A Systematic Comparison of Types of Rocket Propulsion Engines

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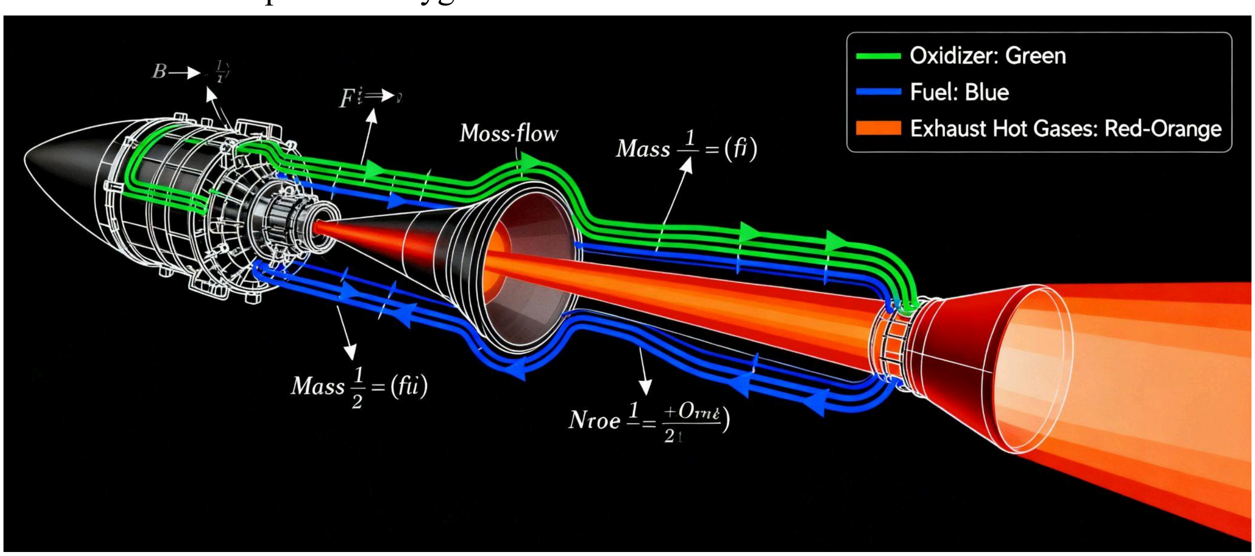
Introduction

All rocket propulsion systems work on the same physical principles of Thrust and Newtonian laws of motion. The required thrust is generated by a propulsion system that accelerates the working fluid created by the combustion of propellants under high temperature and pressure from subsonic to supersonic speeds, converting thermal energy into directed kinetic energy. This gives a time component to the change of momentum (force or thrust) of the working fluid, which in turn produces a force on the system.

The propellant is a chemical mixture of fuel and an oxidiser that burns to produce the working fluid for thrust. Fuel is a chemical that combusts when it comes in contact with oxygen, and since a rocket engine has a limited space and an oxidiser has more density and can produce more energy relative to oxygen when burnt with the fuel, the system uses an oxidiser to produce oxygen.



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Literature Review

1. Liquid Propellant Engine

In a liquid propellant system, the fuel and the oxidiser are stored in separate tanks and are connected through a system of pipes, shafts, valves and turbo-pumps that all lead to a combustion chamber where they're burned to produce the working fluid. This engine can control the flow of propellant and hence is relatively easier to stop, throttle and restart. Liquid propellant systems, despite their many advantages, are somewhat more complex than their solid counterparts and are prone to many malfunctions due to their many mechanical and hardware components.

When choosing a liquid propellant, the following parameters are considered:
a. High Specific Impulse (Isp): Thrust per unit propellant weight
- A high Isp suggests that the engine is more fuel efficient and is calculated by the thrust generated(F) and the propellant mass flow rate (m) times the acceleration due to gravity (g0)

Propellant Type	**Specific Impulse (Isp) [s]**	**Specific Fuel Consumption [g/(kN·s)]**
LOX/Liquid Hydrogen	350–450	~226
LOX/RP-1	250–300	~340

b. Density of the propellant: A low-density propellant will require more space and hence will increase the mass of the system
c. Storage temperature: A cryogenic propellant, i.e a fluid with low storage temperature, will require thermal insulation and hence will increase the system mass
d. The corrosive nature: it is important to use a fluid that is compatible with the storage material used.

Liquid propellents are classified into:
1. Petroleum
2. Cryogens

3. Hypergols (fuels and oxidisers ignite spontaneously on contact with each other and don't require an ignition source)

Efficiency

- Liquid Propellants have the highest Isp out of all the types of propellant used in a rocket engine
- The propellant is highly controllable and can be throttled, stopped and restarted at will.

Reusability

- Liquid propellant engines are highly reusable due to their high controllability
- The complex systems of pipes and valves can survive multiple flights with refurbishments and repairs.

Cost

- These are the most expensive out of all the options due to it's complex network of turbo-pumps, valves and cryogenic systems
- These have manufacturing and ground support equipment and teams.

Safety

- Cryogenics can freeze surrounding systems or cause a leak.
- Oxidisers like LOX might be reactive, but are far from explosives themselves.
- The engine can be shut down at will.

2. Solid Propellant Engine

Solid propellant engines are relatively simpler, consisting of a steel casing with is filled with a solid mixture of fuel and oxidiser. When ignited, it burns at a rapid rate from the centre towards the casing. Thrust can also be controlled in a solid propellant, though not as much as in liquids, but the shape of the centre channel determines the rate and pattern of burn and hence can be controlled to a certain degree.

Solid propellants are of two categories:
1. Homogenous: has either a single simple base (nitrocellulose) or a double base (nitrocellulose, nitroglycerine and plasticiser)
2. Composite: composite propellants are heterogeneous powders that use crystallised or finely ground mineral salt as an oxidiser, and fuel is generally aluminium that is held together by a polymeric binder.

Composite propellants are often identified by the type of polymeric binder used.

Efficiency

- Have a lower specific impulse compared to liquid engines.
- Burn rate is hard to control. Throttle ability is almost zero.

Reusability

- Not reusable in practice since the fuel one ignited burns itself out completely.
- Casings can be recovered and reused.

Cost

- Cheap to manufacture.
- Have simple designs and have fewer moving parts.

Safety

- Stored propellant is highly sensitive.
- Once ignited, it cannot be shut down.
- Accidental ignition is catastrophic.

3. Hybrid Propellant Engine

A hybrid propellant engine uses both liquid and solid components to make its propellant. The fuel used is usually solid, whereas the oxidiser is liquid. The fuel storage tank acts as a combustion chamber where the oxidiser is injected.

Efficiency

High performance, similar to solid propellant engines, but the combustion can be moderated by controlling the flow of oxidiser.
The regression rate of solid fuel limits maximum thrust.

Reusability

- It can be reusable depending on the design.
- Fuel is used up in one ignition, but the tank can be reused.

Cost

- Cheaper to sustain than liquid propellant systems, but more expensive than solid propellant systems

Safety

- It is safer than solids because fuel and oxidiser are stored separately.
- No risk of explosive “mass ignition” like solid propellants.
- Good for educational and experimental rockets.

Results

A Comparison Table

Feature	**Solid Engines**	**Liquid Engines**	**Hybrid Engines**
Efficiency	**Low–medium**	**High**	**Medium**
Throttle / Control	No	Yes	Partial

Restart capability	No	Yes	Yes (if design allows)
Reusability	Poor	High	Medium
Cost	Low	High	Medium
Safety	Low (risk of accidental ignition)	Medium–High	High
Tech complexity	Low	Very high	Moderate
Best For	Boosters, missiles	Launch vehicles, crewed missions	Research, safe training rockets
Feature	**Solid Engines**	**Liquid Engines**	**Hybrid Engines**

Conclusion

- Solid engines excel in simplicity, cost, and instantaneous high thrust—perfect as boosters.
- Liquid engines dominate in efficiency, control, and reusability, making them the preferred choice for modern orbital rockets
- Hybrid engines fill the gap between the two, offering safer handling and controllability with simpler engineering

Reference

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