Designs, Simulations, and Products for Rocket Engines

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Abstract. As a matter of fact, rocket engine technology has developed rapidly in the last 100 years, which plays a crucial role for stellar travelling and detection for astrophysics usages. To be specific, different models, designs and simulation computer software had been developed in order to investigate and explore the dynamic process of the engines as well as evaluate the effectiveness and ability of the rocket engines. With this in mind, this paper gives a basic description of the designs, simulations, and products for rocket engines. In detail, this study will include description of four basic designs of rocket engine systems, a summary of simulation software and, two examples of rocket engine products including nuclear engines. According to the analysis, the current results and the limitations for the advanced facilities will be demonstrated. Overall, these results shed light on guiding further exploration of designs, improvements and implementations for rocket engines based on the state-of-art techniques.

Keywords: Rocket engines; simulation software; nuclear rocket engines.

1. Introduction

Human beings of all ages want to go in to the vast universe. The earliest rocket was invented in the early 14th by a Chinese named Wan Hu. His rocket consists of 47 fireworks tied to a chair and a kite in his hand. On March 16, 1926, Goddard, an American inventor of rocket engines and the father of modern rocket technology, launched the world's first modern rocket in Auburn, Massachusetts. His rocket used liquid oxygen and gasoline as its fuel. Later, rocket was widely used as weapon and scientific research tools. The Nazi Germany use V-2 rocket as its weapon in World War II. It is the first supersonic rocket, the first large rocket missile, and the first ballistic missile put into practical use in the world. It has laid the foundation for modern rocket and ballistic missile technology. The V-2 rocket is 47 feet long, with a liftoff weight of 28000 to 29000 pounds, and can produce about 60000 pounds of thrust. The propellant is alcohol and liquid oxygen [1].

The competition of military force and technology between America and the Soviet Union during the age of cold war promote the technology enhancement of rocket dynamics. The F-1 engine, which produces a thrust more than 7,500,000 pounds, was in the first stage of NASA’s Saturn V vehicle. It is a liquid bipropellant engine and can develop a thrust of 1,522,000 pounds at sea level with a specific impulse of 01265.4 seconds. Engine propellants were LOX and kerosene fuel at a mixture ratio of 2.27: 1 [2]. RD-170 is a LOX/kerosene staged combustion cycle engine developed by the former Soviet Union. Its sea level thrust is 7259kN, and the sea level specific impulse is 3028m/s. The fuel mixing ratio is 2.6:1. The engine has a weight of 12 tons, a total height of 4.01 meters, and a diameter of 3.71 meters. A single high-pressure turbine pump simultaneously supplies four identical injectors and thrust chambers. The two prechambers use oxygen rich combustion products to drive single-stage turbines. It was used in the Zenith launch vehicle [3]. In the 21th century, rocket scientists in different part of the world mainly focus on reusable engines and high efficiency engines. In Japan, scientists cool the temperature in the combustion chamber down to make sure the engine can still work well after retrieved [4]. NASA scientists are considering a production technique called metal additive manufacturing (AM). This is a new cheaper production process in the combustion chamber [5].

In order to summarize the progress of rocket industry, this paper will introduce some basic equations of Rocket dynamics, designs and simulations of rocket engines, and an outlook of the future rocket dynamic system. The Sec. 2 will gives a basic description of rocket dynamics. The Sec. 3 will introduce some designs of rocket dynamic systems. The sec.4 will introduce a rocket dynamic simulation system. The sec.5 will provide 2 active rocket engine. The sec. 6 will give a future outlook for rocket engines. Eventually, a brief summary will be given in Sec. 7.

2. Basic Descriptions of Dynamics

The basic principle of rocket dynamic is the Newton Second law, which gives scientists a relationship between force and momentum as following.

$$F = \frac{dp}{dt} \tag{1}$$

Ignoring the air resistance and gravitational force, at a certain moment, ***m*** is the mass of the rocket, ***v*** is the velocity and ***p*** is the momentum. After a short time, the rocket ejects the working medium with a mass of ***Δm*** at a constant speed ***ve*** relative to the rocket body. Assuming the whole system is free from external forces, according to Newton's second law:

$$F = \frac{dp}{dt}=0 ,p = mv \tag{2}$$

The velocity of the rocket can be deduced through integration of following Equation:

$$F = m\frac{dv}{dt} + v_e\frac{dm}{dt} = 0 \tag{3}$$

Hence, one obtains

$$\int_0^{v_f} dv = \int_{m_0}^{m_f} -v_e\frac{dm}{m} \tag{4}$$

$$v_f = v_e \ln\frac{m_0}{m_f}, \Delta v = v_e \ln\frac{m_0}{m_f} \tag{5}$$

This equation is the Tsiolkovsky rocket equation. It can be used to estimate the mass of propellant to be carried by the rocket and the influence of engine parameters on the ideal speed. However, the Tsiolkovsky equation is a logarithmic equation, which is a relationship with extremely slow growth. It shows that the increase of fuel quantity,m_0, plays a very limited role in the increase of speed. This greatly limits the launch efficiency of the rocket. Tsiolkovsky proposed the idea of multistage rocket. A multi-stage rocket consists of several single-stage rockets. Stage one burns first, and then it is separated from the other rockets after the work is completed. Then Stage two works, and so on. The advantage of multistage rocket is that it separate the structure that is no longer useful after a period of time, and it does not need to consume propellant to fly with it and the payload. In order to get the precise trust of the rocket engine at a certain period of time, modern scientists often apply this equation. Fig. 1 shows the engine ideograph.

$$F = \frac{mv}{t} + A(P_1 - P_0) \tag{6}$$

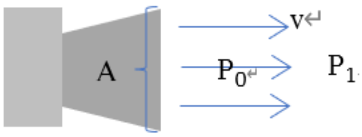

Fig. 1 Engine ideograph.

3. Designs of Rocket Engines

Rocket engines have different kinds of designs. The designs shown in Fig. 2 have different advantages and disadvantages. The pressure fed cycle is a form of power cycle of liquid rocket engine. Propellant is squeezed by high pressure gas and enters the combustion chamber. The advantage of extrusion circulation is to avoid the turbine, pump and delivery pipeline with complex structure. Since the use of the squeeze cycle can significantly reduce the cost and complexity of the engine. Its disadvantage is that the pressure generated is not high enough, so the engine efficiency is not high.

This cycle is often used by American spacecraft, such as Apollo's service module engine, lunar module engine and its attitude control engine [6].

The expansion cycle is a power cycle of the bipropellant liquid rocket engine, which can improve the efficiency of fuel supply. In the expansion cycle, the fuel is usually heated by the waste heat of the main combustion chamber before combustion. When the liquid fuel passes through the cooling channel in the combustion chamber wall, it changes into a gaseous state. The gas pressure difference generated by the gaseous fuel drives the turbine pump to rotate, so that the propellant enters the thrust chamber at a high speed to burn and generate thrust. After the fuel is converted into gas, its temperature is usually close to room temperature, causing little damage to the turbine. Compared with other designs, the engine turbine operates at high temperature, leading to greater damage to the turbine, which improves engine reusability [7].

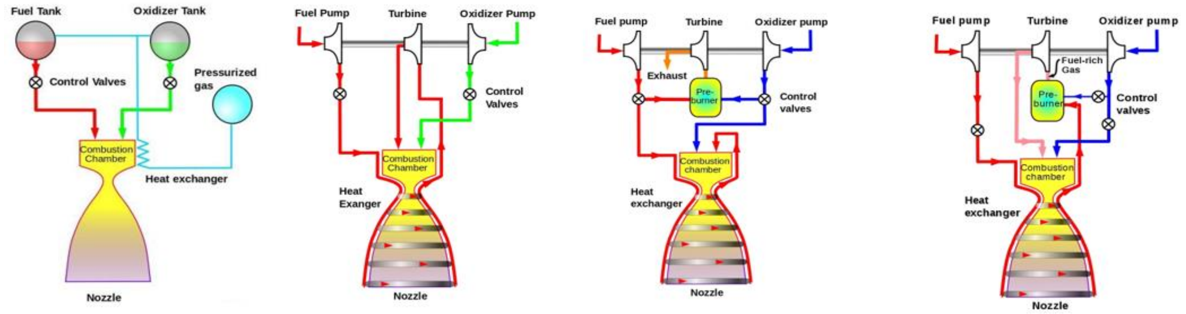

Fig. 2 Differenet processes of the cycle (from left to right): pressure-fed cycle, expansion cycle, Gas-generator cycle, staged combustion cycle.

Gas generator cycle, also known as open cycle, is a kind of power cycle of dual liquid propellant rocket engine. A small portion of the propellant is burned in the gas generator to produce gas to drive the turbine pump of the engine. Compared with the similar staged combustion cycle, the gas generator cycle has many advantages. The turbine of the gas cycle does not have to cope with the back pressure when discharging exhaust gas into the combustion chamber. Therefore, the turbine has higher working efficiency and higher pressure to provide fuel, thus increasing the specific impulse of the engine. Another advantage is that gas cycle turbines have a longer and more reliable life. Some reusable launch vehicles have great advantages in using this power cycle. The main disadvantage of this cycle is the loss of efficiency. As a part of the fuel is used to drive the turbine, the exhaust gas is discharged directly, so the net efficiency is relatively low [8].

The staged combustion cycle, also known as high-pressure staged combustion cycle, is a kind of cycle of bipropellant liquid rocket engine. Part of the fuel is burned in the precombustion room to generate high-temperature gas to drive the pump of the engine. The exhaust gas is then injected into the combustion chamber together with the propellant. The main advantage of staged combustion cycle is that all gas and heat are eliminated through the combustion chamber, with almost no loss. Thus, this cycle is also often called closed cycle. Another important advantage of this cycle is that it can withstand very high combustion chamber pressure, which makes nozzles with higher expansion ratio available for engines. The main disadvantage is that the working environment of the turbine is harsh, so many additional conduits need to be added to transport high-temperature gas [9].

4. Simulations of Rocket Engines

During analyzing data from a rocket engine's trial run, scholars have to use certain kinds of software called Computational Fluid Dynamics (CFD). CFD is a new interdiscipline integrating fluid mechanics and computer science. It starts from calculation methods and uses computers to obtain approximate solutions of fluid control equations. At present, the mainstream CFD software includes CFX, Fluent, Phoenics, etc. They can solve nearly all kinds of fluid problems [10]. Aiming at the characteristics of each flow physical problem, the numerical solution suitable for it is adopted to achieve the best in terms of calculation speed, stability and accuracy. The FLUENT software adopts the finite volume method based on completely unstructured grids and has a gradient algorithm based on grid nodes and grid elements. The FLUENT software has a strong grid support capability. The FLUENT software also has a combination of dynamic grid and grid dynamic adaptive technologies. It is applicable to Newtonian fluids and non Newtonian fluids; Heat conduction with forced/natural/mixed convection, heat conduction and radiation of solid/fluid; Mixing/reaction of chemical components; cavity two-phase flow model, wet steam model; Melting, melting/solidification; Evaporation/condensation phase transition model and other complex simulation situations [11]. Figure 3 is an example of Fluent simulation.

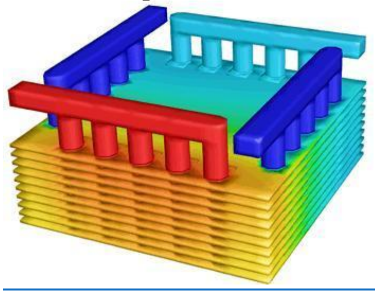

Fig. 3 An example of Fluent simulation.

5. Products for Rocket Engines

Rocket engine producers design different types of engines in order to meet different customers' need. The following text will list two competitive rocket engines as an example. They are cheap, efficient and safe to carry cargoes into the space. As shown in Fig. 4, the YF-100 is a 120t staged combustion cycle LOX/kerosene rocket engine designed by China National Space Administration (CNSA). The YF-100 applies the advanced oxygen enriched precombustion staged combustion cycle technology, with self starting, adjustable mixing ratio and thrust, single turbine pump arrangement, which can provide heat and oxygen for pressurization of the oxidant tank, and high-pressure kerosene as the power source for the servo mechanism. There are two main turbine pumps, of which the oxygen pump is single-stage and the kerosene pump is two-stage, both of which are driven by oxygen rich gas in the precombustion chamber. There are two pre pressure pumps, of which the kerosene pre pressure pump is driven by one of the primary high-pressure kerosene of the main pump. Compared with conventional engines, LOX kerosene engines have many advantages. First of all, this engine is very environmentally friendly. Its fuel, liquid oxygen and kerosene, are environmentally friendly dyes, which are easy to store and transport. Meanwhile, it is relatively more economical. Its propellant is 60% cheaper than conventional engines. Its high stability also makes customers like this engine [12].

Fig. 4 The YF-100 engine.

The Merlin engine is developed by SpaceX. The Merlin engine used the throat plug nozzle that was first used in the landing module of the Apollo program. Propellant is delivered through a turbine pump into the combustion chamber. In the meantime, the turbine pump also provides high-pressure liquid to drive the hydraulic controller, and then enters the low-pressure fuel inlet. This eliminates the dependence on the independent hydraulic power system, which means that there will be no loss of control over the thrust direction due to hydraulic exhaustion. The third usage of the turbopump is to provide lateral thrust to control rocket spin. In 2011, SpaceX announced that the vacuum thrust of Merlin 1D engine will be 690kN (155000lbf), the vacuum specific impulse (Isp) will be 310 seconds, the expansion ratio will increase to 16, and the chamber pressure will be 9.7MPa (1410psi). The engine can operate at a minimum of 40% of full thrust. The advantages of the new engine include its reliability (long fatigue life, heat allowance of combustion chamber and nozzle), good performance (design target 140000 pounds force (620 kN) and 70-100% throttling capacity), and easier manufacturing. (fewer parts, less man hours). After the engine test was completed in June 2012, SpaceX said that the engine had completed a full mission duration (185 seconds) test ignition, successfully generated a thrust of 650kN (147000lbf), and confirmed a thrust weight ratio higher than 150. The specific impulse of Merlin 1D engine is the highest among the gas generator circulating liquid oxygen kerosene engines [13].

6. Limitation and Future Outlooks for Rocket Engines

Space exploitation will be a hot project. Different nation and companies all want a piece of cake from the project. The rocket engine's efficiency and price will be the key factor for its market competitiveness. According to the Tsiolkovsky rocket equation:

$$\Delta v = v_e \ln \frac{m_0}{m_f} \tag{7}$$

Here, m_0/m_f represents the rocket's properties of High Strength and Low Mass Rocket Materials, which is hard to reach a big progress. What scientists can do is to increase v_e, the engines jet speed so that they can increase the rockets' delta v. The value of v_e is closely related to the performance of the engine. Seen from Table. 1, the data in line 1-3 shows the corresponding m_0/m_f of a certain v_e of a rocket that have the ability to get into the space. The data in line 4 shows if a rocket have a m_0/m_f same as a jet plane, its engine's v_e have to reach 11 km/s. It is nearly impossible for traditional rocket engine. In order to breach the restriction, researhers came up with different designs of new engine. Nuclear thermal engine is one of them.

Table 1. The corresponding m_0/m_f of v_e

Lines	v_e(km/s)	m_0/m_f
1	2	104
2	3(LOX/kerosene)	22
3	4.5(LOX/Hydrogen)	8
4	11(certain type of rocket engine)	2.4(jet plane)

Nuclear thermal rocket has many advantages, such as high thrust, high specific impulse, multiple starting, etc. It is generally composed of reactor, storage tank and turbine pump system, pipeline and cooling system and nozzle assembly. The structure of the reactor is high temperature gas cooled reactor, including fuel assembly, support structure, moderator, control rod or control drum, reflector and pressure chamber. Nuclear thermal rocket usually uses hydrogen as working medium and coolant. Hydrogen has excellent thermal conductivity. Under high temperature and low pressure, it is easy to dissociate into atomic hydrogen and absorb a lot of heat. Its thermal conductivity is comparable to that of metal materials, and it is one of the best cooling media. Simulataneously, because of its small molecular weight, it becomes the best working medium. The working medium is heated after flowing through the reactor, and then ejected at high speed through the contraction expansion nozzle. The control rods of the reactor are used to control the neutron flow in the reactor. The Fig. 4 shows the working principle diagram of a nuclear thermal rocket. However, launching rockets with nuclear thermal engine in a large scale will cause a environmental problem. If the launch mission failed and the nuclear fuel spread into the atmosphere, it will cause large area abandoned and countless people suffer from radio sicknesses [14].

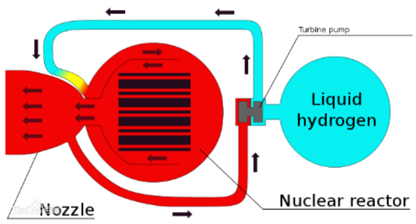

Fig. 4 A sketch of the nuclear thermal rocket.

7. Conclusion

In summary, from an attempt to military application to scientific research, the design of rocket engines has been progressing and developing over time. Entering the 21st century, countries began to focus on reducing the cost of developing rocket engines and launching rockets. Based on CFD software to test engine performance instead of a large number of engine tests, scientists can get accurate data more quickly. By improving the performance of the combustion chamber, commercial companies can recycle launched rockets to reduce costs. With the development of technology, the traditional chemical power rocket engine also shows systematic defects. Scholars are also constantly developing new types of rocket engines. In the future, new types of engines will emerge and help human to go farther in the deep space. Overall, this study introduces the design, simulation, products and future prospects of rocket engines. These results can make a modest contribution to the cause of human space.

References

[1] Perring W G A. A Critical Review of German Long-Range Rocket Development. Journal of the American Rocket Society, 1946 (65): 1-17.

[2] Warren D, LANGER C. History in the making-the mighty f-1 rocket engine. 25th Joint Propulsion Conference. 1989: 2387

[3] Katorgin B, Chelkis F, Limerick C. The RD-170, a different approach to launch vehicle propulsion. 29th Joint Propulsion Conference and Exhibit. 1993: 2415.

[4] Yoshida M, Kimura T, Hashimoto T, et al. Overview of research and development status of reusable rocket engine. Chemical Rocket Propulsion, 2017: 905-931.

[5] Kerstens F, Cervone A, Gradl P. End to end process evaluation for additively manufactured liquid rocket engine thrust chambers. Acta Astronautica, 2021, 182: 454-465.

[6] Chakroborty S, Bauer T. Using pressure-fed propulsion technology to lower space transportation costs. 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. 2004: 3358.

[7] Zhou C, Yu N, Wang J, et al. Analysis of dynamic characteristics and sensitivity of hydrogen-oxygen expansion cycle rocket engine system. Acta Astronautica, 2021, 189: 624-637.

[8] Cho W K, Park S Y, Seo W S. Development of performance analysis program for gas generator cycle rocket engine. Journal of the Korean Society of Propulsion Engineers, 2008, 12(5): 18-25.

[9] Naderi M, Liang G. Static performance modeling and simulation of the staged combustion cycle LPREs. Aerospace Science and Technology, 2019, 86: 30-46.

[10] Tu J, Yeoh G H, Liu C. Computational fluid dynamics: a practical approach. Butterworth-Heinemann, 2018.

[11] Matsson J E. An Introduction to ANSYS Fluent 2022. Sdc Publications, 2022.

[12] Jianhua C, Chen C A O, Yongqiang Y, et al. General technical review of Long March 5 liquid oxygen kerosene engine. Journal of Deep Space Exploration, 2021, 8(4): 354-361.

[13] Naderi M, Karimi H, Guozhu L. Modeling the effect of reusability on the performance of an existing LPRE. Acta Astronautica, 2021, 181: 201-216.

[14] Emrich Jr W J. Principles of Nuclear Rocket Propulsion. Butterworth-Heinemann, 2016.