74] indicates that the power ratio of PPT using N_2 is between tens of mN/kW, which is the maximum at low energy (158 J) and high mass (348 μg). If the propellant is sufficient, the thrust efficiency is not so important to the design, and the above thrust power ratio becomes the main design criterion. However, the corrosion problem of cathode needs to be paid more attention.

For ion thruster, the resistance on the target orbit of the ion thruster exceeds the maximum achievable thrust [32]. Besides the suboptimal operation due to the propellant, the grid erosion due to the oxygen from the thermosphere is also a problem. So the research of this type of thruster needs to be further optimized.

As the most widely studied ABEP product, HET can provide a higher thrust density, which is in the range of 19~60 mN/kW. However, it also presents the problem of corrosion to some extent.

Several types of ABEP products mentioned above have their own advantages and disadvantages and generally involve the problem of electrode corrosion. IPT products of the University of Stuttgart can effectively avoid electrode corrosion problems, which is worth studying in the future ABEP product development.

4. Prospect of Continued Research on ABEP

It identified the limitations of previous research through the review above, which provides the potential avenues for continued research on ABEP.

4.1. Improve the Performance of Air Intake. Romano et al. [38] indicate that the flow rate of the atmospheric propellant needs to be greater than 3 mg/s to satisfy the thrust compensation at an altitude of 250 km. The configuration and material of the intake determine its ability to absorb atmospheric molecules. Improving the efficiency and compression rate can provide sufficient propellant for the thruster. Hruby et al. [46] has pointed out that the parabolic configuration has higher efficiency under specular reflection condition, but lower under diffuse reflection. Therefore, promising research should focus on the use of intake material. The selection of the material should have sufficient heat resistance and collision resistance and better performance of capture, adsorption, and storage for atmospheric molecules.

4.2. Solve the Problem of Electrode Corrosion. The use of an atmospheric propellant will inevitably introduce oxygen to the electrode system of the electric thruster. Therefore, the electrode is susceptible to oxidative corrosion. This limitation poses a challenge to the research of ABEP. A possible way to solve this problem is to determine a thermal ion source, after a simple operation to filter out the oxygen-containing substances without being oxidized, and finally design a thruster that does not require cathode operation. In addition, the latest research of the University of Stuttgart [58] uses IPG products to solve this problem. This device is electrodeless, which directly eliminates electrode corrosion but reduces performance over time (RIT and HET).

4.3. Improve the Utilization Efficiency of Propellant. Compared with the traditional xenon propellant, the utilization rate of atmospheric propellant is lower. The main component of the atmosphere has a lower ionization cross-section and higher ionization energy. Although current ionization technology is sufficient to achieve high propulsion efficiency of xenon, it is still insufficient for atmospheric propellants. Possible potential methods are to identify new ionization technologies and optimize existing technologies. Shabshelowitz [51] seems to be able to improve this phenomenon by using RF excitation technology. The use of nuclear energy can also be considered.

As alluded to above, all studies of ABEP are based on the tests on the ground. However, feasibility on the ground is not equivalent to feasibility in space. The ground system and the space system have different environments, and the ground system has sufficient power and cooling conditions. Therefore, the ABEP system needs to be analysed and verified under more severe environmental conditions. For instance, when the flow mass of the atmospheric propellant is the largest, the system still cannot generate sufficient thrust compensation. In this case, the use of combined power propulsion may be one of the solutions.

Table 3: Comparison of previous studies about ABEP systems.

Thruster	Reference	S/C mass (kg)	Cross area of S/C (m^2)	Area of intake (m^2)	Damping coefficient (Cd)	Length of collector (m)	Inlet pressure (Pa)	Orbit altitude (km)	Lifetime (years)	Thrust (mN)	Power (kW)	Power density (mN/kW)	Efficiency (%)
GIE	ESA [31]	1000	1	0.15~0.6	2.0	0.2~1.3	10^{-3}	200~250	3~8	2~20	1		
MABHET	BUSEK [32]		0.3	0.15	3.0							19~30	35
ABIE	JAXA [33, 34]		1.5	0.48	2.0		0.5±	200±	>2		3.3+	10~14	
Intake	Lanzhou ISTP [36]	>5.7		$d = 0.5$ m			0.3-	150~240					41~57
ABIT	Jackson and Marshall [40]	50~100		0.01	2.2	0.05~0.1		>80					10
2-stage HET	Diamant [42, 43]		0.5	0.25	2.2		0.01	200			1		35
HET	Cifali et al. [44]									19~24	1.4		
RIT-10	Cifali et al. [44]									5.25-6	0.45		
HET	Pekker and Keidar [45]							90~95		9.1~22N	700~2000	13	
HET	Garrigues [47]		1		2.0		10^{-3}	250		20	1		10
ABIE	Tagawa et al. [48]					0.15		140-200		0.13			
HET	Andreussi et al.[49]	50	$d = 0.5$ m	0.126~1	2-3	1.0		200		6	2.4		28~32
RF-HET	Shabshelowitz [51]	325	0.39		2-4	2.1		200	3		0.306	29-59	90
PPT	Johnson et al. [52]		20		0.05			22-40		5		7.5+	
MPD	Göksel and Mashek [53]							20		2 N	75		
PPT	Schönherr et al. [41, 54, 55]		0.3				10^{-3}	200		4.4		20~30	
IPT	Romano et al. [38, 56, 58–60, 71–73]			0.3~1		0.3-3		120		5~250	0.5-3.5		25

5. Conclusion

In this paper, the great advantage of the ABEP application is introduced. Using atmospheric molecules as the propellant has great economic value, effectively reducing the weight of the propellant carried and extending the lifetime of S/C.

The main space propulsion systems are compared firstly, and the results show that the electric propulsion system may be the best selection for ABEP products for its higher specific impulse and more efficient structures.

This review has also introduced the previous studies of researchers about ABEP systems, which mainly include pulsed plasma thruster (PPT), magnetoplasma dynamic (MPD) thruster, ion engine (IE), and Hall-effect thruster (HET). The main performance of different ABEP concepts is summarized in Table 3, and their limitations are also pointed out. The corrosion problem of cathode or grid needs to be paid more attention for PPT, MPD, and IE. In addition, HET and ion thrusters need a neutralizer, and they cannot be operated with thermospheric gases.

The potential avenues to develop the further ABEP products are introduced in the last, which focus on the air intake efficiency, the corrosion phenomenon, and the utilization efficiency.

As a result of an increasing interest to study the space and the great potential to operate satellites at low Earth orbit, the concept of ABEP is promising but the application of this concept requires further development. By understanding previous studies in this paper, researchers can continue to develop ABEP technology into a fieldable technology.

Abbreviations

ABCHT: Air-breathing cylindrical Hall thruster
ABEP: Atmosphere-breathing electric propulsion
ABHT: Air-breathing helicon thruster
ABIE: Air-breathing ion engine
ABREP: Air-breathing ramjet electric propulsion
AF: Applied-field
APT: Atmospheric plasma thruster
BNTR: Bimodal nuclear thermal rocket
DBD: Dielectric barrier discharge
ECR: Electron cyclotron resonance
EHD: Electrohydrodynamic
ESA: Europe Space Agency
FEEP: Field emission electric propulsion
HET: Hall-effect thruster
IE: Ion engine
IPG: Inductively plasma generators
IPT: Induced plasma thruster
IRS: Institute of Space System
JAXA: Japan Aerospace Exploration Agency
LEO: Low earth orbit
LP: Liquid propellant
MABHET: Martian air-breathing Hall-effect thrust
MFR: Mass flow rate
MPD: Magneto plasma dynamic
MPP: Magneto plasma propulsion
NASA: National Aeronautics and Space Administration
PCTV: Piloted Callisto transfer vehicle
PPT: Pulsed plasma thruster
PTFE: Polytetrafluoroethylene
RAM-EP: Air-breathing electric propulsion
RF: Radio frequency
RIT: Radio-frequency ion thruster
S/C: Spacecrafts
SDBD: Single dielectric barrier discharge
SF: Self-field
VIPER: Variable Inlet feeding air-breathing PPT for Electrode eRo-sion measurements
XIP: Xenon ion propulsion.

Data Availability

The numerical data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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