Comprehensive Exploration on Performance Improvement of Rocket Thruster

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Abstract. Since mankind has been carrying out space research for decades, rockets are one of the most important tools used by mankind to explore space. In this article, the structure of a rocket is analyzed, and the function of each part is understood. Tsolkovsky's rocket equation is used to analyze the relationship between the initial and final mass of the rocket. Through the study of engine thrust, the calculation of engine thrust was demonstrated using the formula. Besides, the ideal specific impulse of different fuels in a vacuum is compared in a graph and some of the fuels in the chart. Ultimately, it was concluded that the performance of rockets could be improved in terms of open-edge construction, enhanced engine thrust, utilization of composite fuels and improved combustion efficiency. In the future, due to the development of rocket technology, perhaps commercial space activities will usher in a new trend.

Keywords: Rocket motor; fuel; specific impulse; thrust-to-weight ratio.

1. Introduction

In recent decades, with the rapid development of space technology in the world, mankind has never abandoned the study of outer space and the exploration of interstellar travel. As one of the few vehicles capable of transporting people or experimental equipment into space, rockets are often used for work in outer space [1,2]. Since Gagarin's first trip into space in 1961, mankind has officially begun the exploration of human spaceflight. During this period, countless astronauts such as astronaut Armstrong and taikonaut Yang Liwei went into space, making new history and the commercial exploration of space starting a new trend. For example, GPS positioning systems, diapers, magnetic resonance imaging machines, and various medical devices are all products that were once part of the space industry's development process, and these products have transformed people's travel, healthcare, and public health.

In recent years, with Musk's SpaceX and Bezos's Deep Blue program in the spotlight, private commercial spaceflight seems to be getting more attention. However, what makes advances in the field of space even more appealing to scientists is that such high-tech tools, when used, can often be used to help mankind observe the universe more clearly and comprehensively, as well as to observe the trajectory of specific asteroids and thus hypothesis about changes in the universe [3]. The Hubble and Webb telescopes were designed with this goal in mind. Scientists' interest in galaxies has not just been satisfied with long-distance observations; in 1977, NASA launched Voyager 1, and in exploring the latter decades, valuable data on Jupiter and its moons have been passed over for the first time, in addition to the features of Pluto, Cayron, and a host of Kuiper Belt asteroids that have been clearly revealed to people. Voyager 1 is expected to be decommissioned around 2025, after which it will no longer send any signals to humans. For the time being, detecting the vacuum is still a formidable challenge. Theoretical breakthroughs in the face of the uncertainty of outer space have almost reached a bottleneck, yet industrial development has not stopped. Nowadays, many countries and organizations in the world, such as the USA, China, India and the European Union, have a strong interest in the field of space. However, using the limited resources and research funds on earth, how to improve the safety, environmental protection, and performance of rockets is an important issue for each country to focus on the development of important issues.

2. Structure of the Rocket

Theoretically, the larger the rocket, the better, as this means that more space can be utilized and more equipment can be carried. However, bigger rockets tend to have more mass, which can significantly increase the budget for fuel and manufacturing processes, and in order to achieve this balance, the overall structure of the rocket is often considered in terms of how efficiently it can be propelled. The whole rocket structure system is illustrated in Fig. 1, including the nose cone, frame and fin sections.

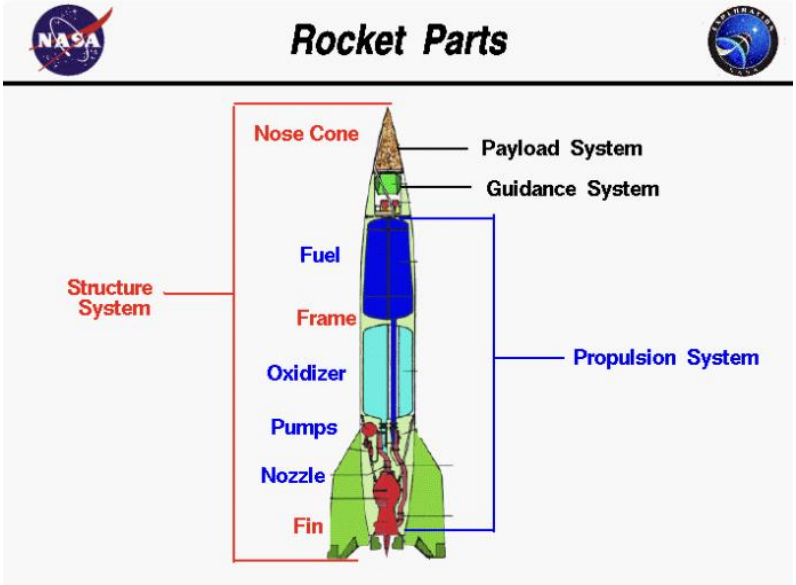


Fig. 1 Rocket parts [1]

2.1. Nose Cone

Nose Cone consists mainly of the payload system and the guidance system. It is also an important part of the rocket launch mission. The Corn Nose is the first part of the rocket that comes into contact with the air during flight, so the size and shape of the Corn Nose will have an effect on the speed and attitude of the rocket.

2.2. Payload System

The payload system is an important part of the rocket that carries the mission equipment and astronauts during a launch mission, and it is required to undertake protection tasks. The main goal of a space mission is often to launch this part of the payload or the astronauts smoothly into space. The items to be carried on the rocket or the astronauts are determined by the objectives of the different artifacts. Nowadays, the options to be carried are also varied due to the advancement of technology, and satellites, astronauts and even warheads can be carried [1]. However, the payload system is only a very small part of the entire rocket. Typically, a 5,000-ton rocket can only carry 300 tonnes of cargo into space. Here is Tsiolkovsky's rocket equation:

$$m_0 = m_f e^{(\Delta v/c)} \tag{1}$$

where m_0/m_f is the mass ratio, V is the velocity, and C is the exhaust gas velocity [2]. This formula elaborates the relationship between the mass at the beginning and the mass at the end of engine work.

2.3. Guidance System

The guidance system is a complex system of navigation, radar, computation and different sensors. Its fundamental purpose is to allow the rocket to adjust its attitude and increase its stability by generating thrust in all directions [1,3]. The key to a guidance system is accuracy, control, algorithms, real-time updates, and integration. The ability to accurately calculate the velocity, position, altitude

and other important information of a rocket is one of the essential functions of a guidance system. In addition, the speed at which information is updated during the rocket's high-speed movement and the ability to change out of a dangerous situation are all indicative of the rocket's performance. Redundancy is also often considered when rockets are designed. For example, in the case of cross-data analysis of multiple computers, additional equipment is often needed to ensure that the rocket operates properly under special circumstances. Advanced spacecraft often have automated judgments and can make decisions automatically in complex situations without human intervention.

2.4. Propulsion System

The propulsion system consists mainly of the rocket's fins, engines and fuel tanks. The main function of this section is to store fuel and provide reasoning for the flight of the rocket. Due to the presence of the fuel compartment, this part of the skin may be more often insulated with insulating materials to ensure that it can be stored at low temperatures before use and, ultimately, that the fuel reaches the combustion chamber to be used without problems [1,4]. The fins act to stabilize the airframe during launch. It uses the fluidity of air to balance the flight attitude of the main part. The fuel inside the rocket reacts in the combustion chamber and can be passed through the tail nozzle to provide thrust for the rocket. This part is often dropped when necessary. In cases where fuel is consumed, the excess tends to detach from the main body of the rocket, thus reducing the overall mass of the rocket so that the thrust can be better distributed to the nose cone. In the latest rocket recycling technology, important parts such as engines can be reused again and again on different rockets, and the launch budget of rockets can be greatly reduced as a result.

3. Thrust of Rocket Motor

The rocket engine is the main power-providing unit in a rocket launch. Therefore, the performance of an engine can often be decisive for the thrust of a rocket. The rocket motor fuel reacts with an oxidizing agent as it passes through the combustion chamber. During the reaction, the internal and chemical energy of the fuel is released to produce gases that converge at the nozzle. Finally, the gases at the nozzle are released at high velocity to generate thrust to provide upward thrust for the rocket [5].

3.1. Thrust and Impulse

Fig. 2 shows an ideal rocket engine. A famous Russian scientist, Tsiolkovsky, came up with the formula for calculating thrust in 1903.

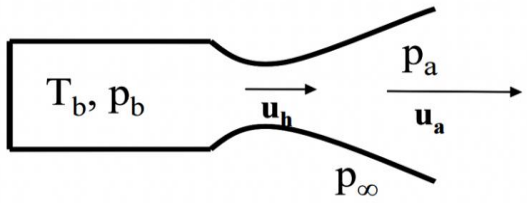


Fig. 2 Ideal rocket engine [5]

$$F = \dot{m}u_e + (p_e - p_\infty)A_e \tag{2}$$

The u_e is the exhaust gas velocity, and the A_e is the cross-sectional area of the exit. The p_e and $p\infty$ mean exit pressure and ambient pressure, respectively [5].

$$F = \dot{m}c \tag{3}$$

Finally, this formula can be simplified as above [5]. From this formula, the thrust can be measured. Another quantity that can be used to assess the performance of a rocket motor is the specific impulse. Calculating specific impulse means calculating the mass flow rate of the expelled gas in relation to the thrust produced by the rocket [6]. Its unit is N-s/kg.

$$I_{sp} = F/\dot{m} = Specific\ impulse \tag{4}$$

The total impulse of the whole rocket is derived, which can be thought of as the time that the force acts on the rocket, which is the integration of the force in terms of the time of combustion (t_b) [6]. The formula is shown below.

$$I = total\ impulse = \int_0^{t_b} F\,dt = Ft_b \ \ for\ F = constant \tag{5}$$

Subfactor F into this formula, the new function can be found as:

$$\mathrm{I} = \mathrm{I_{sp}} \int_0^{\mathrm{t_b}} \dot{\mathrm{m}}\,\mathrm{dt} = \mathrm{I_{sp}} \mathrm{m_p} \tag{6}$$

where the m_p is the total initial mass of the propellant [6]. From this equation, the conclusion can be obtained that increasing the cross-sectional area of the nozzle and increasing the pressure as it flows out of the nozzle both boost thrust and boost the time that the gas is in the combustion chamber is also a way of boosting the total impulse.

3.2. Saft and Hazards of Motor

Since rocket engines are often used in complex environments during operation, the performance model in some high-temperature and high-pressure environments is just as critical as the performance in the ideal state. Various eventualities often occur during engine operation, causing the engine to malfunction or leading to an accident [7]. And following aspects may cause accidents: delayed propulsion due to late ignition and excessive fuel entry in the combustion chamber, causing accidental explosion as well as poor contact in the engine system.

A rocket explosion is a very dangerous event, firstly because of the almost irreversible damage it can cause to the motor and secondly because of the possibility of debris hitting ground facilities and causing additional damage. On the environmental side, the explosion of a rocket may cause overpressure in the surrounding atmosphere, which may be in the range of several kPa or several MPa [7].

4. Rocket Fuel

Fuel, as the primary source of thrust for a rocket, occupies most of the rocket's storage space. The superiority and safety of various fuels are measured against different mission requirements. The fuel reacts with the oxidizer in the combustion chamber to produce energy to provide kinetic energy for the rocket. Oxygen from the outside is often not used during fuel combustion to avoid dangerous incidents such as leakage. With the rapid development of space technology, the following fuel technologies have been successively utilized in rocket propulsion such as liquid rocket fuel, solid rocket fuel, ion engine fuel, liquid-solid hybrid rocket fuel, and liquid hydrogen and liquid oxygen rocket fuel.

Among these technologies, hybrid fuels are being researched as a priority in many countries. There have also been many technological breakthroughs in this field. High-resistivity modified fuel is a method that uses a liquid oxidizer with solid materials. After much experimental analysis and comparison, it was found that it could produce more impulse than solid rocket motors and was more flexible and easier to control in terms of thrust. Finally, it is also popular for its multiple restart capability. Its low cost and simple structure compared to liquid rockets have also made this technology widely explored [8-10].

As shown in Fig. 3, hybrid fuels have different properties from each other. Combining all the advantages of high-density propellants and high specific impulse propellants with each other can utilize their properties to a greater extent to boost thrust. For example, the combination of LOX, Kerosene and LH_2 is often studied. At low altitudes, the engine can burn LOX Kerosene for energy conversion, and at high altitudes, the advantages of the high specific impulse of LOX LH_2 can be utilized [5]. Another benefit of hybrid fuels over solid fuels is the ability to incorporate additives,

which can be added to enhance control of the regression rate. Although the corrosive nature of some metal additives may reduce nozzle life and performance, some metal hydrides take advantage of unique chemical properties that can reduce this effect in ways such as reducing oxidation [11].

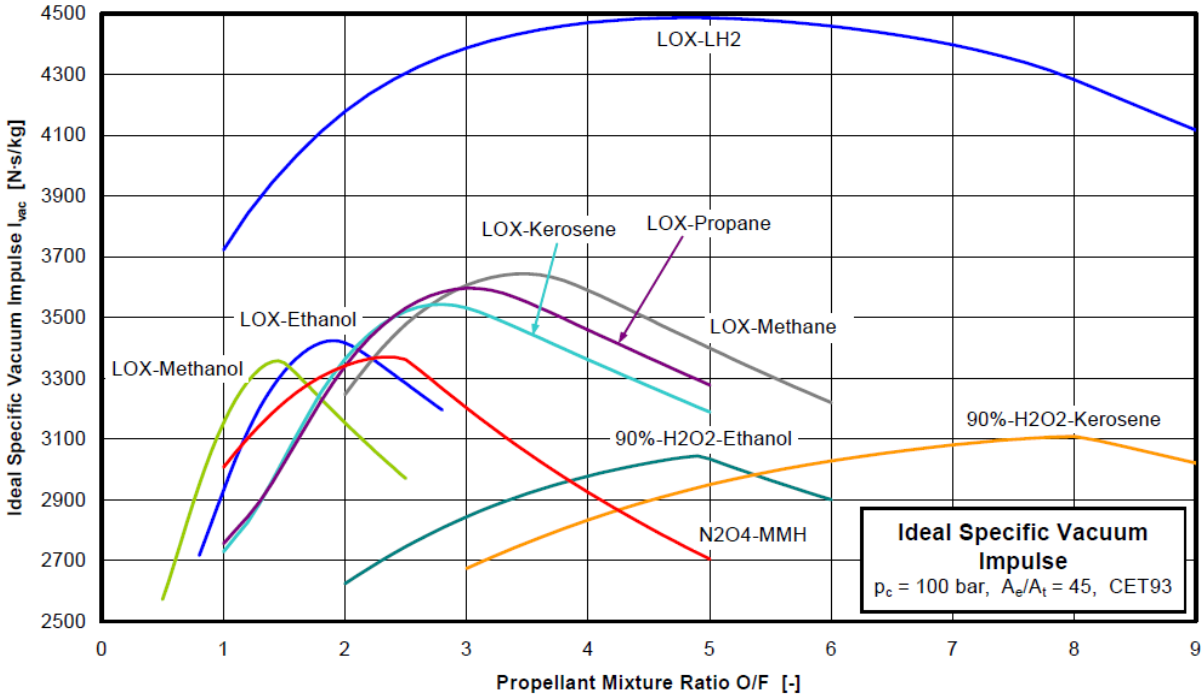


Fig. 3 Ideal specific impulse and propellant combination [5]

5. Efficiency Improvement of the Thrust

During the launch of a rocket, the powerful thrust provides a strong driving force for the rocket. However, only a portion of this energy can be utilized, so more ways to increase the efficiency of propulsion are always being looked for. The propulsive efficiency of a rocket is an important indicator of a rocket's performance. It is often related to a variety of different factors, such as the maximum propulsive speed, the overall mass of the rocket, and the payload. The thrust-to-weight ratio is an often-referenced metric that calculates the effect of thrust on the overall mass of a rocket motor when it is in operation. In order for a rocket to alter its propulsion system by enhancing the thrust-to-weight ratio, thereby increasing the rocket's payload and guaranteeing that it can fulfill its mission more efficiently, improvements in the following aspects have been discussed by mankind [12].

Propellant formulations: Various fuel blends have been tested by engineers during the development of rocket technology. According to the test results, some fuels can produce higher thrust-to-weight ratios for the same mass of propellant under different fuel mixes. Therefore, the breakthrough of rocket thrust from the fuel point of view is an important research direction. Propellant combustion efficiency: Improving the combustion efficiency of a fuel can result in the release of more energy for the same mass of fuel used. Aspects such as combustion chamber construction, air inlet design, and combustion stability can all be considered aspects of improving combustion efficiency.

Material and structure: The use of lighter composite materials or improvements in the structure of the rocket can also improve the thrust-to-weight ratio. Without compromising the overall structural strength of the rocket, a lighter airframe allows the fixed fuel to push the whole planet farther. In addition, aerodynamically satisfying structures, such as reducing the cross-sectional area of the nose cone or changing the angle of the tip of the nose cone, can also reduce air resistance. Motor design: By enhancing the performance of the engine, the thermal efficiency can be fully utilized to increase the thrust of the rocket, which helps to increase the thrust-to-weight ratio, for example, by designing multiple exhaust pipes and outlets to increase the exhaust volume to achieve the effect of increasing the thrust.

6. Conclusion

Rockets are one of the most common methods used by mankind for exploring the universe, and the process of launching a rocket can be affected by several factors, such as the overall structure of the rocket, the efficiency of the engine, the overall mass of the rocket, the efficiency of the fuel, and other parameters. n deep space exploration, the gravitational pull between celestial bodies often makes it difficult for space probes to travel the shortest possible distances or requires a lot of wasted excess fuel. Nuclear-powered rockets have long been recognized as the best way to save fuel, but given the dangers of developing nuclear energy, there is still a long way to go in the future. In terms of materials, their properties will also be tested according to different tasks, such as high-temperature-resistant materials or high-strength lightweight materials will also be the focus of future research. Besides, in terms of rocket recycling technology, some rockets already have this technology, such as Musk's SpaceX program, which is already able to recycle and reuse important parts of the rocket, such as the engine. In the future, with the progress of science and technology, small rockets may become the mainstream trend, the advantages of which lie in the need for a small loading platform, flexibility and mobility, as well as in the event of accidents will be relatively less harmful to the environment, with the rocket recycling technology can greatly reduce the cost of launching rockets for human beings only need to launch the platform and the cost of fuel, which will help mankind to develop the space mission further. In addition, commercial space programs will gradually become mainstream as a result of the development of space technology, and some private space programs can enable more people to travel to space. Finally, the development of rocket technology has unlimited prospects for mankind.

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