Principles of Multistage Rocket Vehicle and Concepts of Propulsion Methods for Rocket Applications

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Abstract. The variety of propulsion methods will reach their peak efficiencies under certain conditions. This paper will focus on the propulsion methods and different propellant choices for certain usage when designing a vehicle or a stage of a rocket with some altitude limitations, their working principles, applications and challenges. The advantages of multistage design for rocket vehicles and the prospects of advanced engine technology using electricity or solar radiation as its main power source will also be discussed. The cost, payload and other attributes such as the thrust-to-weight ratio of every propulsion concept are the main factors for determining the general performance. MRV is the ideal design for rocket vehicles that are launched from the surface of a planet consider the massive amount of energy it requires to get into the orbit or escape the gravity, but the propulsion system can be various depends on the applications under certain conditions of launching and space travel.

Keywords: propulsion methods; propellant choices; rocket; working principles.

1. Introduction

Human activities are severely limited by the earth resources, the developing over population and environmental problems are pushing the limits of both mankind and the earth [1]. October 4, 1957, the Soviet Union launched the first uman activities are severely limited by the earth resources, the developing over population and environmental satellite to the earth orbit. Shortly after that, the first human Yuri Gagarin was launched successfully in 1961 [2]. In 1969, the American astronaut Neil Armstrong stepped onto the lunar surface and started a new era of human exploration. Although these technologies were invented due to the tensions from the cold war, they still play a significant role in the modern space travel. The history of multistage rocket can be traced back to the beginning of human's astronautic travel, the multistage design is still considered as the most practical approach for rocket vehicles [3].

This paper will explain the principles and limitations of various propulsion methods, and how to apply each methods and technologies in different stages of a rocket to achieve a higher speed, better performance or lower cost. Air-breathing engine, chemical rocket engine and other rocket propulsion concepts using nontraditional energy will be introduced with their theoretical principles, challenges and possible future applications.

The concepts and applications of MRV will be introduced later with detailed analysis of combining different propulsion systems for certain applications. Examples of existing designs and productions will be presented to support author's concepts [4].

2. Propulsion methods for different altitude

2.1 Air-Breathing Engine (ABE)

2.1.1 Principles & Challenges

Air-breathing engine, also known as the duct engine, is the most commonly used engine type for aviation within stratosphere. The principle of duct engine is to entrain and compress air flow, using the energy from igniting the propellant to heat and further accelerate the flow [1]. High speed mass has been exhausted and a reaction force is applied to accelerate the aircraft.

Several types of ABEs are designed for totally different applications, turbojets, turbofans,ramjets and pulse-jets are the main four types of duct engines. The most commonly used duct engine is the turbojet engine which plays a significant role in modern day's commercial airlines. However, ramjet engine will be the focusing topic in this subsection because of its decent thrust-to-weight ratio which is 7:1 with Mach number 3 at around 9,144 meters (30,000 feet) above sea level [1]. The thrust-to weight ratio is an important dimensionless group when this term can be used to determine the payload of a rocket vehicle. It describes the ratio of an engine's thrust to its total weight which is one of the most significant factors when analyzing the performance of a rocket [5].

Another feature of ramjet that makes it more suitable for rocket vehicle is that the ramjet has higher altitude limitation compared to other duct engines. With lower air pressure at high altitude, the efficiency of other duct engines will decrease dramatically and most of them are nonfunctional at the altitude higher than 14,000 meters (45,932 feet) above sea level.

Fig. 1 [2] is an illustration of a ramjet engine with a supersonic inlet because of its converging/diverging inlet design. Air flow has been compressed by the inlet compression section, fuel injectors inject fuel into the compressed flow and then been ignited in the combustion chamber which is located right after the injection section. Flame Holder is for controlling the ignition position for continual combustion, the continual combusted fuel with high speed oxidizer (air in duct engines) will exhaust high speed mass from the nozzle and thus, produces thrust. Some may have afterburner to get an acceleration boost when takeoff and landing. An exhaust nozzle may be installed to control the mass flow rate in order to get extra acceleration or prevent the back pressure from damaging the engine itself [6].

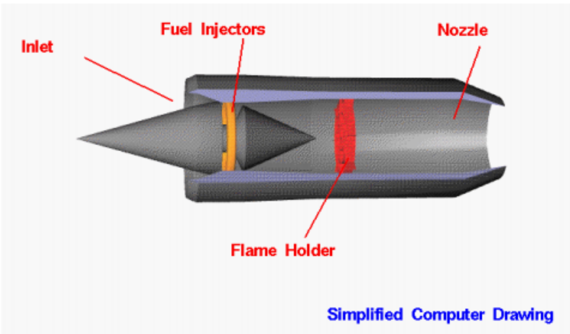

Fig. 1 Simplified schematic diagram of a ramjet [2].

The altitude limitation of a ramjet engine may differ from its speed. The theoretical altitude limit of a ramjet engine with Mach number 5 is 30,000 meters (98,425 feet). With low air pressure at high altitude, the total pressure on an aircraft can be expressed by the follow equation [3]:

$$P_t = p + q_c \quad (1)$$

where the P_t is the total pressure, p is the static pressure or the atmospheric pressure at the aircraft's altitude, and q_c is the impact pressure.

The impact pressure is proportional to the drag force caused by the air flow, the total pressure drops when the altitude increase which means higher performance but lower lift. The aircraft will be able to reach higher speed due to less drag force, it also needs to reach certain mach number to create enough lift [7].

Although the ramjet engine is efficient when operating under supersonic and hypersonic condition, its payload capacity is relatively low compared to the traditional chemical rocket engine which will be discussed in the next section [8]. Another limitation of ramjet is its oxidizer choice, all ABEs use the air as oxidizer, many designs even consider the bypass air flow as the main source of thrust and cooling system. Therefore, an aircraft with ABE has a theoretical altitude limitation of 45,000 meters (147,638 feet) above sea level when operating at Mach 12 [1], which is technically feasible, but with no existing application nowadays. The most inconvenient feature of ramjet is that it requires certain initial speed to operate. Because the air flow must enter the inlet section with a minimum speed in order for the inlet section to compress the flow, and the bypass flow, if it has a fully designed bypass system, will also need an operating speed to provide thrust and cooling. This requires a pre-stage which can provide enough payload capacity and thrust to carry the rocket vehicle and reach the minimum operating speed for ramjet engine, this pre-stage can be a newly designed aircraft with turbojet engine or a chemical rocket engine.

2.1.2 Prospects

The ramjet engine may have more payload capacity since it does not need an individual oxidizer supply system, which commonly includes compressed oxidizer, oxidizer tank, various valves, pipes and filters [9]. This can greatly increase the efficiency and speed of a rocket when operating under the stratosphere, with more payload capacity, the cost will decrease significantly.

A dual mode rocket engine called the Synergetic Air-Breathing Rocket Engine (SABRE) designed by Alan Bond uses the similar concept of reducing the weight of oxidizer by using a ramjet engine when operating in a relatively low altitude. This design has a special geometry which contains both the rocket mode and air-breathing mode.

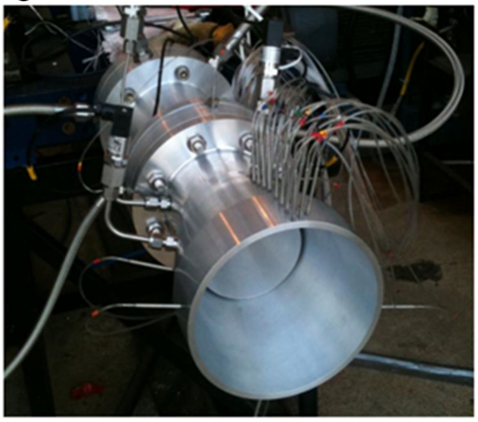

Fig. 2 Strident cold flow rocket engine with dual-throat nozzle [4].

Fig. 2 [4] is a produced and tested strident rocket engine which shares the similar geometric and theoretical concept as the SABRE, but had been designed only for cold flow testing [10].

The idea of SABRE is to use CRE (rocket mode) for providing enough thrust to reach certain operating speed and altitude for ABE (air-breathing mode), and switch to other propulsion system after reaching even higher altitude where the air-breathing method has been fully nonfunctional. The detecting and modes switching processes are unforgiving, the application for space travel using SABRE is still under development.

2.2 Chemical Rocket Engine (CRE)

2.2.1 Principles & Challenges

Chemical rocket propulsion is the most feasible and commonly used propulsion method for rocket vehicle launching.It has an extremely large thrust-to-weight ratio of 75:1 [1] with no altitude limitation. CRE is the most compatible engine for rocket launching due to the massive total mass and the high required escape velocity of space travel. The Liquid Propellant Rocket Engine (LPRE) ignites the mixture of fuel (e.g., liquid hydrogen) and oxidizer (e.g., liquid oxygen) in a high-pressure chamber and exhaust through a converging/diverging nozzle (rocket nozzle) to produce thrust.

CRE has different feed systems, one is the gas pressure feed system which uses gas in a high-pressure supply tank to feed fuel and oxidizer into the thrust chamber, some designs may have more than one thrust chamber. The pressurized gas may also be used for draining and flushing out the residual propellant in the tanks and pipes. This design is commonly used for attitude control due to its relatively low thrust. A gas pressure feed system can also be used to press the liquid oxidizer into the combustion chamber where the oxidizer and solid fuel have been mixed and ignited, this design is called the hybrid propellant rocket propulsion systems. Missiles and the first stage of a rocket usually choose to use this hybrid propulsion system since it can produce significant amount of acceleration and its stability for long-term storage.

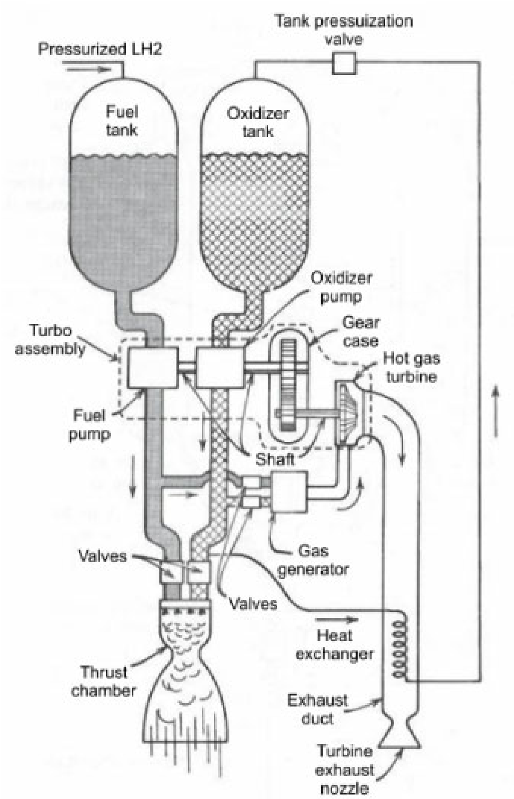

Fig. 3 Simplified schematic diagram of a liquid propellant rocket engine with turbopump feed system and gas generator [1].

Fig. 3 [1] is a simplified example of a liquid propellant rocket engine using turbopump feed system. The pressurized fuel and oxidizer are fed by the turbopumps and been injected and ignited in the combustion chamber which ejects high velocity mass through the supersonic nozzle. The heated gas has been cycled in a separated gas generating system to drive the high speed turbine and keep the tank pressurized.

Since CRE has an extremely high thrust-to-weight ratio and a limitless altitude limitation, it is suitable for launching, accelerating and operating at any altitude, this makes it a perfect choice for space travel.

However, CRE has a low specific impulse (thrust force per unit propellant) of only 270 sec [1] which is much more inefficient compared to the turbojet and ramjet engines. This makes CRE become economically non-ideal for commercial use. Many rocket organizations make one-time-use stages which basically scraps the boosting stages after the fuel has been totally consumed. The lacking of a reusable rocket design in most countries and corporations has further increased the cost of every kilogram of payload.

2.2.2 Prospects

Since CRE has low specific impulse and high thrust-to-weight ratio, the design of a rocket vehicle using CRE as the first stage should be focused on the launching section. By replacing chemical rocket propulsion with other propulsion method which has a better specific impulse under stratosphere, the problem of CREs' low efficiency problem can be avoided.

Fig. 4 Falcon 9 launching capture [5].

As for further lowering the cost of space travel, a reusable rocket vehicle must be developed. Space shuttle was an attempt for reusable rocket vehicle, but it did not successfully reach its purpose and the space shuttle technologies had been abandoned since 2011. Luckily, such concept has been fully applied by a space corporation - Space X. Fig. 4 [5] is a picture of Falcon 9 two-stage rocket which is manufactured by Space X, which has already been launched 169 times with 129 times total landing of the first stage. Other countries, organizations and corporations such as China and Blue Origin also intend to follow the steps of Space X. More and more engineers and scientists have realized the significant economic and industrial advantages of this reusable rocket technology.

2.3 Other Rocket Propulsion Designs

Various engine designs use other sources of energy such as nuclear, solar and electricity. Nuclear rocket engine does not seem promising due to its safety issues. Electric Rocket Propulsion (ERP) shows high performance in the outer space, its low thrust makes it a possible practical choice for long distance interstellar travel and many outer space maneuvers. Energy sources of ERP engine can be nuclear, solar radiation or batteries [1].

The applications of using solar radiation for energy source are plenty especially on satellite designs. The nuclear energy is currently under development and no industrial and scientific applications of a nuclear electric propulsion system will be presented in the near future. Therefore, these two concepts will not be focused in this section.

2.3.1 Ion Propulsion Thruster

Ion Propulsion Thruster, which is also known as electrostatic thruster or hall thruster, the fluid (such as xenon - an inert gas with high molecular weight) stored inside the thruster will be ionized due to the impact from electrons.

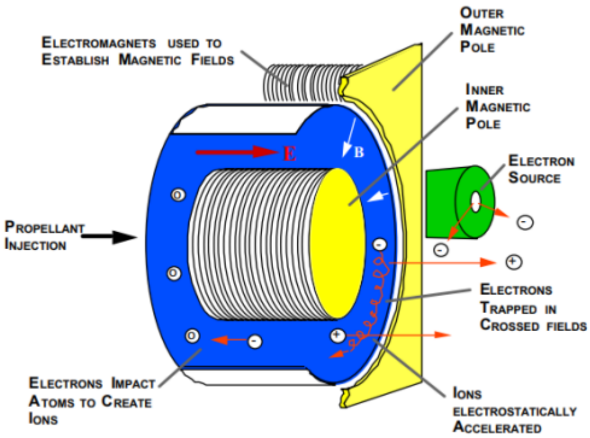

Fig. 5 Simplified schematic diagram of an operating ion thruster [6].

Fig. 5 [6] is an illustration of a working hall thruster, the electrical discharge will be generated between a cathode and an annular anode. A radial magnetic field will spin the electrons and then, the spinning electrons collide with xenon, creating ionized xenon gas. Ions are accelerated by the electrodes and thus, producing thrust.

The applications of ion thruster for earth orbit and in-space maneuvers already existed for a few years. Its environmental-friendly energy source and high performance for long distance space travel make hall propulsion system one of the optimal approaches for future space travel.

2.3.2 Solar Thermal Propulsion

Fig. 6 [1] illustrates the basic concept of solar thermal propulsion. The solar radiation be reflected by a parabolic reflector and then concentrates on a heat receiver. Fluid inside a heat exchange system (may have a gas pressure feed system), usually liquid hydrogen, will be heated through the receiver and the peak temperature may even reach 2500 ℃.

Therefore, the heat receiver must be made of high-temperature metal. One or more nozzles will exhaust the hot gas to produce the propulsion.

This propulsion concept can also provide a performance than the traditional chemical propulsion, but the low thrust and its special solar reflecting design make it only be possible to operate in space just as similar as the ion propulsion.

3. Combined Concept for MRV

The applications of MRV are plenty nowadays, some new concepts such as single-stage-to-orbit vehicle are proposed. Although the single stage vehicle has less complexities which will lower the cost of designing and maintaining, the payload will be too small for commercial operation. Since this design does not have many practical applications, this section will only be focusing on MRV.

The early successful applications of MRV could be traced back to the Apollo program. One of the most iconic rocket, the Saturn V, had been the first man made vehicle that transited 3 men to the lunar orbit, accomplished several lunar landing missions and carried the Skylab to the earth orbit.

Fig. 7 [7] is a schematic diagram of Saturn V rocket. The first stage, which was the largest stage of Saturn V, was powered by five F-1 engines and the propellant choice was the mixture of kerosene and liquid oxygen. The second stage with five J-2 engines used liquid hydrogen and liquid oxygen as propellants. The third stage used the same propellants as the second one, but with only one J-2 engine. The first two stages carried astronauts near the earth orbit and the third stage put them onto the orbit or push them towards further destination such as the moon [8]. Each stage would be detached and abandoned after the fuel was fully expanded to maximize the payload, therefore, Saturn V was not designed for reusable launching. This is the largest rocket vehicle in human launching history as this article is being written.

NASA has been using the multistage design for all the rocket vehicles that are operating right now, same as many other corporations such as Space X. The Falcon 9 rocket also has multiple stages with a fully reusable first stage. MRV is the most reliable design concept for carrying payloads onto the earth orbit or further destinations. The best thrust-to-weight ratio compared to other concepts of propulsion which was discussed in the section of CRE gives this type of engine a tremendous advantage for rocket launching. The high performance of ion propulsion, solar thermal propulsion and other various propulsion designs make them suitable for outer space vehicle propulsion. The air-breathing engine, although shows high performance under stratosphere, is not an ideal choice for rocket vehicle consider its low thrust-to-weight ratio and its dependency on the existing air outside the engine. The designs such as SABRE are technically feasible, but have not yet been demonstrated and applied.

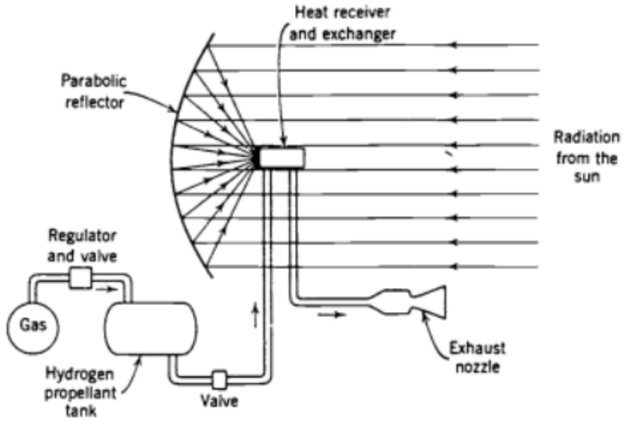

Fig. 6 Schematic diagram of a solar thermal rocket concept [1].

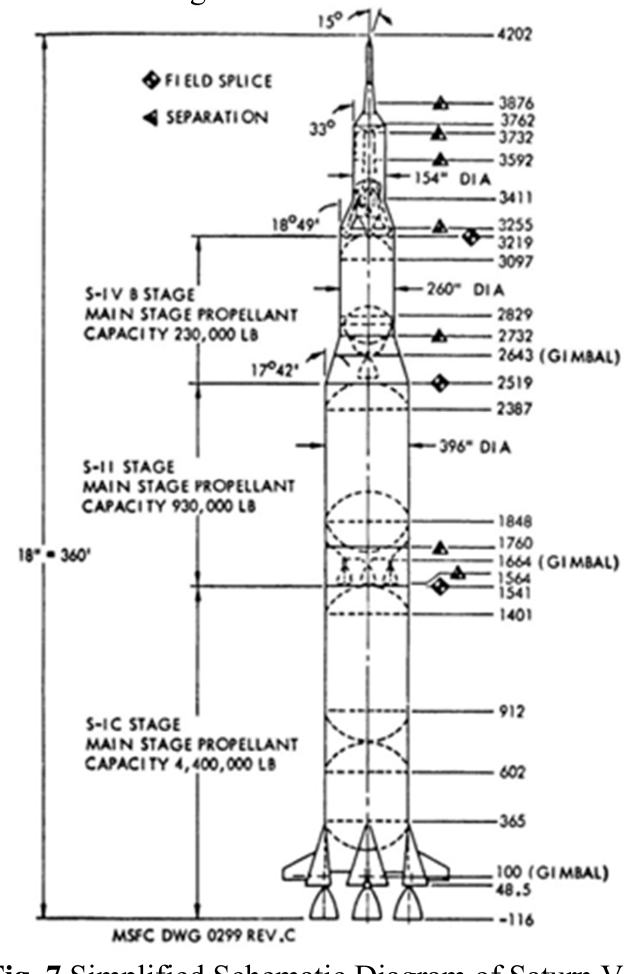

Fig. 7 Simplified Schematic Diagram of Saturn V [7].

4. Conclusion

MRV design is crucial considering the massive amount of energy it required to carry all the equipment and astronauts onto the earth orbit and other planets' surfaces. The choices must be made carefully to fully exploit the value of every propulsion concepts. New space technologies have been proposed and it will be too soon to predict the prospects for space exploration. Increasing the maximum payload, lowering the cost and expanding the exploring area should be the priorities under the current circumstances of the space travel field. Improving the reliability and lowering the cost of MRV may even make it possible for future commercial space travel. Plenty of other concepts and experiments of new propulsion technologies have not yet been discussed in this article, and they may also play a significant role in the future space explorations.

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