

The Development and Future Trends of Aerospace Propulsion Systems

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Abstract:

Since ancient times, humanity has harbored a thirst for exploring the unknown world. From the discovery of fire to the advent of the steam era, human curiosity about the universe has never waned. In the twentieth century, our fascination with the stars, efforts to understand the mysteries of the cosmos, and aspirations to conquer realms beyond our own have made aerospace propulsion a critically important research area, especially in providing the power to leave Earth. This article will focus on the historical development of aircraft engines, the classification and advantages and disadvantages of aerospace propulsion systems, and explore the current demand for innovation, ultimately proposing a feasible solution.

Keywords: Spacecraft propulsion systems, Rocket engines, new energy, Innovation and trend, sustainability

1. Introduction

Reflecting on humanity’s exploration of the skies reveals a long and storied history that dates back to ancient times. Throughout this journey, there have been many historic moments, such as the dream of flight shared by countless individuals, the invention of the airplane by the Wright brothers, the momentous debut of the Saturn V rocket in the United States, which played a crucial role in the successful moon landing, and the ongoing advancements in modern aviation. The diversity of aerospace systems that have emerged over time serves as a testament to human ingenuity, with notable innovations like the F-1 engine, renowned for its unparalleled thrust output, standing as a prime example.¹

2. The main steam of today’s rocket engine

Today, rocket propulsion methods are highly standardized globally, primarily falling into two categories: liquid and solid propulsion systems. While each type has its own characteristics, this also leads to differences in their combustion chambers and where they store fuel and oxidizers. Liquid rockets require additional components to mix fuel and oxidizers before combustion, whereas solid rockets can store fuel and oxidizers together, allowing part of the combustion chamber to serve a dual purpose. However, they both ultimately generate thrust through the combustion of propellants, resulting in high-speed exhaust gases, in accordance with Newton’s third law of motion.²

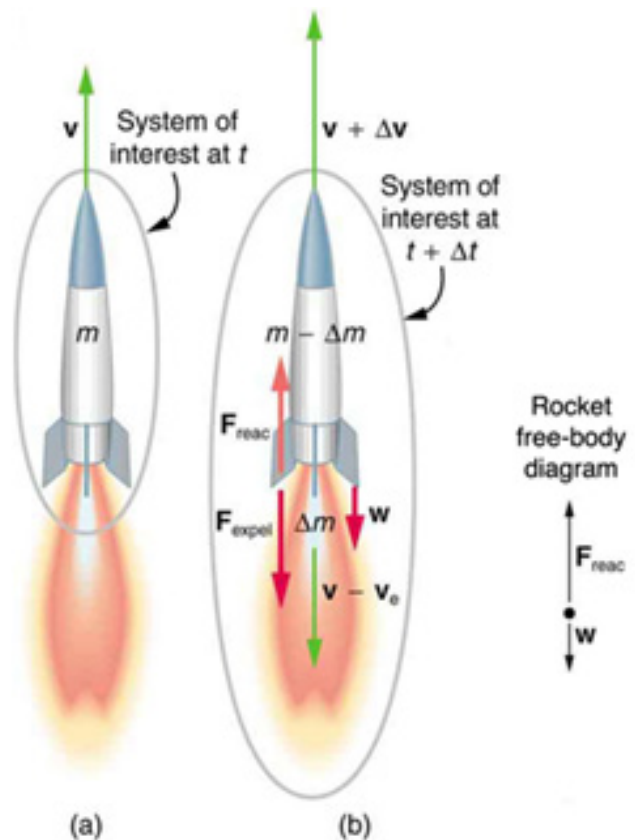


Figure 1 Newton’s principle of recoil(4.4 Newton’s Third Law of Motion: Symmetry in Forces – Douglas College Physics 1104 (bccampus.ca))

2.1 Advancement and Disadvantage

For liquid rockets, naturally, having electrically controlled valve manifold control allows for better thrust regulation, enabling precise adjustment of flow rates according to the requirements of different missions to ensure smooth orbital insertion of large payloads. However, this necessitates the provision of more complex turbine piping and other intricate designs, leading to increased maintenance and construction costs as well as additional weight. Furthermore, proper measures are required for the correct handling of flammable and volatile liquids during transportation.³

On the contrary, solid rocket engines have simpler structures and are easier to maintain, as their fuel is in a solid state, making it easier to transport and store. However, once the fuel is ignited, thrust modulation decreases, and the thrust remains constant without the ability to be changed randomly according to the mission requirements. Additionally, they may be subject to the influence of weight and volume during usage. In the current scenario, research directions for traditional propulsion systems are rather limited, and certain bottlenecks have been identified. The fundamental goal of development is to obtain more energy with less energy input. It is well-known that energy conversion entails inevitable losses, thus the focus is on improving propulsion efficiency and energy conversion ratios. This involves optimization of structures, enhancement of adaptive systems, fuel calorific value, and cost control. However, there are barriers in current technological aspects as well.

Research and development on energy density are pivotal. Currently, the most mature and high-calorific fuels and oxidizers in human possession are liquid oxygen and liquid hydrogen, primarily used as propellants in high-thrust engines. Moreover, fine control over structure is essential, requiring technological breakthroughs for further enhancement. This will undoubtedly pose an inevitable challenge for humanity in exploring various novel propulsion methods in the future.

3. The basic concept of Aerospace propulsion systems

3.1 propulsion systems

Aircraft propulsion system

The aircraft propulsion system is designed to generate sufficient thrust to overcome the aircraft's drag and guide it through the atmosphere during flight. Its primary purpose is to provide lift.

Generally, it relies mainly on turbine engines, including turbofan engines and turbojet engines. They work by com-

pressing a large volume of air, mixing it with fuel, and then igniting it to produce high-speed jet streams, thereby generating thrust. However, there are exceptions. Specialized aircraft requiring supersonic or high-altitude flight may also use rocket engines. Rocket propulsion relies on expelling exhaust gases to generate thrust and does not depend on the atmosphere. ⁴

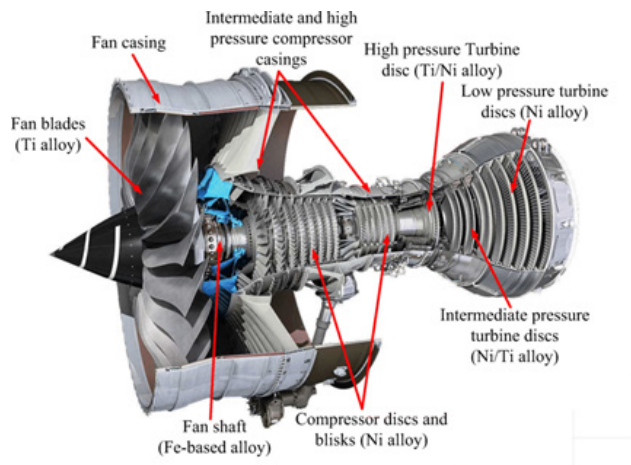


Figure 2 Aircraft engine structure diagram (Main components of a jet engine | Download Scientific Diagram (researchgate.net))

Spacecraft propulsion system

The spacecraft propulsion system is designed to provide sufficient velocity and kinetic energy to overcome Earth's gravity and enter orbit, enabling space missions. Outside the Earth's atmosphere, propulsion systems must consider the vacuum environment and long-duration operation.

Rockets are the most common propulsion system for spacecraft. They operate in a vacuum, generating thrust by expelling high-speed exhaust gases to produce a reaction force. Various combinations of fuels and oxidizers can be used.

Different branches of propulsion systems have been derived to meet various mission requirements and environmental conditions. Some specialized spacecraft may carry two types of propulsion systems simultaneously to adapt to both atmospheric and vacuum requirements. For example, vehicles that need to frequently enter and exit the atmosphere may be equipped with both aviation engines and space engines on the same airframe. This allows for maneuverability and control within the atmosphere while ensuring sufficient thrust outside the atmosphere. Although such solutions have not yet entered the market and are limited by market and environmental protection factors, they remain in the experimental stage in laboratories. One practical application example is horizontal takeoff and landing aircraft, such as Vertical Takeoff and Landing (VTOL) aircraft or similar vehicles. These aircraft need

to achieve vertical takeoff and landing within the Earth’s atmosphere, but also require sufficient thrust for space flight once they leave the atmosphere. To overcome this challenge, some research teams and companies are exploring solutions that involve using two different propulsion systems.

Inside the Earth’s atmosphere, aircraft can utilize aviation engines, such as jet engines, to achieve greater maneuverability and control. Once in space, these aircraft may switch to space engines, such as ion propulsion systems or other efficient space propulsion technologies, to ensure sufficient thrust in the vacuum environment.

Such a design can accommodate requirements both within and outside the Earth’s atmosphere during mission execution. For example, vertical takeoff and landing aircraft may be used for rapid response missions, such as emergency rescue or military operations, requiring vertical takeoff from within the atmosphere and then flight in space.

However, such solutions are currently mainly at the laboratory research and concept verification stage and have not yet been widely applied in the commercial market. This is mainly due to considerations such as market demand, technological maturity, and environmental protection. In the future, with the advancement of technology and the increasing demand for space exploration, such dual-system propulsion aircraft may enter more substantive application areas.

4. New Spacecraft propulsion technology

4.1 The latest Propulsion system

A. Ion thrusters

Ion thrusters, as an advanced means of efficient and long-term propulsion for spacecraft, are based on the principles of ionization and acceleration of ions. Firstly, gas atoms or molecules are ionized by introducing sources such as electron beams or solar energy photons. Subsequently, an electric field is established within the thruster, efficiently accelerating these ions by applying a potential difference. The generated charged ions, when expelled through the thruster nozzle, create a reaction force, thus producing thrust. In some ion thruster systems, magnetic fields can be introduced to control and focus the ion beam, optimizing propulsion efficiency. To sustain this process, a reliable energy supply, such as solar panels, is required. The profound understanding and precise control of this principle make ion thruster technology a crucial propulsion

choice for future deep space exploration, satellite orbit maintenance, and long-term spaceflight missions. 5

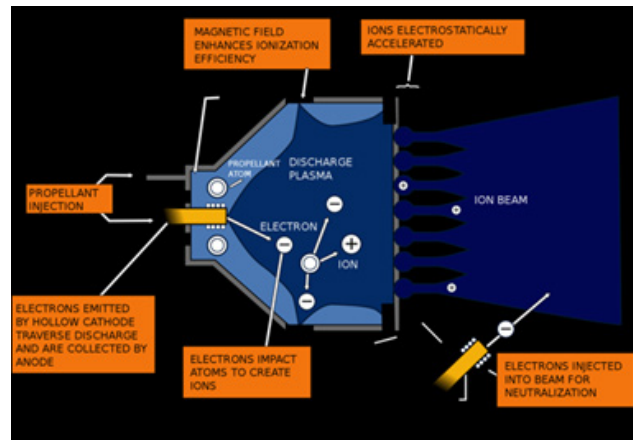


Figure 3 Schematic diagram of structure of the Ion thruster (Ion Thrusters: Not Just For TIE Fighters Anymore | Hackaday)

Thanks to its extremely high specific impulse and fuel efficiency, ion thruster technology is suitable for long-term deep space exploration missions. It also greatly assists in precise orbit corrections for satellites. Despite its broad application prospects, we still need to overcome some technical challenges such as increasing thrust, improving ionization efficiency, and extending the lifespan of thrusters.

B. Nuclear Thermal Propulsion

Nuclear propulsion, as an advanced space propulsion technology, is based on the principle of utilizing the heat generated by a nuclear reactor. The basic concept involves integrating a nuclear reactor inside the spacecraft, where the reactor undergoes fission processes to produce high-temperature working fluid. This high-temperature fluid is then transferred to the propellant (usually hydrogen) through a heat exchanger or other thermal exchange devices, heating it and causing it to expand. Subsequently, the heated and expanded propellant is expelled through the nozzle, generating a high-speed jet stream and thus producing thrust.

The advantages of nuclear thermal propulsion lie in its high thrust and specific impulse, making it potentially advantageous for long-duration deep space exploration missions with substantial fuel consumption. Compared to traditional chemical rockets, nuclear thermal propulsion technology can offer more efficient propulsion, thereby significantly enhancing performance in missions requiring longer distances and more complex orbits.

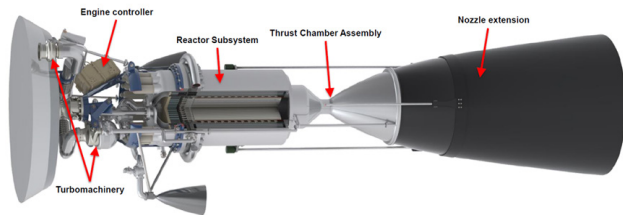


Figure 4 Schematic diagram of the structure of a nuclear thermal thruster (Nuclear Thermal Propulsion Systems | Glenn Research Center | NASA)

Of course, the current proposals are still confined to laboratory settings, and equipping such thrusters poses numerous challenges that need to be overcome. Controlled nuclear fusion is regarded as the core scheme for reactors. While there has been progress in reactor development, more practical applications are required. Enhancing safety and minimizing size are inevitable considerations. In spacecraft and space environments, every inch must serve a crucial function that cannot be compromised, and any minor error under such complex conditions could lead to significant consequences.

Simultaneously, engineers need to improve and upgrade thruster designs, ensuring efficient conversion of thermal energy into propulsion and guaranteeing their long-term operation to meet the demands of deep space exploration. These are significant obstacles in the development of nuclear propulsion technology.

4.2 Comparison of today's

- a. Propulsion Efficiency: Future propulsion designs are typically focused on improving propulsion efficiency. This includes increasing specific impulse (the ratio of the speed of the propellant to the thrust), allowing for longer flight times or greater distances traveled using the same amount of fuel.
- b. Reusability: Future propulsion designs may prioritize reusability to reduce the cost of space missions. Such thrusters can return to Earth after completing a mission for maintenance and reuse, thereby reducing the cost and resource requirements for each mission.
- c. Intelligence and Autonomy: Future propulsion designs may focus more on intelligence and autonomy to enhance mission autonomy. This includes utilizing advanced autonomous navigation, control, and decision-making systems to make space missions more flexible and adaptable. Intelligence is something we constantly strive for.
- d. Environmental Friendliness: Future propulsion designs may prioritize environmental friendliness to reduce their impact on Earth and space environments. This may involve innovations such as using cleaner fuels and reducing waste emissions during propulsion processes.

e. Advances in Material Science and Advanced Manufacturing: Future thrusters may employ more advanced materials and manufacturing technologies to improve durability, lightweighting, and performance. Advanced materials can reduce the mass of the thruster, enhancing overall performance. Improvements in manufacturing capabilities may also facilitate mass production of thrusters and rockets, laying a solid foundation for future deep space exploration.

5. Sustainability and environmental friendly

5.1 The implications belong environment by propulsion

The impact of conventional propulsion technologies currently in use is undoubtedly significant, which is why we continually seek to upgrade technologies and fuels. Emissions generated during rocket launches, such as solid particles, gases, and chemical substances, have a direct impact on the Earth's atmosphere and ozone layer. Aerosols and gas emissions produced during combustion processes can lead to air pollution and ozone layer depletion, potentially affecting the Earth's climate system. Both aviation and space engines face the increasing risk of emissions as the population continues to grow, and reliance on aerospace engines becomes more apparent. 6

5.2 The way to protect environment

Environmental protection is multifaceted and requires collective efforts from various parties. Improving fuel efficiency demands significant effort.

High-efficiency Engine Design: Research and develop more efficient and advanced engine designs, including improving the efficiency of compressors and turbines, and reducing energy losses during internal combustion processes.

Advanced Material Applications: Utilize lightweight, high-strength advanced materials such as composite materials and new alloys to reduce engine weight and improve fuel efficiency.

High Specific Impulse Propulsion Technologies: Promote research and application of high specific impulse propulsion technologies such as ion propulsion and nuclear thermal propulsion to enhance spacecraft speed and efficiency. *Measures in line with carbon neutrality regulations include.*

Biofuels and Renewable Energy Sources: Promoting the use of biofuels and other renewable energy sources to reduce dependence on fossil fuels and thereby lower carbon emissions.

Hydrogen Fuel Cells: Researching and implementing hy-

drogen fuel cell technology, which produces only water vapor as its sole emission, making it more environmentally friendly compared to traditional fuels.

Low NO_x Combustion Technology: Developing low nitrogen oxide (NO_x) combustion technology to reduce emissions of nitrogen oxides and mitigate adverse impacts on the atmosphere.

Refined Combustion Control: Adopting advanced combustion control technology to ensure more thorough and efficient combustion processes, thereby reducing the generation of harmful gases.

6. Trend

The future trends in aerospace present several key directions that lead the industry's continuous evolution. Firstly, sustainability will become the core concept of aerospace development, with a focus on adopting more environmentally friendly fuels, propulsion technologies, and reducing carbon footprints to mitigate the impact on both the Earth and space environment. Secondly, the rise of commercialization and private enterprises will propel space activities into a new era, with private companies actively participating in space exploration and resource utilization. Deep space exploration is a crucial direction for the future, with humanity expected to achieve deeper exploration of celestial bodies such as the Moon, Mars, and possibly establishing permanent human settlements on other planets in the coming decades. Space resource utilization will also become a strategically significant development direction, potentially addressing Earth's resource issues. With the advancement of new propulsion technologies, the future will explore more efficient and sustainable propulsion methods to enhance the flexibility and efficiency of space exploration missions. However, this hopeful future is accompanied by challenges such as technological innovation, cost control, environmental protection, international cooperation, among others. Through global cooperation and continuous technological innovation, the aerospace industry will continue to move towards a broader and more sustainable future. This is also the crisis and challenge we face. 7

With the globalization of the world, various technologies will inevitably arise through international cooperation. We must value such opportunities and challenges as international cooperation is an inevitable trend and outcome. I believe that on the path of future exploration, relying solely on the power of one nation is insignificant, and win-win cooperation is evidently the crucial foundation for deep

space exploration.

Furthermore, the development of propulsion systems also depends on the improvement of supporting equipment. Progress in materials science, physics, structural engineering, chemistry, and other fields is necessary to combine into a perfect engine.

7. Conclusion

This article aims to explore the development history of aerospace engines, covering current propulsion system technologies and the inevitable needs, directions, and challenges of future human deep space exploration. It meticulously analyzes the advantages and disadvantages of various types of aerospace engines, refines future trend systems, and considers more era requirements. Under their guidance, such an informative article about the trends in aerospace propulsion has been completed, providing people with a good direction and feasible ideas. It is hoped that people will make remarkable progress in overcoming the challenges in propulsion system development.

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