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Research on the comparative analysis of thrust and specific impulse performance - different cycle types of liquid rocket engines

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Abstract. As one of the most crucial parts of deep space exploration and interstellar colonisation in the global space industry, the development of rocket engines plays a vital role. The subject of this study is to investigate the effect of different cycling methods on the thrust and specific impulse of liquid rocket engines. The study will cover seven typical cycle methods and hopes to contribute to the subsequent development of more efficient and reliable liquid rocket engines, provide designers and engineers with a reference for optimising design and performance, and provide the basis for other future research in related fields that will have a profound impact on the space industry.

Keywords: thrust, impulse, liquid rocket engines, cycle methods.

1. Introduction

As the main power source for sending spacecraft, satellites, and missiles into space, liquid rocket engines have become the most critical component of the entire global space exploration industry, and its application scope is gradually increasing. Within the broad category of liquid rocket engines, each type of liquid rocket engine has its own performance depending on its characteristics, including the different cycle methods [1].

This research will discuss the impact of different circulation methods on the thrust and specific impulse of liquid rockets, and cover seven typical cycle methods of liquid rocket engines, pump-fed expander cycle, exhaust-gas expander cycle, expander bleed cycle, gas generator cycle, staged combustion cycle, combustion tap-off cycle, and electric pump feed cycle.

This research can make some contributions to the later development of more efficient and reliable liquid rocket engines. Simultaneously, identifying the most important factor in the cycles related to the thrust and specific impulse of liquid rocket engines helps designers and engineers optimize their designs and improve performance.

2. Three subcategories

This paper divided seven different cycle methods into three subcategories according to their unique features, expander type, combustion type, and electric type.

Pump-fed expander cycle, exhaust-gas expander cycle, expander bleed cycle are in the first subcategory, expander type. Gas generator cycle, staged combustion cycle, and combustion tap-off cycle

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are grouped into the second subcategory called combustion types. Electric pump feed cycle are classified separately into a third subcategory called electric type.

2.1. Expander type

Pumped expander cycles, exhaust gas expander cycles, and expander bleeder cycles can be considered to belong to the same subcategory called expander types since they all have expanders and no pumps inside the engine. Thus, this type of liquid rocket engine basically has a similar working principle [2].

Fuel and oxidant are simultaneously introduced into the combustion chamber to generate high temperature and high pressure gas. A part of it is ejected directly into the atmosphere through the nozzle for thrust, and the rest is introduced into the expander for depressurization and cooling.

Due to the depressurization and cooling of the gas, this low pressure zone will squeeze more fuel and oxidant from the storage tank to mix with the fuel gas in the combustion chamber for the second burn.

Meanwhile, depressurization and cooling will cause the gas to have a higher velocity during the ejection process, thereby significantly increasing the specific impulse.

However, due to the transfer of gas during the first burn, the overall thrust of this type of liquid rocket engine will be limited.

2.2. Combustion type

Combustion types include gas generator cycles, staged combustion cycles, and combustion split cycles, all with pumps powered by gas fuel directly from the combustor or pre-combustor chamber [3].

After the fuel and oxidizer are mixed and burned in the combustion or pre-combustion chamber, part of the high-temperature and high-pressure fuel gas is introduced into the pumps. Thus, a constant stream of fuel and oxidizer is pushed into the combustion chamber.

Due to the constant input stream of fuel and oxidizer to the combustion or pre-combustion chamber, a mixture of new fuel and waste fuel gas will re-enter the combustion chamber to complete the cycle. This will give some of chemical elements in the waste fuel gas that have not reacted in the past a chance to re-burn and maximize the conversion efficiency of energy from chemical energy to thermal and kinetic energy.

However, due to the diversion of fuel gas from the combustion chamber into the pumps, some thrust must have been lost from the nozzle. This process is also called specific impulse increase [3].

2.3. Electric type

The electric type is mainly an electric pump feed cycle, which is a brand-new propulsion system in the current world aerospace industry.

This cycle method is the simplest in theory and structure since neither fuel oxidizer, nor gas are recovered, and the pump is driven by electricity. The use of the pump is similar to that of a combustion type liquid rocket engine [4].

But the similarity to the combustion type subcategory is the use of pumps in the liquid rocket engine. The theory and structure behind this cycling method are the simplest since neither fuel, oxidizer, nor fuel gas are recovered and the pump is powered by electricity.

Since the engine is not shunted, no part of the engine in the electric version loses thrust, and all thrust is properly applied to the rocket.

However, since there is no connection between the combustion chamber and the pump, the fuel gases are directly enter the nozzle, ready for ejection into the atmosphere to generate thrust. And some chemical elements may not burn in the combustion chamber, so there will be some waste of energy.

Thus, this cycling method is unlikely to have the highest specific impulse compared to other cycling methods.

3. Side-by-side comparison

3.1. Expander type

In the expander type subcategory, although the three cycle methods all have expander participation, how the expander participates and where the expander joins in the cycling matter a lot. A slight difference may cause huge differences in the general thrust and specific impulse of the liquid rocket engine.

For the three cycles in the expander type, although the expanders are all located between the output valve of the combustion chamber and the propellant transfer pipes, they evolve step by step [5].

3.1.1. Pump-fed expander cycle. The pump-fed expander cycle is the simplest and most reliable one, and the cost of manufacture and maintenance is the lowest. But the temperature and pressure of the fuel gas after burning in the combustion chamber will be high. There must be some way to cool it down when it is entering the expander. This will use the storage propellant in the tank. In general, the liquid rocket will carry a huge amount of hydrogen or oxygen in the liquid phase as the propellant, and liquid hydrogen and oxygen have the feature of having an extremely low temperature. Thus, they become the best material to cool down the waste fuel gas. But this extra propellant usage is an enormous waste of specific impulse. Furthermore, for some extreme mission conditions, the requirement for cooling efficiency will go even further. Hence, the specific coolant has been introduced into the expander. Nevertheless, the coolant will occupy volume in the expander from the propellant and cause a reduction in thrust [5].

3.1.2. The exhaust-gas expander cycle. Considering the Exhaust-gas expander cycle is specifically designed to solve the problem of low specific impulse for the previous cycle method, it cuts off the connection between the expander and the propellant transfer pipes and connects the expander to the nozzle directly. The only function of the expander here is to expand and depressurize the waste fuel gas for the nozzle. Thus, there is no cooling requirement for the expander without any form of propellant loss, which improves the specific impulse. However, the expansion and depressurization by the expander will make the waste fuel gas have a lower speed and pressure when entering the nozzle. Which means there is not any positive effect on the thrust [6].

3.1.3. The expander bleed cycle. The expander bleed cycle is the final cycle method in this subcategory, based on the desire to solve problems for the previous two cycle methods. The position of the expander is the same as in the Pump-fed expander cycle. The only difference is that there is no longer a need for expander cooling, depending on the better material and more complexity in the structural design for the whole engine. Also, the coolant no longer takes place in the expander. All the propellant and space can be used for combustion to generate thrust [7].

Therefore, the specific impulse and thrust for this cycling method will both be relatively high compared to the previous two cycle methods.

3.2. Combustion type

In combustion type subcategory, the pumps are participated in the engine instead of the expander and all the processes have been done by multi-combustion chambers or the pre-combustion chamber. These pumps are located at the pipes for transferring the propellant into the combustion chamber.

3.2.1. The gas generator cycle. The gas generator cycle is the easiest and cheapest way to accomplish the targets, simple and durable. A pre-combustion chamber is added to the engine between the pump and the main combustion chamber, which is supply with propellant directly from the storage tank. After the burn in the pre-combustion chamber, the waste fuel gas will be used to power the pumps [8].

However, this transfer of propellant from storage tanks to the pre-combustion chamber instead of the main combustion chamber would result in a significant loss of thrust. Meanwhile, after the pump is powered, the waste fuel gas produced by the pre-combustion chamber will be released into the atmosphere, and the reuse of incompletely burned chemical elements is not considered, which will cause a huge loss of specific impulse.

3.2.2. The combustion tap-off cycle. The combustion tap-off cycle is an advanced version of the gas generator cycle. The major difference between them is that there is no pre-combustion chamber in the combustion tap-off cycle, and the propellant is mixed and burned only in the main combustion chamber. Then, the waste fuel gas with high temperature and pressure is diverted into the nozzle and pumps, and the waste fuel gas after powering the pumps is expelled directly from the engine, just like in the gas generator cycle. But the proportion of fuel gas entering the pumps is really small. Thus, the thrust loss and the specific impulse loss of the engine are much smaller than those of the gas generator cycle [9].

3.2.3. The staged combustion cycle. The staged combustion cycle offers a lot of upgrades over the previous two cycle methods to achieve better general performance.

First, there is no pre-combustion chamber, instead of two main combustion chambers. One of them is only used to generating fuel gas to power the pumps. Another one is only used to generate thrust, powering liquid fuel rocket. The waste fuel gas is pumped back into the combustion chamber and only used for thrusting production, where it is mixed with propellant for reburned. This avoids the waste of no fuel gas, and improve the efficiency of energy transfer as much as possible [9].

Therefore, the thrust and specific impulse for this cycling method are the highest.

3.3. Electric type

The electric type of subcategory is similar to the combustion type of subcategory, all having the same critical component in the engine, which is the pumps on the propellant transferring pipes. The electric category has only one circulation method, called the electric pump feed cycle. Its performance is roughly the same as that of the combustion type, with only some differences in some key performance indicators [10].

As the latest form of cycle method, the electric type is fundamentally aimed at increasing the controllability of the liquid rocket engine. In both the expander and combustion types, whether the engine uses an expander or pump, once the whole cycle is running, the only thing that can be controlled is turning on or off the engine. Although many can limit the amount of propellant transferring into the combustion chamber to control the thrust of the engine, the accuracy of the control will be very low, and it might increase the instability of the engine, which can lead to serious catastrophic engine failure. Therefore, based on the current level of technology, the most accurate and stable way to control the thrust of the engine is to use the electric drive for pumps. This means that instead of diversifying from either propellant or waste fuel gas into the expander or powering the pumps, all the propellants stored in the storage tanks are used to generate thrust in the combustion chamber. This approach could help the liquid rocket engine increase its efficiency and specific impulse, as well as the general thrust produced by the engine [11].

4. Discussion

In general, the liquid rocket engine using the combustion type has the highest thrust and specific impulse, mainly due to the different ways in which it gains propellant from the storage tanks. For the cycle methods of the expander type, the expander will create a low-pressure region by expanding and depressurizing the waste fuel gas. This low-pressure region will suck propellant out of the storage tanks and send it into the combustion chamber. All work is done through a pressure differential, the higher the pressure difference, the more propellant is transferred. But the pressure difference quickly reaches its limit, and after that, it becomes almost impossible to increase any further. That means that the thrust and specific impulse of the engine will also reach its limits very quickly.

Nevertheless, with a liquid rocket using a combustion cycle approach, the thrust and specific impulse limitations of the engine can be much higher due to the extra pump. The use of pumps can potentially increase the differential pressure even more, so the thrust and specific impulse of the engine can continue to rise.

Apart from this, the electric type can theoretically have the highest thrust and specific impulse compared to the expander type and combustion type. However, to achieve such a high level of performance, the requirement for electrical pumps is enormous, and due to the huge consumption, the rocket needs to carry a massive battery. The weight of these large electric pumps and giant batteries, called dead weight, is a major taboo in the aerospace industry. Thus, the thrust and specific impulse benefits of electric pump cycles in liquid rocket engines are limited. Moreover, this advanced technology is mostly used for launch missions that require high precision.

But, not to mention the fact that battery technology is now advancing at a dramatic pace, more and more batteries with higher energy density, even power batteries, are already being used. The negative impact of the size and weight of the battery will become smaller and smaller, even negligible, at some point in the future.

5. Conclusion

The cycle methods that can produce the highest thrust and specific impulse should be chosen from the staged combustion cycle and the combustion tap-off cycle. But, due to its complexity of design, high cost of manufacture and maintenance, it is only suitable for fewer countries and enterprises in the world that can develop and use it.

In addition, although the gas generator cycle is a cycle method that was developed at an early age, it is still widely used worldwide because of its simple structure and high reliability. But, due to its insufficient thrust and specific impulse, it is only suitable for some launch missions that do not require high performance.

After considering the value for money, the pump-fed expander cycle and the exhaust-gas expander cycle offer a certain balance between performance and cost. So this is suitable for applications that require high performance but not too high cost.

Finally, the Electric pump feed cycle has the advantages of control accuracy, ease of maintenance, and low cost compared to the other cycles, but the thrust and specific impulse are relatively low due to the electric power restrictions and the high dead engine weight. The liquid fuel rocket engine using this cycling method is for launch missions that require accurate controllability, such as reusable rockets.

This study only discusses the effects of structural characteristics and different cycling methods on the thrust and specific impulse of liquid rocket engines, but all the cycling methods mentioned in this study are only used as a typical example; in reality, many liquid rocket engines are used in combination with many different cycling methods and cannot be fully categorized for discussion. In addition to this, there are many other key factors such as propellant selection, fuel-to-oxidizer ratio, nozzle design, etc. In this study, all studies were based on all other factors remaining the same or not being considered, but differing only in the way they were cycled, so in practice, it is more rigorous to combine this study with the actual situation.

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