A Review on Bi-Propellant Engines

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Abstract - *Bipropellant rocket engines have been playing a vital role in space vehicle launches and advancements in space exploration. This paper mainly focuses on providing a brief analysis of Bi-propellant engines, their essential components, the types of engine cycles, and the cryogenic engine. The paper begins by discussing the propellant-feed mechanism, giving a detailed review of each type of rocket engine cycle, their limitations, a brief look at the cryogenic engine, and what makes it take the edge over normal rocket engines and its challenges.*

Key Words: gas generator, pre-burner, turbine efficiency, multi-stage turbopumps, twin shaft, inter-propellant turbine seal, backflow, thermal shock, pre-chill.

1. INTRODUCTION

A Bipropellant rocket engine utilizes two different propellants to generate high thrust and propel spacecraft beyond the sky. Knowing and understanding the challenges and advancements of these engines are necessary to improve their reliability and efficiency.

One of the primary advantages of the bi-propellant engine is its ability to create high specific impulse and its greater efficiency to convert chemical energy into kinetic energy. There is a lot of flexibility in changing performance and reliability within themselves, which can be achieved by simply changing the combination of fuel, and oxidizer and changing the engine cycle.

The processes that happen inside the engine are mainly based on the principle of pressure gradient force, which states that any fluid naturally will travel from high-pressure regions to low-pressure regions.

2. Propellant-fed mechanism

A propellant-fed mechanism's role is to ensure that the propellants reach the combustion chamber. As we know, fluid flow always occurs from the high-pressure region to the low-pressure region. This means that the pressure in the propellant storage should be higher. The higher the pressure in storage tanks, the thicker should be the walls of the tank, which intern makes it heavier and one of the worst enemies of any launch vehicle is weight. To avoid the issue of extra weight that heavier tanks cause and to make sure the propellants enter the combustion chamber with high pressure, comes the play of the propellant feed mechanism. Other reasons why we need propellant to have high pressure are

1) increased flow rate: which helps in achieving high thrust and specific impulse.
2) Prevent cavitation: when the fluid travel through pipes at faster rates there is a tendency to form air bubbles which can cause an efficiency drop by interrupting the combustion process. These bubble formations don't occur when the fluid is highly pressurized.

There are two types,

1. **Pressure-fed**: it uses inert gases stored in small highly pressurized tanks to push the propellants from their tanks.
2. **Pump-fed**: it uses motor pumps to pull the propellants and pressurize them to drive into the combustion chamber.

3. BIPROPELLANT ROCKET ENGINE:

A bipropellant rocket engine uses two propellants as its name suggests. Which are fuel and oxidizer. These are stored in separate tanks and get mixed in the combustion chamber at the times of combustion. Generally, bi-propellant rocket engines are far more efficient and provide better performance than mono-propellant engines. So, bipropellant engines are most commonly used in space applications and launch vehicles compared to monopropellant engines.

- 3.1 Pressure fed
- 3.2 Pump fed
  - 3.2.1 Electric pump fed
  - 3.2.2 Open cycle or Gas generator cycle
  - 3.2.3 Closed cycle
    - 3.2.3.1 Closed cycle (oxidizer-rich)
    - 3.2.3.2 Closed cycle (fuel-rich)
    - 3.2.3.3 Full-flow staged combustion
  - 3.2.4 Combustion tap-off cycle
  - 3.2.5 Expander cycle

3.1 Pressure-fed Bipropellant engine

In this type of engine, the two propellant tanks i.e., the fuel tank and oxidizer tank are connected to two different highly pressurized tanks which are filled with an inert gas, generally, Helium to make sure that these pressurized fluids don't interact with the fuel or oxidizer which may affect the combustion process.

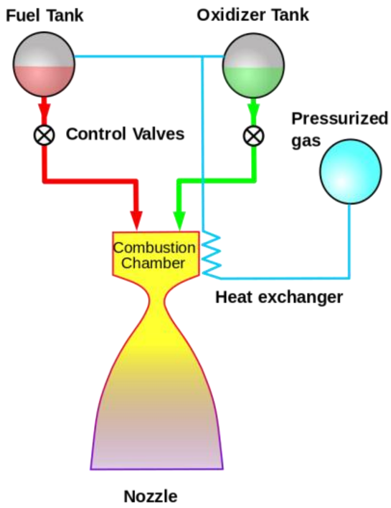

Fig -1: Pressure-fed rocket engine

Before the start of the engine the valves of the two pressurized Helium tanks are opened to pressurize the propellant tanks. After the propellant tanks reach the required amount of pressure, then the valves of the propellant tanks are opened to pass down the propellants to the combustion chamber.

The main constraint here comes in the form of the amount of pressure the pressurized Helium tanks can provide, which is limited.

Example:

1) Orbital maneuvering system (OMS) engine in the space shuttle.
2) Upper stage of SpaceX Falcon 1, powered by Kestrel engine.
3) SpaceX Draco and superDraco engines.
4) Second stage of Delta II launch vehicle, powered by AJ10 and TR-201 engines.

Table -1:

Engine name	stage	propellant	Thrust (N)	Specific impulse (s)
Kestrel	upper	RP-1/LOX	28,000 (vacuum)	317
SuperDraco	upper	NTO/MMH	32,000 (sea level)	235
AJ10	2nd	N_2O_4/Aerozine 50	43,700 (sea level)	316

3.2 pump-fed bipropellant engine

In this type of engine, the propellants are pumped to the combustion chamber from the propellant storage tanks using a pump.

3.2.1 Electric pump-fed Bipropellant engine

The amount of pressure that a pump can generate is a lot compared to the pressure that is created by the pressure-fed system and there is no need for us to pre-pressurize the propellant in the storage tanks themselves as they are pressurized by the pumps after they pass.

Here electric motors are used to run the pumps which are powered by batteries.

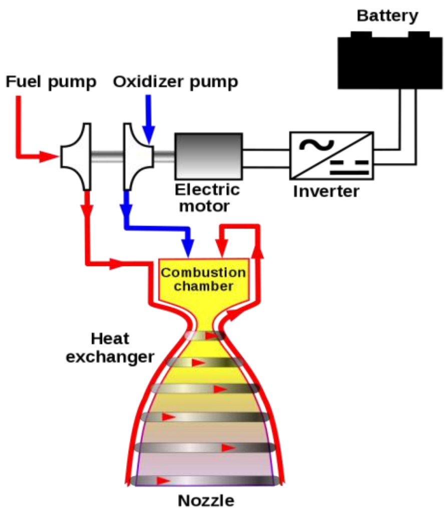

Fig -2: Electric pump-fed rocket engine

The limitation here is the amount of power that the motors required to run at that high rpm is very high. The more power it requires to run, the greater number of batteries or heavier batteries should be used which again can affect the performance of the launch vehicle by increasing the weight.

Example:

1) Rocket lab's electron rocket, powered by the Rutherford engine.
2) Astra Space's Rocket 3, powered by the Delphin engine.

Table -2:

Engine name	stage	propellant	Thrust (N)	Specific impulse (s)
Rutherford	1st	RP-1/LOX	25,000 (sea level)	311
Delphin	1st	Kerosene/LOX	28,000 (sea level)	

3.2.2 Open cycle or Gas generator cycle

As we said earlier the amount of pressure produced by a pump is huge. So, keep it in mind now we need to come up with some idea that makes the pump run at higher speeds without much investment in the power source that makes the launch vehicle comparably heavier. Here comes the gas generator which is a mini rocket engine that intakes quite a small amount (2 to 7 percent) of fuel and oxidizer from the main flow pipes that reach the combustion chamber.

As the fuel and oxidizer reach the gas generator, combustion starts with the help of a small igniter. The high-velocity, high-pressure exhaust gases of this gas generator are then flushed over the turbine to run at greater speeds. This turbine is again connected to a shaft which is connected to the fuel pump and oxidizer pump which drives their respective propellant into the main combustion chamber. This exhaust gas is again driven out into the atmosphere.

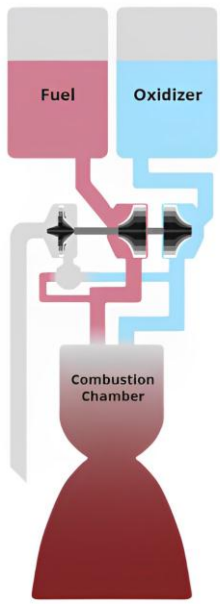

Fig -3: Gas generator cycle

Generally, the propellants that are fed to the gas generator have a large amount of fuel compared to the oxidizer making them a fuel-rich mixture. Because we would like to keep the temperature of the exhaust gas a bit low, as we don't want our turbine to melt away due to the large amount of heat that is produced while combustion. The amount of heat that a fuel-rich mixture produces is low compared to the oxidizer-rich mixture. As we know in a fuel-rich mixture there is not enough oxygen to completely oxidize the fuel, as a result, the amount of heat produced per unit of fuel is less.

Whereas in an oxidizer-rich mixture, the fuel is completely burnt as there is enough oxygen to oxidize the fuel completely, as a result, the amount of heat produced per unit of fuel is very high. So, we try to avoid using the oxidizer-rich mixture at the expense of the safety of the turbine.

One of the major disadvantages of the open cycle is the wastage of fuel in the form of fuel-rich exhaust gas from the gas generator. As we can see in the picture below, the exhaust from the outlet nozzle on the right side is the exhaust gas of the gas generator. It is in a black, sooty colour because of the unburnt carbon-based fuel present in the fuel-rich exhaust.

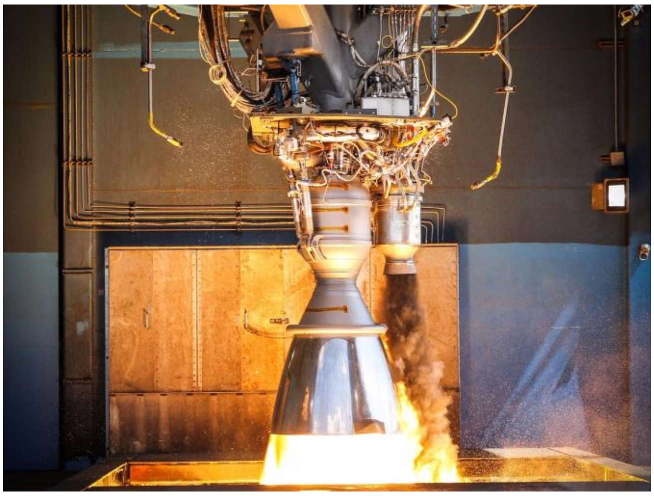

Fig -4: Merlin engine

Example:

1) Ariane 5 rocket, powered by Vulcain 2 engine.
2) Saturn 1B and Saturn V rockets, powered by J-2 engine.
3) SpaceX's Falcon 9 B5 rocket, powered by Merlin 1D FT engine.
4) Delta IV rocket, powered by RS-68A engine.

Table -3:

Engine name	stage	propellant	Thrust (N)	Specific impulse (s)
Vulcain 2	1st	LH2/LOX	939,500 (SL) 1,359,000 (vacuum)	318 (SL) 429 (vacuum)
J-2	2nd, 3rd	LH2/LOX	486,200 (SL) 1,033,100 (vacuum)	200 (SL) 421 (vacuum)
Merlin 1D FT	1st	RP-1/LOX	845,000 (SL) 914,000 (vacuum)	311 (vacuum)
RS-68A	1st	LH2/LOX	3,135,996 (SL) 3,558,577 (vacuum)	362 (SL) 411 (vacuum)

3.2.3 Closed cycle or Pre-burner cycle

As we saw in the earlier cycle, the amount of power that a gas generator produces to run the turbine is enormous. So, now we would further want to go and make the open cycle more efficient and reliable.

Closed cycle, as the name suggests we are interested in making a closed loop by redirecting the exhaust of the gas generator into the main combustion chamber to make use of the unburnt fuel. So, can we connect the gas generator exhaust pipe directly to the main combustion chamber? NO. Because there are quite a few consequences.

1) If we consider a fuel-rich mixture of RP-1 (Refined Petroleum-1), RP-2 (Refined Petroleum-2), or any carbon-based propellants, they produce soot when they are unburnt. This soot is heavy and dense which can cause clogging in the injectors and they can also get arrested on the walls of the main combustion chamber which reduces the efficiency of the engine by interrupting the flow. In worst-case scenarios, this clogging might even cause the engine to explode.

2) Another main reason is the low pressure in the turbine section. As we know the turbine extracts the energy from the exhaust gases of the gas generator, here the exhaust gases expand and lose pressure which is used to rotate the turbine. So, to increase the efficiency of the turbine by efficiently extracting energy from the exhaust gases the pressure difference between the upstream and downstream of the turbine should be high i.e., the pressure before crossing the turbine should be higher than the pressure after passing through the turbine. Hence the pressure in the exhaust pipe is generally lower. But in the main combustion chamber, the pressure is a lot higher. So, if we plug the exhaust pipe into the main combustion chamber the flow will be reversed, as a flow always tends to move from a high-pressure zone to a low-pressure zone.

In order to answer this question, scientists have come up with a solution by making either all of the fuel or all of the oxidizer pass through the gas generator. Now, here the gas generator is not only used to run the turbine but also is used for the preliminary combustion of the fuel and oxidizer mixture before it enters the combustion chamber. Hence, now the gas generator is called a pre burner because of the extra task it has acquired and due to the redirection of exhaust gas into the main combustion chamber.

Now the closed cycle is again categorized based on the type of propellant that passes through the pre-burner completely and enters the main combustion chamber through the turbine,

A) Closed cycle (oxidizer-rich)

B) Closed cycle (fuel-rich)

3.2.3.1 Closed cycle (oxidizer-rich)

As we said earlier the closed cycle engines are classified depending on the type of propellant that passes through the pre-burner and enters the main combustion chamber through the turbine. Now, for this cycle, we are considering the oxidizer as the propellant that passes completely through the pre-burner with a little fuel added to it to start the combustion. Which makes the propellant mixture entering the pre-burner, oxidizer-rich.

But we already know the behaviour of the oxidizer-rich mixture when combusted. It produces a vast amount of heat energy as the fuel is completely combusted and the amount of heat produced per fuel burnt is very high which may totally melt the pre-burner, turbine, or anything that comes in its way.

Now we are particularly interested in using the oxidizer-rich closed cycle, despite the fact that it can melt down the engine completely. We might even try cooling techniques such as regenerative cooling, film cooling, etc, but it just makes things more complex and add a few more challenges to the problem we want to solve. The most challenging part here is the highly reactive nature of the oxidizer. It straight up wants to react with anything in contact, even the cooling pipes. So, for now, the only solution that we have in our hands is to create an alloy that can withstand the brute heat that the oxidizer-rich mixture produces during combustion.

Suppose say that we have successfully created an alloy that can withstand this heat and now we are ready to go.

Coming to the pre-burner, all the oxidizer is now flowing through it and we just want to make sure that sufficient and just the right amount of fuel is passing along with the oxidizer in order to start the combustion. Because as we know, the oxidizer-rich mixture produces more heat. Even if you increase the amount of fuel passing through it, it remains oxidizer-rich and produces more heat when compared to the sufficiently right amount of fuel. To maintain the pre-burner at as minimal temperature as possible we only allow a sufficient amount of fuel to pass through it.

Fig 5-: oxidizer rich closed cycle

Now coming to the problem that we discussed earlier, which was about the low pressure after the exhaust gas expands and loses pressure to rotate the turbine. So, to make things work the exhaust pressure must be higher than that of the chamber pressure. For this to happen we need to compress the complete oxidizer that passes through the pre-burner to the maximum pressure which should remarkably be higher than that of the main combustion chamber.

What about the small amount of fuel that pairs up with the oxidizer while entering the pre-burner? Here we need to make sure that not all the fuel is compressed to its maximum limit. Because only a small fraction of fuel is entering the pre-burner which needs to be highly compressed and the remaining large portion of the fuel is compressed to a sufficient amount to run directly into the main combustion chamber. If we compress all the fuel in the fuel tank to its maximum pressure, not only in the pre-burner will the pressure be increased but also in the main combustion chamber. Which again leads us back to the same problem of reverse flow. So now we need a pump which can compress some fuel to the maximum and some fuel to just a sufficient amount.

In order to solve this issue, we have multi-stage turbo pumps. As the name suggests these turbo pumps have multiple stages of pumps. The propellant travels through a series of stages with each stage providing an extra boost in pressure. In this case, the fuel which is sent to the main combustion chamber is pumped only through a few stages, which are sufficient enough to get the required pressure, and the fuel which is sent to the pre-burner for pre-combustion is pumped all the way through the last pump to attain maximum pressure to make sure that the pressure after the turbine section has higher pressure compared to the main combustion chamber.

Now we are done solving our issue. The oxidizer-rich mixture has attained enough pressure which is higher than the pressure in the main combustion chamber and now more or less it is in a gaseous phase and with more energy due to the pre-combustion. As it is an oxidizer-rich mixture there still is a large quantity of unused oxidizer. This unused gaseous oxidizer in the oxidizer-rich mixture will now mix with the fuel from the fuel tank and starts combustion giving out an enormous amount of energy.

Example:

1) Energia rocket, powered by RD-170
2) Proton rocket, powered by RD-253
3) Vulcan and New Glenn rockets, powered by BE-4
4) Atlas III, V rockets, powered by RD-180

Table -4:

Engine name	stage	propellant	Thrust (N)	Specific impulse (s)
RD-170	1st	LOX/RP-1	7,250,000 (SL) 7,900,000 (vacuum)	309 (SL) 337 (vacuum)
RD-253	1st	N_2O_4/UDMH	1,470,000 (SL) 1,630,000 (vacuum)	285 (SL) 316 (vacuum)
BE-4	1st	CH_4/LOX	2,400,000 (SL)	339 (SL)
RD-180	1st	RP-1/LOX	3,826,555 (SL) 4,152,136 (vacuum)	311.9 (SL) 338.4 (vacuum)

3.2.3.2 Closed cycle (fuel rich)

In this case, the propellant that passes completely through the pre-burner and enters the main combustion chamber is the fuel. So now the pre-burner will run with a fuel-rich mixture as we are adding just the right amount of the oxidizer required to start the precombustion and rotate the turbine. We know from the earlier discussions that the fuel-rich mixture tends to create soot due to the presence of unburnt fuel if the fuel is based on long-chained carbons. So how possibly can we send this pre-combusted fuel-rich mixture directly into the main combustion chamber while it has a tendency to choke the injectors?

The answer is not to use fuels like RP-1 which have long chained carbon structure. Instead fuels like liquid hydrogen and liquid methane can be used. Based on the design requirements staged combustion engines can be classified as

1) single-shaft
2) twin shaft.

The single-shaft design consists of a single pre-burner and a single turbine that runs both the fuel and oxidizer turbopumps. Here the turbopumps and the turbine are located on the same shaft. It is a simple design that doesn't require the use of a lot of gears, bearings, and ceilings.

The twin-shaft design consists of dual pre-burners which are intern connected to their respective turbines and pumps. Each set of pre-burners and the turbines power the fuel and oxidizer turbopumps. It allows more flexibility as the fuel and oxidizer pumps can be controlled independently by setting up the amount of propellant passing through them.

As fuels with long chained carbons cannot be used, let us consider liquid hydrogen as the fuel and see the working of the Twin-shaft design as the single-shaft works the same as we saw in the oxidizer-rich closed cycle.

So now all the fuel in this cycle should pass through both the pre-burners. Here one pre-burner runs a fuel turbopump and another pre-burner runs an oxidizer turbopump. The fuel is passed into both the pre-burners separately along with the sufficient amount of oxidizer required to start the pre-combustion.

Even in this engine cycle, we face the same issue with the pressure. So, our goal should be that the pressure after the turbine section should be much greater than the pressure in the main combustion chamber. To attain that we need to pressurize the fuel to the maximum in this case.

Here comes another complication. We are here talking about pressurizing hydrogen fuel, which is the least heavy fuel and it has very low density. Because of these properties, it occupies a large amount of space in tanks and it is hard to pressurize. It requires a greater number of stages in the turbopump compared to the oxidizer to make it reach the required pressure. It is one of the main reasons why launch vehicles using liquid hydrogen fuel use twin-shaft designs for their engines.

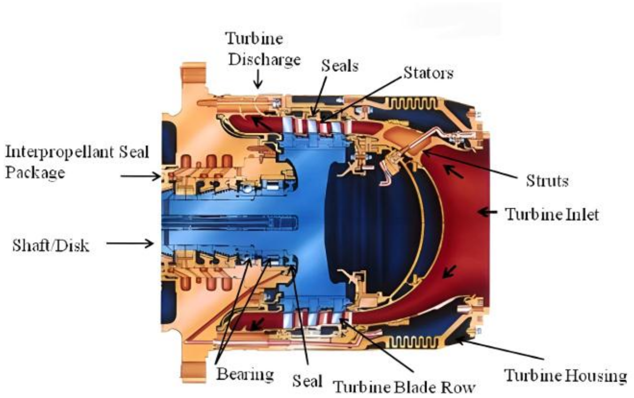

Fig 6-: Inter-propellant turbine seal

Low density and low weight are not only the issues with hydrogen. It has a lot of mobility and a piercing nature. Hydrogen tries to get into even the tiniest crack in the walls. Keeping this property in mind now let's look at the oxidizer turbopump. Here the pre-burner consists of a hot gaseous hydrogen-rich mixture. The turbine that runs with this exhaust gas lies on the same shaft as the oxidizer pumps. As we know for a shaft to rotate it should not be constrained completely and there should be at least a possible gap between the shaft and the wall. This is at most enough gap for the hot gaseous hydrogen to escape and reach the oxidizer pump to react with the oxidizer and cause an explosion. Here comes the role of inter-propellant turbine seal which prevents the leakage of propellant between stationary and rotating parts by sealing the gaps between them.

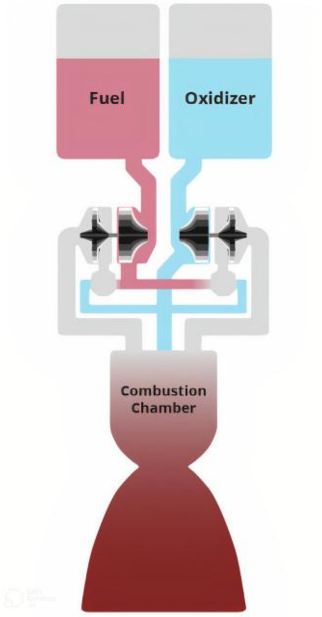

Fig 7-: Fuel-rich closed cycle

Firstly, the hydrogen is passed down into the fuel turbopump and goes through a series of turbopump stages. Then some of the pressurized hydrogen fuel passes into the pre-burner that runs the fuel turbopump and the remaining fuel is sent to the other pre-burner that runs the oxidizer turbopump. In the oxidizer turbopump, only a fraction of the oxidizer that mixes with the fuel is passed down to multiple stages to reach the pressure of the fuel. The remaining oxidizer that passes directly into the main combustion chamber just goes through only a few stages of turbopump to acquire sufficient pressure in order to avoid the backflow as far as possible.

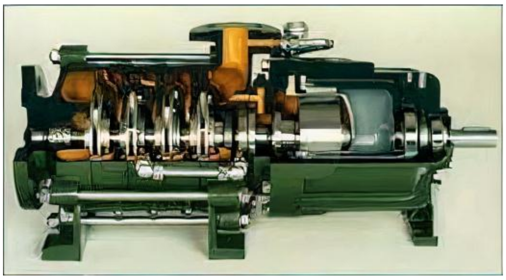

Fig 8-: Multi-staged turbopump

Now all the hot gaseous fuel-rich mixture from the pre-burners passes through their respective turbines and enters the main combustion chamber. There is still unburnt fuel in the pre-combusted fuel-rich mixture. It combines with the oxidizer that is pumped into the main combustion chamber to start the combustion.

Example:

1) space shuttle and SLS rocket, powered by RS-25 engine.
2) Energia rocket, powered by RD-0120 engine.
3) GSLV Mk1 rocket, powered by RD-56 (KVD-1) engine.

Table -5:

Engine name	stage	propellant	Thrust (N)	Specific impulse (s)
RS-25	1st	LH2/LOX	1,860,000 (SL) 2,279,000 (vacuum)	366.0 (SL) 452.3 (vacuum)
RD-0120	1st	LH2/LOX	1,526,000 (SL) 1,962,000 (vacuum)	353.2 (SL) 455 (vacuum)
RD-56 (KVD-1)	upper	LH2/LOX	69,626 (vacuum)	462 (vacuum)

3.2.3.3 Full-flow staged combustion

Now coming to the most complex engine cycle that ever existed. It is the combination of both the fuel-rich closed cycle and oxidizer-rich closed cycle. It is a twin-shaft staged combustion engine. Unlike single complete propellant passing through the individual pre-burners, in this cycle, both the fuel and the oxidizer pass through both the pre-burners respectively. Which makes propellant in one pre-burner fuel-rich and propellant in another pre-burner oxidizer-rich.

Here the oxidizer-rich pre-burner runs the oxidizer turbopump and the fuel-rich pre-burner runs the fuel turbopump. The oxidizer from the storage tank is first passed into the oxidizer turbopump completely to get pressurized and the pressurized oxidizer is sent to the oxidizer-rich pre-burner that runs the oxidizer turbopump and a fraction of oxidizer is sent to the fuel-rich pre-burner to start the pre-combustion that runs the fuel turbopump. Similarly, the fuel from the storage tank is passed into the fuel turbopump completely to get pressurized and the pressurized fuel is sent to the fuel-rich pre-burner that runs the fuel turbopump and a fraction of fuel is sent to the oxidizer-rich pre-burner to start the pre-combustion that runs the oxidizer turbopump.

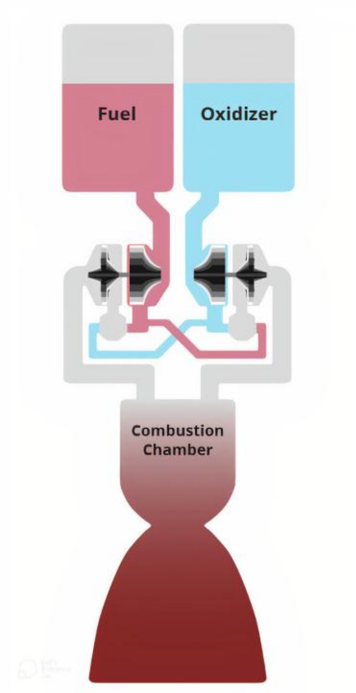

Fig 9-: Full-flow staged combustion cycle

As both the fuel and oxidizer enter their respective pre-burners for pre-combustion, the exhaust outcome from them will be a hot gaseous propellant mixture. So, from a fuel-rich pre-burner, the end outcome is a hot gaseous fuel-rich mixture, and from an oxidizer-rich pre-burner, the end outcome is a hot gaseous oxidizer-rich mixture.

In contrast to the situation in the fuel-rich closed cycle where there was an issue with hot gaseous hydrogen reaching up the oxidizer pump through the gap between the shaft and the wall, here there is no need to worry about it. Because the turbine that runs with a hot gaseous hydrogen-rich mixture lies on the same shaft as the hydrogen fuel turbopump. So, even if the hot gaseous hydrogen goes up the gap and meets the liquid hydrogen there won't be any reaction. A similar explanation is applicable to the oxidizer turbopump where the hot gaseous oxidizer-rich mixture runs the oxidizer turbopump. Hence there is no particular requirement for an inter-propellant turbine seal.

Generally, in the main combustion chamber of a fuel-rich closed cycle or an oxidizer-rich closed cycle, there will be an interaction between a hot gaseous fuel-rich mixture and a liquid oxidizer or hot gaseous oxidizer-rich mixture and liquid fuel. where the interaction is between liquid and gas. Unlike them, in the full-flow staged combustion cycle, the interaction is between the hot gaseous fuel-rich mixture and the hot gaseous oxidizer-rich mixture. The gas-gas interaction provides a faster chemical reaction and is very efficient.

Another important feature that makes the full-flow staged combustion cycle more efficient compared to other cycles is the workload on the pre-burner. This reduced workload and increased efficiency can be interpreted in two ways;

1) High mass flow rate.

2) Work distribution between the pre-burners.

In this cycle, the amount of mass flow is very high compared to other cycles. The mass flow that we are talking about is the propellant that passes through the pre-burners. Only in the full-flow staged combustion cycle both the fuel and oxidizer flow completely through the pre-burners, whereas in either fuel-rich closed cycle or oxidizer-rich closed cycle, only either of the propellants is passed completely through the pre-burners.

The efficiency also depends on the temperature difference between the upstream and downstream of the turbine. The turbine expands the flow that passes through it by extracting the energy. So, after the flow passes through the turbine the temperature of the flow decreases. The higher mass flow rate means the amount of gas passing through the turbine is more, which indicates that the temperature drop is gradual, which is a low-temperature difference. But the lower mass flow rate represents that the temperature drop is more rapid, which is a high-temperature difference. As we know the temperature difference is the driving force for a heat flow. The higher the temperature difference, the higher will be the heat transfer. The higher the heat transfer, the higher will be the heat load, which is considered as one of the biggest obstacles that should be avoided. This cycle has a low heat load in the turbine which means less energy loss for the pre-combusted gases before they enter the main combustion chamber and hence, has more efficiency.

Unlike the single shaft engine design where a single pre-burner runs both the oxidizer and fuel pumps, here twin shaft design is used where the workload is distributed between two pre-burners. A lesser workload means the amount of temperature required to do the same amount of work is less. Lesser the temperature in the pre-burner, the lesser will be the heat loss to the surrounding and the walls. The lesser the heat loss in the pre-burner, the more efficient it is.

The only disadvantage of that full-flow staged combustion cycle has been the complexity of making, maintaining, and using the engine. Because everything in this engine cycle is connected to one another. Even a small issue in one part of the engine might affect the working of the whole engine.

Examples:

Due to the complexity of making the engine, only a handful of these engines were made.

1) Starship rocket, powered by Raptor engine.
2) UR-700 (cancelled) and UR-900 (cancelled), powered by RD-270 engine.

Table -6:

Engine name	stage	propellant	Thrust (N)	Specific impulse (s)
Raptor	1st, 2nd	CH_4/LOX	2,640,000 (SL)	327 (SL) 350 (vacuum)
RD-270	1st	N_2O_4/ UDMH	6,270,000 (SL) 6,710,000 (vacuum)	301 (SL) 322 (vacuum)

3.2.4 Combustion tap-off cycle

As we know most of the pump-fed rocket engines have either gas generators or pre-burners to run the turbopumps. But the tap-off cycle doesn't have either of them, instead, they take the gas to run the turbine directly from the main combustion chamber and after running the turbine the flow is exhausted. It is made possible by making a connection from the main combustion chamber by using a pipe and routing it to the turbine. The high-pressure hot gases flow from the outlet and run the turbine.

It sounds simple when we say to use the hot gases from the main combustion chamber to run the turbine. But we are here talking about the hot gases which have their temperature around 3000 k. This is more than enough temperature to melt down the turbine. So, we need to cool down the hot gases coming from the outlet. To cool the gases down we can add extra fuel to it, but not oxidizer as it mixes to form an oxidizer-rich mixture which again causes high-temperature issues.

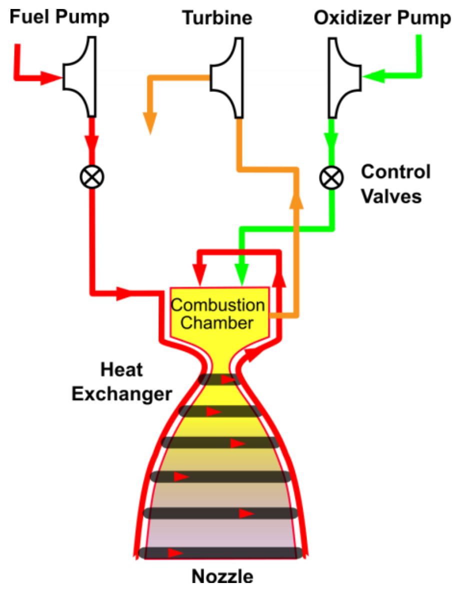

Fig 10-: Combustion tap-off cycle

To reduce the wastage of fuel in the process of cooling the incoming gas, we can consider taking the hot gases from the cooler parts of the main combustion chamber where the combustion gas is more likely to be fuel rich. This cycle is closely related to the open cycle or gas-generator cycle but with the absence of a gas generator.

One major disadvantage of this cycle is the loss of efficiency of the combustion chamber due to the extraction of combustion gas out through a hole.

Example:

1) New Shepard rocket, powered by BE-3 engine.
2) Alpha rocket, powered by Lightning 1 engine.
3) Alpha rocket, powered by Reaver 1 engine.

Table -7:

Engine name	stage	propellant	Thrust (N)	Specific impulse (s)
BE-3	1st	LH2/LOX	490,000 (SL) 710,000 (vacuum)	
Lightning 1	2nd	RP-1/LOX	70100 (SL)	322 (SL)
Reaver 1	1st	RP-1/LOX	184,000 (SL)	295.6 (SL)

3.2.5. Expander cycle

It goes into the same category as the tap-off cycle without requiring either gas generators or pre-burners to run the turbine. Here there is no need to worry about the performance loss of the main combustion chamber like in the tap-off cycle due to the outlet. As we know the walls of the main combustion chamber are very hot due to the high temperature created inside by combustion. Basically, we just want to use the heat that the chamber walls possess to run the turbine.

The walls of the chamber are covered with small tubes entirely and either fuel or oxidizer is pumped through them to cool the chamber. While cooling, the heat is picked up by the propellant that passes and changes its phase to gas. This high-temperature, high-pressure gas is then passed on to the turbine that connects the fuel and oxidizer turbopumps. The hot gases then drive the turbine and the propellant is injected back into the combustion chamber.

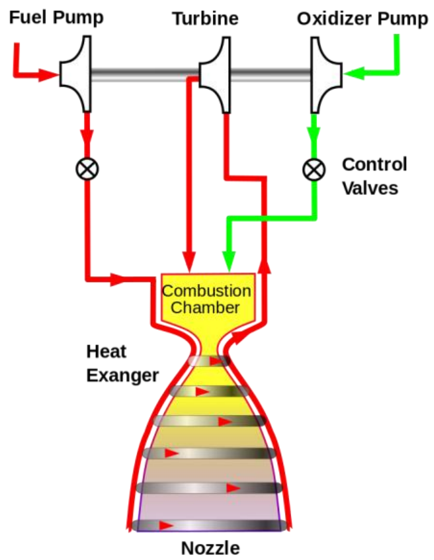

Fig 11-: Expander cycle

For this engine to run the phase change of the propellant is at most necessary as it is required to run the turbine. It is limited by the square-cube law, which states that when a shape's size increases, in this case, a bell-shaped nozzle, the surface area is increased by the square of the radius (R^2), and the volume is increased by the cube of the radius (R^3). So, the amount of the propellant to be heated at the walls is the square of the radius and the amount of the propellant that is combusted is the cube of the radius.

As we increase the size of the combustion chamber the propellant flowing through the walls increases and so as the cooling capacity of the chamber. But the cooling gets difficult if we decrease the size of the combustion chamber. The same positive attribute that large engines have can lead to another problem. As the size of the engine increases, we would require more energy to run the turbopumps, but the amount of energy gained by the propellants in the walls of the combustion chamber is less as the flow rate is more. The heat exchange becomes less efficient as the size increases.

Another issue to be considered is the pressure of the exhaust of the turbine while entering the main combustion chamber. The pressure after the turbine section should be more than the inlet of the main combustion chamber. But as the size of the engine increases the amount of pressure created in the gas entering the turbine section is less due to the poor heat exchange. Hence, limiting the usage with the size of the engine.

Example:

1) Angara rocket, powered by RD-0146 engine.
2) Atlas IIIB, V rockets, powered by RL-10A-4-2 engine.
3) Delta III, IV, and SLS rockets, powered by RL-10B-2 engine.
4) New Glenn rocket, powered by BE-3U engine.

Table -8:

Engine name	stage	propellant	Thrust (N)	Specific impulse (s)
RD-0146	Upper	LH2/LOX	68,600 (vacuum)	470 (vacuum)
RL-10A-4-2	Upper	LH2/LOX	99,195 (vacuum)	451 (vacuum)
RL-10B-2	Upper	LH2/LOX	110,093 (vacuum)	465.5 (vacuum)
BE-3U	2nd	LH2/LOX	710,000 (vacuum)	

4. Cryogenic Rocket Engine

The fundamental element which differentiates a cryogenic engine from a normal rocket engine is the type of propellant used. As the name suggests the propellants used are liquified and stored at extremely low temperatures, which is less than -150 ºC or -238 ºF. But why do we need to use propellants of such low temperatures? To answer this question, first, let us know about the term specific impulse. It is known as the amount of thrust produced per weight flow rate of propellant.

$$\text{Specific impulse} = \frac{\text{Thrust}}{\text{weight flow rate of propellant}}$$

$$I_{sp} = \frac{T}{mg/t} \quad [units: sec]$$

So, the more the specific impulse, the more thrust will be produced for the same amount of the propellant consumed, which is a necessity for rocket engines. Now the thrust basically depends on the exhaust velocity of the gases, which in turn depends on the temperature of the exhaust gases. So, to produce high thrust we would require more temperature in the exhaust, which is obtained by the combustion of the fuel and oxidizer. For the fuel to release more amount of heat, the calorific value should be higher.

The fuel with the highest amount of calorific value is hydrogen, whose calorific value is 150 MJ/kg and has the least weight compared to other fuels. As the specific impulse is directly proportional to thrust and inversely proportional to the weight of the propellant, Hydrogen gives the highest amount of specific impulse compared to any other fuel. As we know hydrogen is very less dense and occupies more volume in gaseous form. So, the amount of gaseous hydrogen fuel required to take the launch vehicle to space would require very large tanks compared to other fuels which are dense and require less volume.

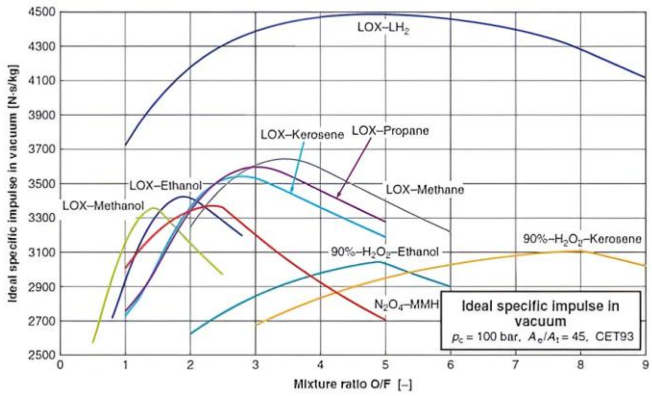

Chart 1-: Specific Impulse vs mixture ratio

These large tanks would definitely result in an aerodynamic efficiency loss of the vehicle as they increase drag. So, for hydrogen or any other lighter fuels to be used without facing those problems, they should be liquified as it increases the density and reduces the volume consumed. Hydrogen liquefies at a temperature below -253 ºC or -423 ºF. Due to the same challenge that gaseous oxygen faces, it is liquified at a temperature below -183 ºC or -297 ºF. liquid hydrogen and liquid oxygen are typically used in cryogenic engines.

Cryogenic engines can run on a gas-generator cycle, expander cycle, or staged combustion cycle. The use of a cycle is totally based on the mission requirement. Gas generators are less efficient and produce more thrust, so they can't be dependable for all the stages of the rocket. Hence, they are typically used as boosters for a rocket. The expander cycle cannot produce more thrust compared to the gas generator cycle due to the less inlet pressure that it possesses because of the absence of a gas generator or pre-burner. Hence, they are typically used in the upper stages of the rocket where the thrust required is less as the earth's gravitational effects are less. The staged combustion cycle is more efficient and produces more thrust compared to the other two cycles. But the only drawback is the complexity of making it. It can be used in any stage of an engine.

One of the main advantages of using cryogenic fuels is, it keeps the temperature of the walls of the combustion chamber as cool as possible with the regenerative cooling method. But this advantage has its own counterpart, which is the temperature gradient of the engine. The parts where the liquid propellants flow has a temperature as low as -150 °C and parts where the hot gases are produced like the pre-burner, gas-generator, and combustion chamber have a temperature as high as 3000 °C. This high-temperature gradient affects the structure of the engine by increasing the thermal stresses. So, while designing a cryogenic engine the insulation of the parts should be most taken care of.

One common problem that rocket engine faces in the turbopump section is the formation of shocks at the tip of the turbines, because of the high amount of RPM that they achieve due to the exhaust of the pre-burner or gas generator.

Now let us write the speed of the sound equation,

$$a = \sqrt{\gamma R T}$$

$$a = \sqrt{\frac{\gamma R_u T}{M}}$$

Here,

a = speed of the sound

R_u = characteristic gas constant

T = temperature

M = molecular mass

As the mass of the molecule increases the speed of sound decreases. This allows the turbines to achieve the speed of sound at a lower RPM compared to the speed of sound when lower molecular mass propellants are used. When the turbines reach the speed of sound it produces shock waves at the tips, which are primarily known for their performance-degrading ability. So, in a cryogenic engine, it won't be the case as the main fuel is hydrogen (H) which is the lightest element out there and they provide the highest turbine efficiency.

One important thing to do before starting a cryogenic engine is Engine Chill or Pre-Chill. This prelaunch procedure is not only for a cryogenic engine but also for any engine that uses a cryogenic propellant combination such as RP-1 and LOX. In this process, the cryogenic propellants are slowly driven into the parts of the rocket engine to make them cool in order to prevent thermal shocks, which are caused due to the high-temperature gradients, which occur when the cryogenic propellant of high pressure is pumped directly into the parts of the rocket engine that are at ambient temperature.

Due to the thermal shock, the walls of the functioning parts might form cracks. Similar to the case when cooled water is poured on a hot metal. Another problem is, we are here talking about cryogenic propellants which have very low boiling points. For example, the boiling point of hydrogen is -252.9 °C and for oxygen is -183 °C. If they come in direct contact with the parts of the rocket engine at ambient temperature they will evaporate and form small gas bubbles. This formation is called Cavitation. These small gas bubbles can disturb the flow and can even interrupt the ignition process which can cause efficiency loss.

The combination of LH2 and LOX is mostly preferred for cryogenic engines and they are typically used in the upper stages of the rocket because they produce the highest specific impulse, which means they can produce more thrust per unit fuel combusted compared to any other propellants. which in turn means the rocket can carry less fuel and more payload. The combustion product of LH2 and LOX is only water in the vapor state, which makes it a clean fuel.

$$2H_2 + O_2 \rightarrow 2H_2O$$

The combination of CH_4 (liquifies at -160 °C) and LOX is another most commonly used cryogenic propellant after LH2 and LOX.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Example:

1) Atlas IIIB, V rockets, powered by RL-10A-4-2 engine.
2) GSLV Mk II rocket, powered by CE-7.5 engine.
3) Space shuttle and SLS rocket, powered by RS-25 engine.
4) Delta IV and IV heavy rockets, powered by RS-68A engines.
5) Starship rocket, powered by Raptor engine.

Table -9:

Engine name	stage	propellant	Cycle used	Thrust (N)	Specific impulse (s)
RL-10A-4-2	Upper	LH2/LOX	expander	99,195 (vacuum)	451 (vacuum)
CE-7.5	Upper	LH2/LOX	fuel-rich staged	73,500 (vacuum)	454
RS-25	1st	LH2/LOX	fuel-rich staged	1,860,000 (SL) 2,279,000 (vacuum)	366 (SL) 452.3 (vacuum)

RS-68A	1st	LH2/LOX	Gas generator	3,135,996 (SL) 3,558,577 (vacuum)	362 (SL) 411 (vacuum)
Raptor	1st, 2nd	CH_4/LOX	Full flow staged	2,640,000 (SL)	327 (SL) 350 (vacuum)

5. CONCLUSIONS

The development and working of a bi-propellant engine are not without any challenges. Each engine cycle has its advantages, disadvantages, and its own way of running the engine. Each of the propellants has to be taken care of individually as from storing the propellant to pumping them into the main combustion chamber is accompanied by a different range of challenges. The selection of the rocket engine cycle is totally based on the mission requirement. For example, the expander cycle is mostly used in the upper stages of the rocket mission due to its precise throttle control, while gas generator and staged combustion cycles are mostly used in primary stages as they produce more thrust.

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