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An Overview of Rocket Engine Power Cycles

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Abstract

Rocket engine cycles significantly impact propulsion system performance, efficiency, and reliability. This paper examines various cycles, including pressure-fed, electric pump-fed, staged combustion, expander, tap-off, and gas generator. Each cycle's characteristics, advantages, and limitations are discussed, focusing on efficiency, thrust-to-weight ratio, specific impulse, complexity, and cost. Pressure-fed cycles offer simplicity but compromise efficiency. Electric pump-fed cycles provide high efficiency and precise control. Staged combustion cycles achieve high efficiency but pose complexity challenges. Mission requirements, resources, and technology influence engine cycle selection. Applications range from small-scale missions to high-performance launch vehicles. The paper highlights key considerations for engineers and researchers, enabling informed decisions for propulsion system design and development. The review provides a comprehensive understanding of rocket engine cycles, including: Characteristics, advantages, and limitations of each cycle; Complexity, cost, and reliability considerations; Applications in space missions and launch vehicles. This study offers valuable insights into the complexities of rocket engine cycles, facilitating optimal engine selection for various space missions. By understanding cycle characteristics and limitations, engineers can design efficient and reliable propulsion systems.

Major Findings: *This research provides valuable insights into the intricacies of rocket engine cycles, aiding in the optimal selection of engines for different space missions.*

Keywords: *Liquid Rocket Engine, Propulsion, Rocket Engine, Space Exploration*

1.0 Introduction

The functionality of a Rocket Engine (RE) adheres to Newton's third law of motion, where each action is paired with an opposing reaction of equal magnitude. This means that the engine releases mass from one end, causing the entire vehicle to propel in the opposite direction[1]. The greater the speed and amount of mass expelled, the higher the thrust and efficiency will be. The engine's thrust capability determines the amount of payload a rocket can carry.

RE are a critical component of space exploration, satellite launches, and military applications. The multiple types of RE cycles have their own set of pros and cons. In general, RE cycles refer to the series of processes that take place within the engine to convert fuel into energy and propel the rocket.

The kinetic energy of a RE is produced by converting pressure and heat inside the Combustion Chamber (CC). This is accomplished through a de Laval nozzle, also known as a convergent-divergent nozzle, which transforms high-pressure, hot subsonic gas into low-pressure, cool supersonic gas. The complexity lies in the dual task of sustaining high pressure and temperature within the engine, all while effectively navigating the challenges associated with heat management. The greater the temperature within the CC, the more advantageous the result, due to the direct relationship between heat and energy. A term related to the performance of a RE is enthalpy, which is the sum of all energy contained within

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a system and consists of the volume times the pressure and its internal energy, which includes heat and microscopic kinetic energy. The higher the enthalpy of a system, the more potential it has to perform work.

$$\text{Enthalpy} = \text{Internal Energy} + (\text{Pressure} \times \text{Volume})^2.$$

The governing principle here is the movement of pressure from high to low, and in the specific domain of REs, this underscores the necessity of preserving high pressure within the CC. The aim is to facilitate the swift expulsion of exhaust gases.

The three most common RE cycles are:

1.1 Solid Rocket Engine Cycle

These use solid fuel that is packed into a casing. When ignited, the solid fuel burns and produces hot gases, which are through a nozzle to create thrust. Solid REs are relatively simple and reliable, but they cannot be turned off once ignited[3].

1.2 Liquid Rocket Engine Cycle

These use liquid propellants, such as liquid hydrogen and oxygen, which are stored in separate tanks and then mixed to produce a chemical reaction that generates thrust. Liquid RE are highly efficient and can be throttled or turned off as needed, but they are more complex and expensive than solid RE[4].

1.3 Hybrid Rocket Engine Cycle

It incorporates components from liquid and solid RE. They use a solid fuel, but the oxidiser is a liquid or a gas. The fuel and oxidiser are kept separate until they are injected into the engine, where they combine and ignite. Hybrid RE offer some of the advantages of both solid and liquid RE, but they are still in the experimental stage and have not yet been widely used.

RE being a broader topic. This paper will focus on Liquid RE, mainly consisting of cold gas thrusters, pressure-fed engines, electric pump-fed engines, gas generator engines, staged combustion engines, tap-off engines and expander engines.

2.0 Cold Gas Thrusters

A cold gas propulsion system that creates thrust through the expansion of pressurised gas, which is typically an inert substance. It consists of a fuel tank, propelling nozzle, regulating valve and plumbing[5]. They are considered for their simple design along with affordability, ease of use and reliability. These factors make it the perfect choice for small-scale space missions that demand clean operation, as well as for orbital maintenance, manoeuvring, and attitude control. The term 'cold gas thruster' is derived from the fact that no chemical reaction takes place during their operation. Instead, these engines utilise the simple expansion of a pressurised gas to generate thrust, as shown in Figure 1[6]. This is achieved by storing a propellant in a high-pressure tank and releasing it through an engine nozzle. The decrease in temperature during the expansion of the gas is known as the Joule-Thomson effect. The basic principle behind cold gas thrusters is that of a simple RE, where the stored propellant is released through an open valve[7].

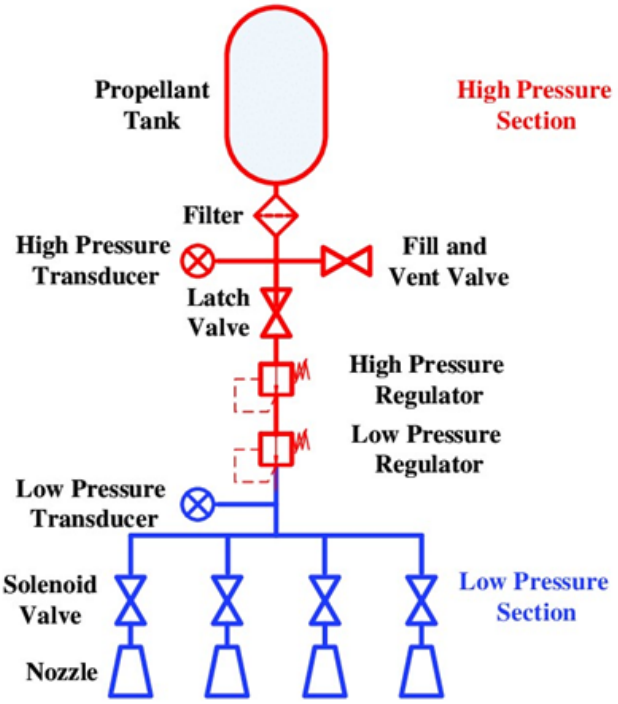


Figure 1. Cold gas thruster [10].

The absence of combustion in a cold gas thruster offers several advantages, such as the ability to operate in areas where conventional liquid RE would overheat, thus eliminating the requirement for heat control systems. Its compact design also makes it suitable for missions with limited volume and weight requirements, and its inexpensive fuel and simple design contribute to a lower risk of failure compared to traditional RE[8]. Additionally, the fuels used in

a cold gas system are safe to handle before and during engine firing. The cold gas system also eliminates the buildup of electrical charges on the spacecraft during operation, and requires minimal electrical energy to operate, especially useful when a spacecraft is in a planet's shadow[9].

However, there are also some limitations to using a cold gas thruster. Due to its lack of combustion, it cannot produce the high thrust achievable by combustive RE, and is less mass efficient. Furthermore, its maximum thrust depends on the pressure in the storage tank, which decreases as the fuel is depleted[10].

3.0 Pressure-Fed Engines

After cold gas thrusters, the pressure-fed RE, as shown in Figure 2, is the simplest form of RE. Like cold gas thrusters, it has minimal moving parts. Additionally, it has an extra gas tank that pressurises the propellant to ensure sufficient flow. The startup procedure conventionally begins with the opening of a valve, with the option of utilising a one-shot pyrotechnic device for assistance. This facilitates the flow of pressurising gas through check valves into the propellant tanks. Pressure-fed engines can be broadly categorised into two types: monopropellant and bipropellant pressure-fed engines.

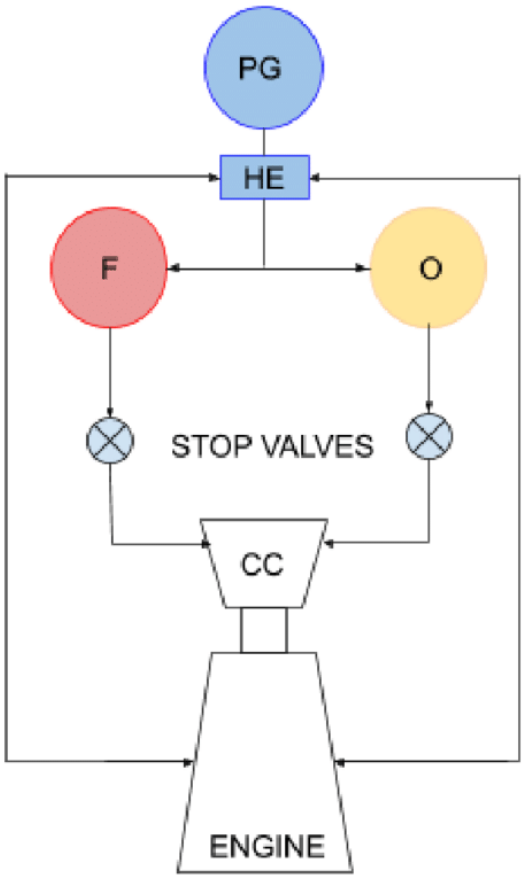


Figure 2. Pressure-fed engine[11].

3.1 Monopropellant Pressure-Fed Engines

These engines represent a decomposition-based chemical propulsion system. In this configuration, stored propellant is directed over a catalyst bed, initiating exothermic decomposition. The resulting chemical energy release produces a high-temperature gaseous medium, which can be released via a nozzle to produce thrust. Hydrazine, a longstanding monopropellant utilised in rocketry since the 1930s, is emblematic of this technology. However, its extensive use is accompanied by its notoriety for extreme toxicity, carcinogenicity, corrosiveness, flammability, and explosiveness.

Monopropellant pressure-fed engines have several advantages. Their simple design, with fewer parts compared to other RE designs, makes them easier to manufacture and maintain. They are also safe and reliable due to their simple design and lack of fuel and oxidiser mixing[12]. Compared to other RE designs, monopropellant pressure-fed engines are comparatively cheap to create, produce and run. They may also have a reduced risk of leaks as they only require a single propellant.

However, monopropellant pressure-fed engines also have some disadvantages. They are not as efficient as other RE designs due to the lower specific impulse. Monopropellant pressure-fed engines tend to produce lower thrust compared to other RE designs, which makes them unsuitable for high-performance missions. They are generally limited in application to smaller, simpler rockets and satellite propulsion systems. Additionally, the range of propellants that can be used in monopropellant pressure-fed engines is limited due to their design, which can limit their performance and versatility.

Monopropellant pressure-fed engines are commonly used in small spacecraft and satellites for attitude control, trajectory correction, and small velocity changes. They are also used in the final stages of rocket launches for small attitude control adjustments. These engines are generally not used for high-performance missions, such as deep space exploration, due to their lower efficiency and thrust compared to other RE designs.

3.2 Bipropellant Pressure-Fed Engines

These engines are similar to monopropellant engines. The only difference is that bipropellant engines use two different propellants: an oxidiser and a fuel. Propellants are stored separately and fed into the CC under pressure, where they react to produce a high-temperature and pressure exhaust gas that is expelled out of the nozzle to create thrust. The two propellants are typically stored in separate tanks and are fed into the CC by a single valve that regulates the flow of each propellant into the engine. The fuel and oxidiser mix and react in the CC, producing hot gases that are accelerated out of the nozzle to create thrust. The high-pressure feed system is typically powered by an inert gas, such as helium or nitrogen, that pressurises the propellant tanks and forces the propellants into the CC[13]. The use of two separate propellants in bipropellant pressure-fed engines allows for a higher specific impulse and greater thrust compared to monopropellant engines. Additionally, the choice of propellants can be optimised for specific mission requirements. Examples of bipropellant systems include combinations like RP-1 and LOx, or CH4 and LOx. Many bipropellant systems opt for hypergolic propellants due to their simplicity, as these propellants spontaneously combust upon contact with each other.

Bipropellant pressure-fed engines offer several advantages over monopropellant engines. One of the main advantages is their high efficiency and specific impulse. Specific impulse is a measure of how effectively a rocket uses its propellant to create thrust. Bipropellant engines typically have a higher specific impulse than monopropellant engines, meaning they can generate greater thrust for a given amount of propellant. This makes them suitable for a wide range of missions, as they can achieve high levels of thrust and efficiency. Additionally, bipropellant engines are highly controllable and versatile, allowing for precise adjustments to thrust and performance. These benefits make bipropellant engines a popular choice for spacecraft and rocket applications.

However, bipropellant engines have some disadvantages. They have a more complex design than monopropellant engines, which can make them more difficult and expensive to manufacture and maintain. Bipropellant engines also carry the additional risk of oxidiser-fuel mixing, which can be dangerous and requires careful handling and safety measures. Leakage is also a risk with bipropellant engines due to the additional connections and valves required for the fuel and oxidiser.

It's crucial to recognise that achieving orbit solely with pressure-fed engines is practically impossible, given their constrained overall performance. Despite advancements in technology, including features like carbon composite tanks, bipropellant pressure-fed engines remain limited in their ability to provide substantial thrust and efficiency. This is why they are typically used in conjunction with other RE technologies, such as staged combustion engines, to provide the necessary thrust to reach orbit.

Despite their limitations, bipropellant pressure-fed engines are still widely used in a variety of spacecraft and rocket applications, including launch vehicles, upper stages, and spacecraft propulsion systems. Their ability to achieve high thrust and efficiency makes them suitable for a range of missions, but their more complex design and additional safety risks mean that they are typically more expensive to develop and manufacture compared to monopropellant engines.

4.0 Electric Pump-Fed Engine Cycle

Gases and fluids can only naturally flow from high pressure to low pressure. To achieve a higher chamber pressure without increasing the propellant tank pressures, rockets need an active mechanism to force the propellants against nature. This is where pumps come in. An electric pump-fed engine cycle (Figure 3) allows the propellants, typically Liquid Oxygen (LOX) and kerosene, to be stored in separate tanks and fed into the CC under high pressure, without the need for an extremely high tank pressure[14]. The electric motor drives the fuel and oxidiser pumps, which pressurise and deliver the propellants to the CC at a constant flow rate, resulting in high efficiency and precise control[15].

The Electric Pump-Fed Engine Cycle has several advantages, such as its high efficiency and controllability[16]. The electric motor is highly efficient and provides a constant and precise flow of propellants, resulting in a high specific impulse. Additionally, the electric pump-fed cycle is highly controllable, allowing for precise adjustments to thrust and performance. Another advantage is the simplicity of the electric motor and pump system, which requires less maintenance and is more reliable than other cycles with more components that can fail[17].

However, the Electric Pump-Fed Engine Cycle also has limitations, such as the added weight of various

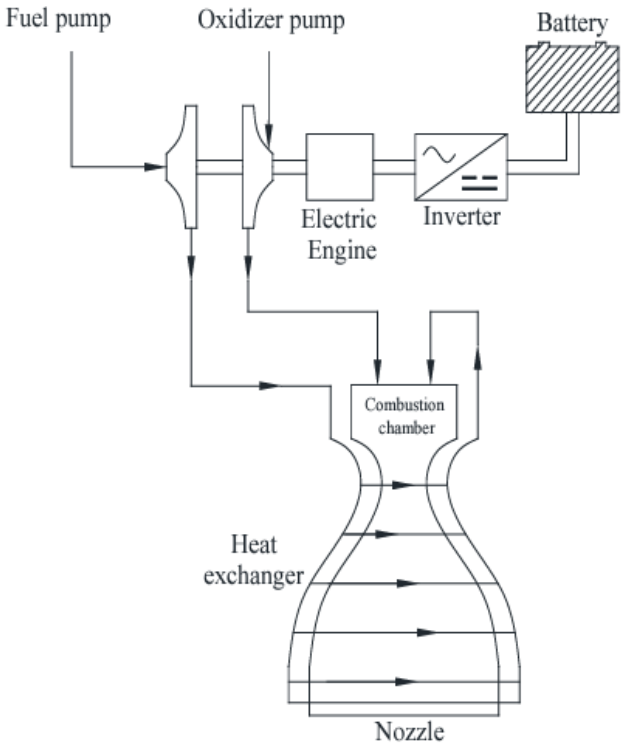


Figure 3. Electric pump-fed rocket engine cycle[14].

components and the complexity of the electric motor and pump system, which can reduce the overall performance of the rocket. Additionally, a reliable and robust power source is required to operate the system, which can add complexity to the rocket[14].

Electric pump-fed engine cycles are commonly used in various launch vehicles, upper stages, and spacecraft propulsion systems where high thrust and efficiency are necessary, and the added complexity and cost of the electric pump-fed engine cycle can be justified[18]. However, they may not be suitable for all applications, and other types of RE cycles may be more suitable depending on specific mission requirements and constraints.

5.0 Gas Generator Rocket Engine

It works by using a small portion of the propellant to generate hot gases, which are then used to drive the turbine that powers the engine's fuel and oxidiser pumps. The rest of the propellant is then burned in the CC, producing thrust to propel the rocket.

The gas-generator cycle typically consists of three main components: the CC, the gas generator, and the turbine[19]. The CC is where the main propellants are burned, producing high-pressure, high-temperature gases that are directed through a nozzle to create thrust. The gas generator is a small chamber that burns a small amount of the propellants, producing hot gases that are used to drive the turbine. The turbine is connected to the fuel and oxidiser pumps and uses the hot gases from the gas generator to spin, providing the power to pump the main propellants into the CC.

During operation, a small amount of the propellants is routed to the gas generator, where they are burned like in the main CC (Figure 4). This generates high-pressure, high-temperature gases that flow through a nozzle to spin the turbine[20]. The turbine is connected to the fuel and oxidiser pumps, which are driven by the turbine's rotation. This pumps the rest of the propellants into the CC, where they are burned to produce thrust.

The gas generator engine cycle has several advantages and disadvantages. One of its main advantages is its high thrust-to-weight ratio, which is due to its relatively simple design and high combustion efficiency. This makes it an attractive choice for rocket propulsion systems where a high thrust-to-weight ratio is necessary. Additionally, the gas generator engine cycle can achieve high specific impulse by optimising the CC and nozzle design, which results in a higher exhaust velocity and increased efficiency. Another advantage of the gas generator engine cycle is its good controllability. The ability to control the flow of fuel and oxidiser to the CC allows for precise adjustments to thrust and performance. In addition, the gas generator engine cycle can be restarted multiple times during a single mission, making it ideal for use in upper stages and spacecraft.

However, the gas generator engine cycle has some disadvantages as well. One of its main disadvantages is its lower efficiency compared to other engine cycles. This is because a portion of the propellant needs to be used to drive the turbine that powers the fuel and oxidiser pumps. Additionally, the gas generator engine cycle has a relatively complex design that can lead to increased manufacturing and maintenance costs. Another disadvantage of the gas generator engine cycle is that it operates at high temperatures and pressures, which can lead to increased wear and tear on engine components and a shorter engine life. Finally, the gas generator engine cycle has more components than some other engine cycles, which can increase the likelihood of failure and reduce overall reliability. Despite its disadvantages, the gas generator

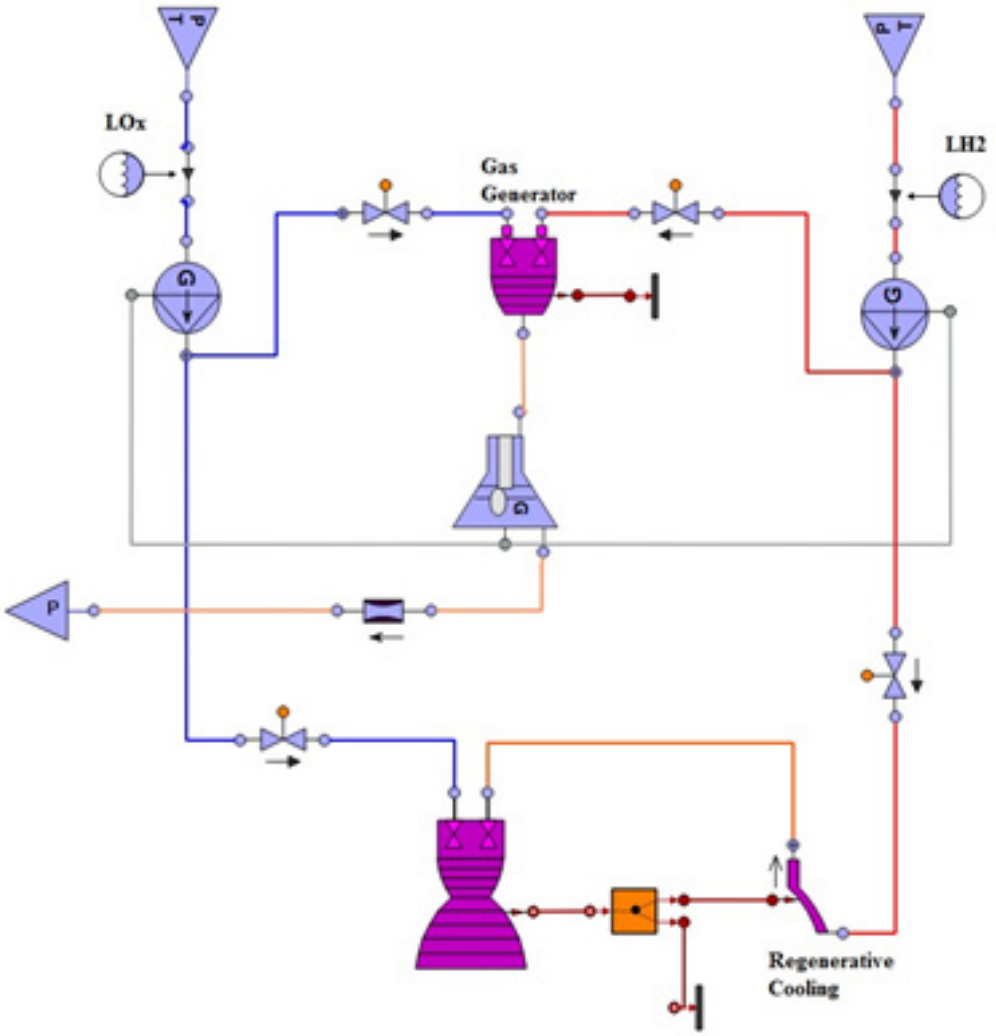


Figure 4. Schematic of gas generator cycle[22].

engine cycle is still commonly used in various launch vehicles and spacecraft propulsion systems, particularly for its high thrust-to-weight ratio and controllability.

The gas generator engine cycle is a widely used engine cycle due to its high thrust-to-weight ratio, good controllability, and ability to be restarted multiple times. However, its complex design, lower efficiency, and reliability issues must be taken into consideration when choosing an engine cycle for a specific mission[21].

6.0 Staged Combustion Engine Cycle

This cycle involves the full combustion of fuel and oxidiser in separate stages, allowing for high efficiency and high specific impulse[23]. The cycle typically involves two combustion stages: a preburner stage and a main combustion stage. In the preburner stage, a small quantity of fuel and oxidiser are burned to generate high-pressure, high-temperature gases that drive the turbine and pump the propellants into the main CC (Figure 5). In the main combustion stage, the rest of the fuel and oxidiser are burned to produce high-pressure, high-temperature gases that create thrust[24].

Staged combustion engine cycles have several advantages, including high efficiency, high specific impulse, and high thrust-to-weight ratios. Because the fuel and oxidiser are fully burned in the engine cycle, staged combustion engines can achieve high combustion efficiency, resulting in higher specific impulse and

better fuel economy compared to other engine cycles. Additionally, staged combustion engines typically have a high thrust-to-weight ratio due to their optimised design and efficient use of propellant.

However, staged combustion engines also have some disadvantages. The main challenge is the complexity of this engine cycle, which can lead to increased manufacturing and maintenance costs. Additionally, staged combustion engines operate at very high temperatures and pressures, which can result in increased wear and tear on engine components and reduced engine life. Furthermore, staged combustion engines are highly dependent on the precise control of fuel and oxidiser flows, which can pose challenges in maintaining engine stability and reliability.

Overall, staged combustion engine cycles offer a highly efficient and effective means of rocket propulsion, but their complexity and maintenance requirements must be carefully considered when designing propulsion systems for space missions.

They can be further bifurcated into three types based on design.

6.1 Oxygen-Rich Staged Combustion Engine Cycle

A type of RE cycle that uses a staged combustion process to burn fuel and oxidiser to generate thrust. In this, a fuel-rich preburner burns a small amount of the fuel with a larger amount of oxidiser to generate hot gases that are then used to drive the engine's turbopumps[25]. The remaining oxidiser and fuel are then mixed and burned in the main CC to generate thrust. This process is called staged combustion because the oxidiser and fuel burn in separate phases. An oxygen-rich staged combustion engine is considered to be highly efficient because it burns a larger portion of the propellants, leading to increased specific impulse and better fuel economy in comparison with other engine cycles.

6.2 Fuel-Rich Staged Combustion Engine Cycle

The pre-burner is designed to operate with excess fuel, meaning that there is more fuel than can be burned with the available oxygen[26]. This produces a mixture of unburned fuel and partially combusted gases, which are then directed into the main CC. The remaining oxidiser in the main CC reacts with the unburned fuel and partially combusted gases, producing high-temperature, high-pressure gasses[18].

6.3 Full-Flow Staged Combustion Engine Cycle

A kind of staged combustion engine that uses both fuel and oxidiser at high pressure and temperature to drive turbines and produce thrust. In this engine cycle, all of the fuel and oxidiser are used in the combustion process, and there is no bypass of any propellant. During operation, the fuel and oxidiser are pumped into the preburner, where they are ignited and burned at high pressure and

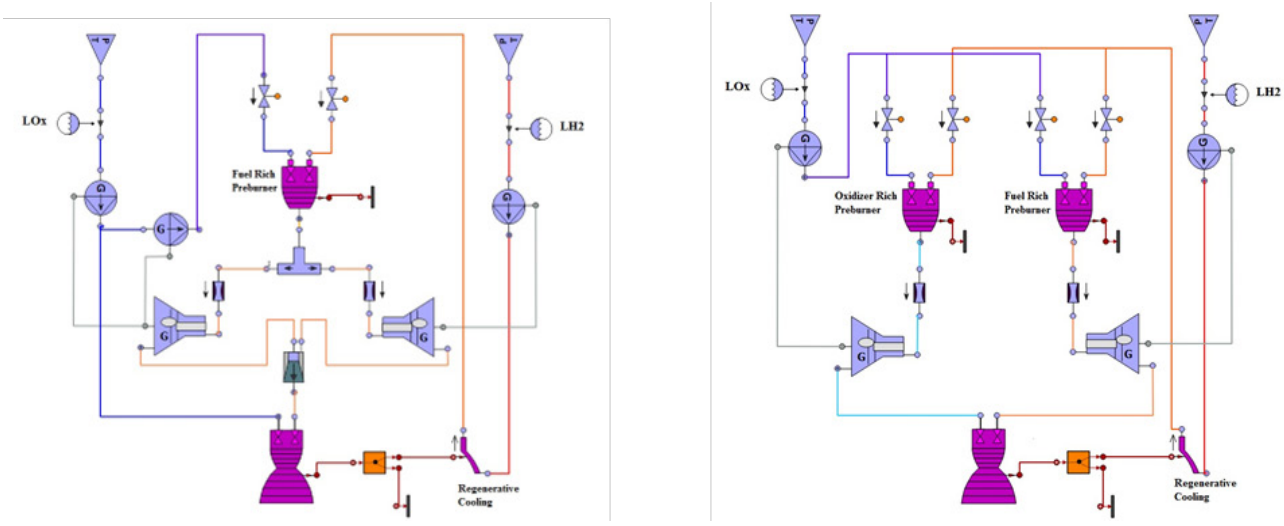


Figure 5. Fuel-rich and full flow staged combustion cycle[28].

temperature. The hot exhaust gases from the preburner are then directed through a turbine, which extracts energy to drive the fuel and oxidiser pumps. After passing through the turbine, the exhaust gases are directed into the main CC, where they mix and burn with additional fuel and oxidiser to produce high-pressure, high-velocity exhaust gases that exit the engine through the nozzle to produce thrust[27].

7.0 Tap-Off Engine Cycle

A tap-off engine cycle is shown in Figure 6. It uses a unique method to extract hot gases from the CC, which allows for more efficient and powerful RE. A portion of the fuel and oxidiser is combusted in the main CC, while the rest is diverted to a separate area called the tap-off point. At the tap-off point, a small amount of fuel and oxidiser are ignited to generate high-pressure, high-temperature gases. These gases are then fed into the turbine, which drives the engine's pumps and generators, before being vented out through the nozzle to provide additional thrust. Meanwhile, the remaining fuel and oxidiser are burned in the main CC to generate the majority of the engine's thrust. The tap-off cycle offers several advantages over other engine cycles, including high efficiency and high specific impulse. The efficient use of hot gases from the tap-off point allows for more complete combustion of fuel and oxidiser, which results in a higher specific impulse and better fuel economy. Additionally, the tap-off cycle enables the engine to operate at higher chamber pressures, which leads to a higher thrust-to-weight ratio and greater performance[29]. To manage the high temperatures and pressures generated in the CC, tap-off engines use advanced cooling systems to protect the engine components from damage. These systems typically involve circulating fuel or coolant through channels in the engine walls, which absorbs and dissipates heat before being recirculated through the engine. In some cases, the cooling system may also involve injecting coolants or propellants directly into the CC to reduce temperatures and improve engine performance.

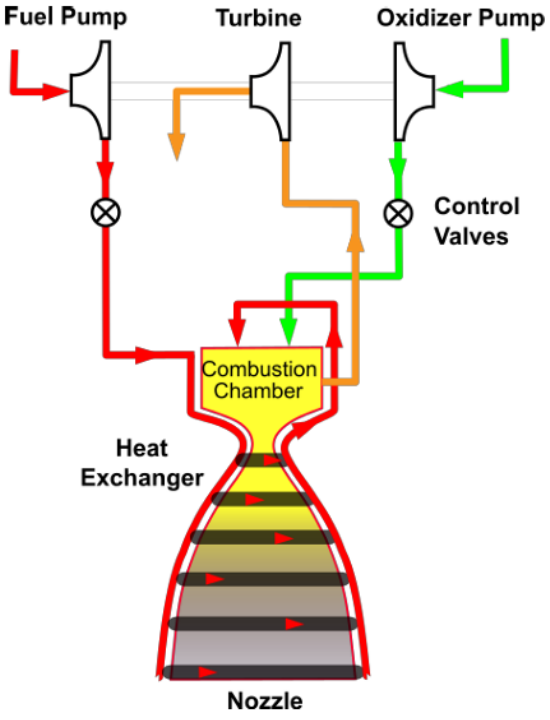


Figure 6. Combustion tap-off cycle[30].

The tap-off engine cycle has several benefits, such as high specific impulse, better fuel economy due to high combustion efficiency, reduced complexity, and longer engine life. However, it also has some limitations, including the need for sophisticated thermal management systems, lower thrust-to-weight ratios than staged combustion engines, and the potential for erosion of turbine blades and nozzles due to the oxidiser-rich turbine exhaust. Moreover, the tap-off cycle engine is not ideal for all mission types and is generally used for lower thrust applications.

8.0 Expander Engine Cycle

This uses a heat exchanger to extract energy from the exhaust gases and drive a turbine that drives the pumps of the engine. Fuel and oxidiser are burned inside the CC, generating hot exhaust gases. These gases are then passed through a heat exchanger, where they transfer heat to a coolant, such as fuel or liquid hydrogen. The coolant then expands, driving a turbine that powers the engine's pumps, which feed the propellants back into the CC (Figure 7). The exhaust gases, now cooled by the heat exchange, are released from the nozzle to generate thrust[31].

Among the primary benefits of this cycle is its high efficiency, which results from the efficient use of exhaust gas heat to drive the turbine. The expander cycle also has a relatively simple design compared to other engine cycles, which can lead to reduced manufacturing and maintenance costs. Additionally, the expander cycle can be used for various types of missions and propulsion needs, allowing it to be a flexible option for RE[32]. The

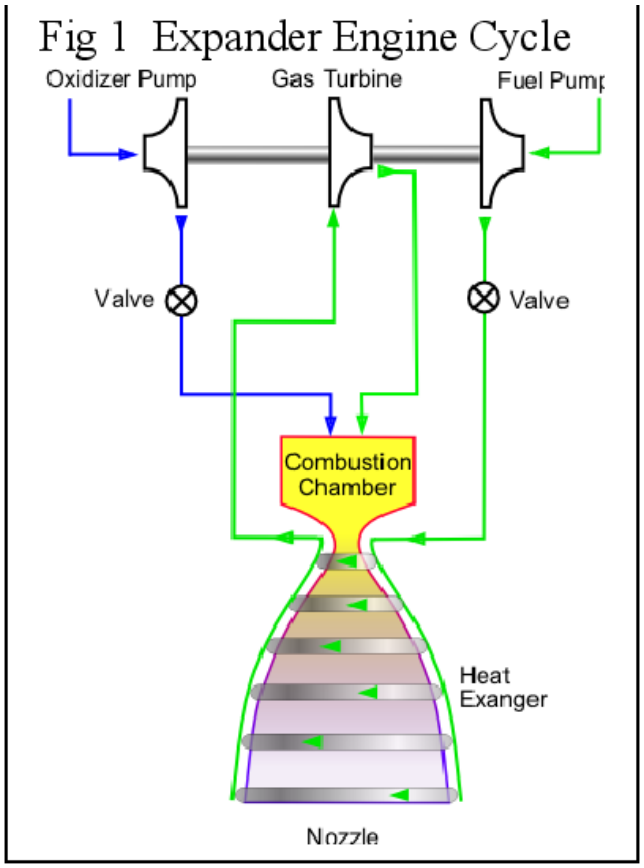


Figure 7. Expander engine cycle[9].

main limitation of this is the potential for thermal stress on engine components due to the high temperatures and pressures generated in the CC. Additionally, this cycle typically has a lower thrust-to-weight ratio than other engine cycles, which can limit its use for high-thrust applications. To address these challenges, expander engine cycles use advanced cooling systems to manage the high temperatures and pressures generated in the CC. These systems typically involve circulating coolant through channels in the engine walls, which absorb and dissipate heat before being recirculated through the engine. Overall, the expander engine cycle offers a balance of efficiency, simplicity, and versatility, making it a valuable option for rocket propulsion systems.

Expander engine cycles are primarily used in upper stages of rockets, where high specific impulse and efficient propulsion systems are required. They are also used in small to medium-sized launch vehicles. In addition, expander engine cycles are used in some satellite propulsion systems and other applications, like space probes, deep space missions, *etc*.

9.0 Conclusion

In conclusion, RE cycles are the heart of a rocket propulsion system, and play a critical role in determining the performance, efficiency, and reliability of the engine. The choice of engine cycle depends on a number of factors, including the specific mission requirements, the desired performance characteristics, and the available resources and technology.

The most common types of RE cycles include pressure-fed cycles, electric pump-fed cycles, open cycle, closed cycle, staged combustion cycle, and expander cycle, among others.

Cold gas thrusters offer a cost-effective and reliable solution for small-scale space missions, particularly those that require a contaminant-free operation and low heat output. Monopropellant pressure-fed engines have a simple design and are safe and reliable. However, they have lower efficiency and thrust compared to other RE designs, limiting their use to smaller and simpler rockets and satellite propulsion systems. They are commonly used for altitude control and small velocity changes in spacecraft and rockets. Bipropellant pressure-fed engines use two separate propellants to generate high levels of thrust and efficiency. They offer several advantages over monopropellant engines, such as greater specific impulse and precise control over performance. However, their more complex design and additional safety risks make them more expensive to manufacture and maintain. Despite their limitations, they are widely used in spacecraft and rocket applications but are typically combined with other engine technologies to achieve the necessary thrust to reach orbit. The electric pump-fed engine cycle uses pumps to force propellants into the CC under high pressure, resulting in high efficiency and precise control[33]. However, the added weight and complexity of the system can reduce overall rocket performance, and it may not be suitable for all applications[19]. Future advancements in battery systems and electric motors could help reduce the weight of the system[19]. The gas generator engine cycle is a propulsion system used in RE that provides a high thrust-to-weight ratio, good controllability, and the ability to be restarted. However, it has lower efficiency, operates at high temperatures and pressures, and has a complex design,

which can affect its reliability and increase manufacturing and maintenance costs. Staged combustion engine cycles provide high efficiency, specific impulse, and thrust-to-weight ratios by fully combusting fuel and oxidiser in separate stages. However, their complexity and high temperatures and pressures pose challenges and require careful consideration for space mission propulsion systems[34]. Further advancement in material science and advances in additive manufacturing can help improve the engine. The tap-off engine cycle extracts hot gases from the CC and diverts them to drive the engine's pumps and generators, resulting in a highly efficient and powerful RE. Although it requires advanced thermal management and has lower thrust-to-weight ratios than staged combustion engines, it offers better fuel economy, reduced complexity, and longer engine life. The expander engine cycle uses a heat exchanger to drive a turbine and generate thrust. It is highly efficient and versatile, but can be limited by thermal stress and a lower thrust-to-weight ratio. It is used primarily in upper stages of rockets and modest to moderate-sized launchers.

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