Propulsion System of Aircraft - Shrusti Patil

1. Introduction

Aircraft propulsion systems are the heart of modern aviation, providing the thrust necessary to overcome drag and lift the aircraft into the sky. Propulsion involves generating a force that moves an aircraft forward, achieved by accelerating a mass of air (or exhaust gases) backward according to Newton's third law of motion. Efficient propulsion systems are vital for achieving high performance, fuel economy, and environmental compliance in both commercial and defense aviation.

2. Concepts of Aircraft Propulsion Systems

- Piston Engine (Propeller System): Operates like a car engine. Converts fuel energy to mechanical energy that drives a propeller. Used in small aircraft.
- Turboprop Engine: A gas turbine engine that drives a propeller through a gearbox. Highly efficient at subsonic speeds.
- Turbojet Engine: Pure jet engine compressing air and mixing with fuel for combustion. Used in military jets.
- Turbofan Engine: A jet engine with a fan that increases efficiency and reduces noise. Used in commercial jets.
- Ramjet Engine: No moving parts; relies on forward speed to compress air. Used in missiles and supersonic aircraft.

3. Working Principles with Diagrams

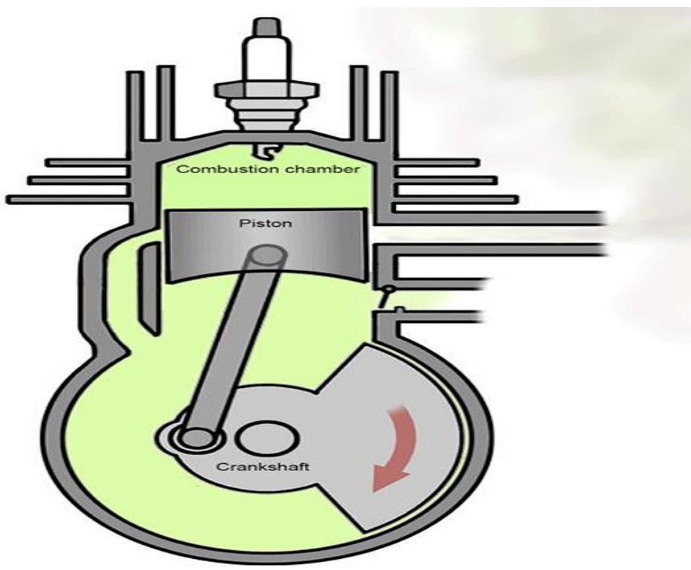

Fig 1: Piston Engine Diagram.

The Piston Engines also known as Reciprocating engines. They operate on the same fundamental principles as car engines, using pistons and cylinders to convert fuel energy into mechanical power. A piston engine is an internal combustion engine that uses one or more pistons to convert the expanding gas energy into mechanical work. This mechanical power is then used to turn a propeller, which generates **thrust** to move the aircraft forward.

Piston aircraft engines operate on the **four-stroke Otto cycle**, consisting of:

1. **Intake stroke** (Suction stroke): Piston moves down, drawing in the air-fuel mixture.
2. **Compression stroke**: Piston moves up, compressing the mixture.
3. **Power stroke** (Expansion stroke): Spark plug ignites the mixture, causing an explosion that pushes the piston down.
4. **Exhaust stroke**: Piston moves up again to push out burnt gases.

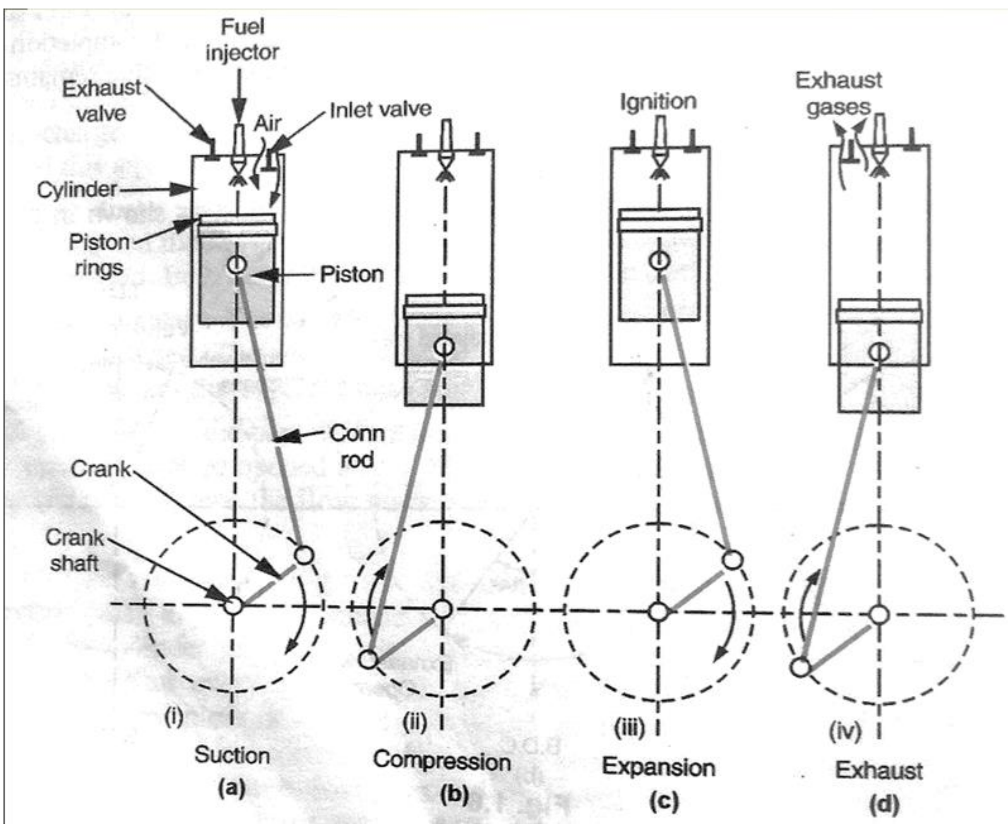

Fig 2: Four Strokes of a Piston Engine.

There are 2 stoke piston engines which completes the process within two strokes.

Four stroke engine	Two stroke engine
1. One power stroke for every two revolutions of the crankshaft.	One power stroke for each revolution of the crankshaft.
2. There are inlet and exhaust valves in the engine.	There are inlet and exhaust ports instead of valves.
3. Crankcase is not fully closed and air tight.	Crankcase is fully closed and air tight.
4. Top of the piston compresses the charge.	Both sides of the piston compress the charge.
5. Size of the flywheel is comparatively larger.	Size of the flywheel is comparatively smaller.
6. Fuel is fully consumed.	Fuel is not fully consumed.
7. Weight of engine per hp is high.	Weight of engine per hp is comparatively low.
8. Thermal efficiency is high.	Thermal efficiency is comparatively low.
9. Removal or exhaust gases easy.	Removal of exhaust gases comparatively difficult.
10. Torque produced is even.	Torque produced is less even.

Fig 3: Difference between 4 stroke and 2 stroke Piston Engine.

Advantages:

- Simple and reliable design
- Easier maintenance
- Lower operational costs
- Efficient at low to medium speeds and altitudes

Disadvantages:

- Limited power output → unsuitable for large or high-speed aircraft
- Decreased efficiency at high altitudes
- Heavier and more vibration than jet engines

Turboprop Engine:

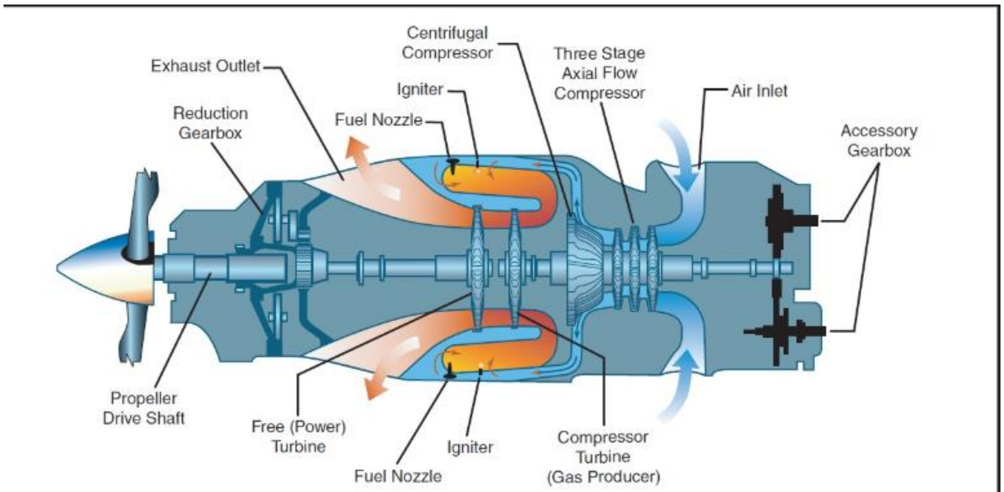

Fig 4: Turboprop Engine Working Diagram.

A turboprop engine is a type of gas turbine engine that drives a propeller to produce thrust. It combines the efficiency of a piston engine (at lower speeds) with the power of a jet engine.

Main Components:

1. **Air Intake**: Draws air into the compressor.
2. **Compressor**: Compresses the air to high pressure.
3. **Combustion Chamber**: Fuel is injected and burned with compressed air to produce hot gases.
4. **Turbine**: Extracts energy from hot gases to drive both the compressor and the propeller shaft.
5. **Reduction Gearbox**: Reduces turbine speed to suitable propeller speed.
6. **Propeller**: Converts shaft power into thrust.
7. **Exhaust**: Expels remaining gases.

Working Process:

1. **Intake:** Air enters the engine through the intake.

2. **Compression:** The compressor increases air pressure.
3. **Combustion:** Fuel is sprayed and burned in the combustion chamber, producing high-temperature, high-pressure gases.
4. **Turbine Expansion:** These gases pass through the turbine, which extracts energy to drive the compressor and the propeller via the gearbox.
5. **Propeller Thrust:** The propeller converts the mechanical power into thrust, moving the aircraft forward.
6. **Exhaust:** Remaining gases exit, adding a small amount of additional thrust.

Advantages:

- Very efficient at low to medium speeds (below Mach 0.6).
- Shorter take-off distance.
- Lower fuel consumption than turbojets.
- Excellent for regional and cargo aircraft

Disadvantages:

- Not suitable for high-speed flight (propeller efficiency drops at high Mach numbers).
- More complex gearbox system.
- Louder compared to turbofan engines.

Turbojet Engine:

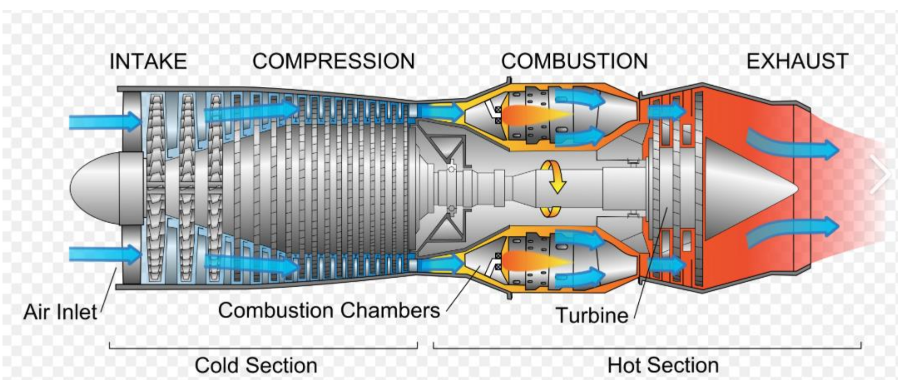

Fig 5: Turbojet Engine Working Diagram.

A turbojet engine is a gas turbine engine that produces thrust solely from the high-speed exhaust jet that exits the nozzle. It is one of the earliest jet propulsion systems used in aircraft and is ideal for high-speed, high-altitude flight.

Working Principle:

1. **Intake:** Air enters through the inlet and slows down slightly to increase pressure.
2. **Compression:** The compressor increases the pressure and temperature of the air.
3. **Combustion:** Fuel is sprayed into the combustion chamber and ignited. The burning fuel-air mixture expands rapidly, forming high-temperature gases.
4. **Turbine Expansion:** The turbine extracts some energy from the gases to power the compressor.
5. **Exhaust and Thrust:** The remaining gases exit the nozzle at supersonic speed, creating thrust according to **Newton's Third Law**: *every action has an equal and opposite reaction.*

Advantages:

- Very high speed (suitable for supersonic aircraft).
- Simple design compared to turbofan or turboprop engines.
- Lightweight and compact.

Disadvantages:

- Poor fuel efficiency at low speeds.
- Very noisy due to high exhaust velocity.
- High temperature exhaust may cause material stress.
- Low thrust at take-off, making it unsuitable for slow aircraft

Key Formula for Thrust: $T = \dot{m}(V_e - V_0)$

Where:

- T= Thrust (N)
- $\dot{m}$= Mass flow rate of air (kg/s)

- V_e= Velocity of exhaust jet (m/s)
- V_0= Velocity of incoming air (m/s)

Turbofan Engine:

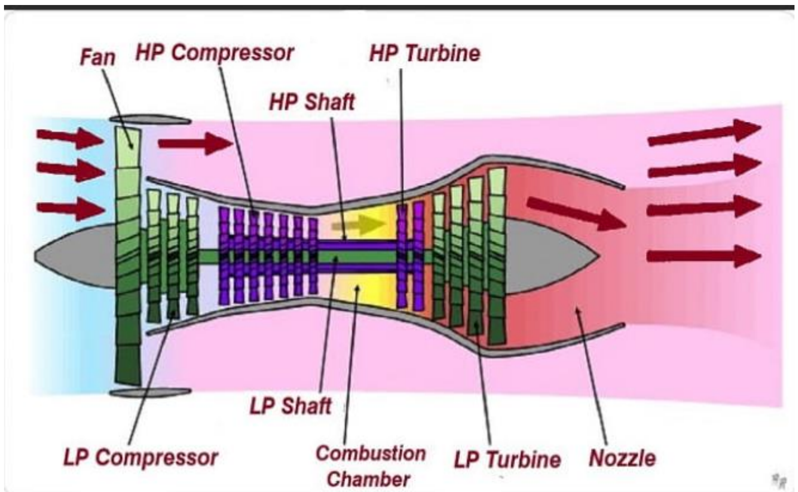

Fig 6: Turbofan Engine Working Diagram.

A turbofan engine is a type of gas turbine engine commonly used in modern commercial aircraft because it offers a good balance between thrust and fuel efficiency. It combines the features of a turbojet and a turboprop engine.

Main Components:

1. **Fan**: Draws in large amounts of air. Some air goes into the core for combustion, and the rest bypasses around the core to produce additional thrust.
2. **Compressor**: Compresses the air to high pressure before combustion.
3. **Combustion Chamber**: Fuel is injected and burned with compressed air to produce high-energy gases.
4. **Turbine**: Extracts energy from hot gases to drive the fan and compressor.

Working Process

1. **Air Intake:** The large fan at the front sucks in air. A part of this air enters the core engine, and the rest bypasses around it.
2. **Compression:** The air entering the core passes through the compressor, where pressure and temperature increase.
3. **Combustion:** Fuel is sprayed into the compressed air and ignited, producing high-temperature, high-pressure gases.
4. **Expansion through Turbine:** The gases expand through turbine blades, making the turbine spin. The turbine, in turn, drives both the compressor and fan.
5. **Exhaust and Thrust Generation:**
    - The **bypass air** (from the fan) produces most of the thrust.
    - The **core exhaust** adds extra thrust as it exits through the nozzle.

Thrust Split

- **Bypass Ratio (BPR):** Ratio of air bypassing the core to the air passing through it.
    - **High-bypass turbofan**: efficient, quieter (used in airliners).
    - **Low-bypass turbofan**: powerful, noisier (used in military jets).

Advantages:

- High fuel efficiency
- Lower noise levels
- Suitable for subsonic aircraft (commercial jets)

Ramjet Engine:

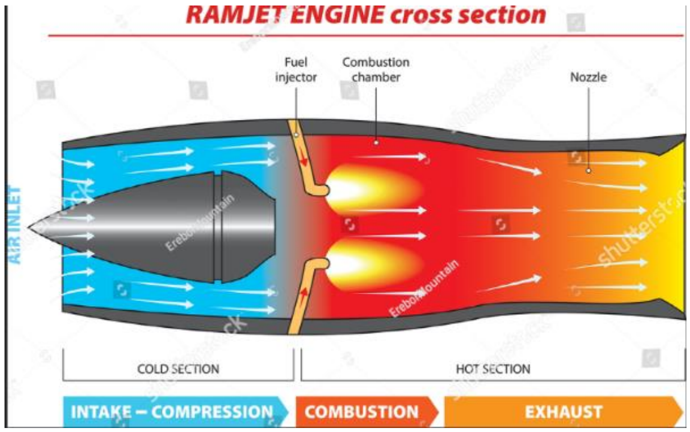

Fig 7: Ramjet Engine Working Diagram.

A ramjet engine is a type of air-breathing jet engine that operates without any compressor or turbine. It relies entirely on the forward motion of the aircraft to compress the incoming air, hence the name *"ram"* jet.

Main Components:

1. **Inlet (Diffuser):** Slows down and compresses the incoming air using the aircraft's forward speed.

2. **Combustion Chamber**: Fuel is injected and mixed with the compressed air, then ignited.

3. **Nozzle:** Expands and accelerates the hot exhaust gases to produce thrust.

Working Process:

1. **Air Intake**: As the aircraft moves at high speed (usually above Mach 2), air is forced ("rammed") into the inlet.

2. **Compression:** The high-speed air slows down in the diffuser, increasing its pressure and temperature.

3. **Combustion:** Fuel is sprayed into this compressed air and burned continuously, producing high-temperature gases.

4. **Exhaust/Thrust Generation:** The gases expand through the nozzle, accelerating
5. backward and generating forward thrust according to Newton's third law.

Advantages:

- Simple design and lightweight
- High efficiency at supersonic speeds

Disadvantages:

- Cannot work at low or zero speeds
- Poor efficiency at subsonic speeds

6. Numerical Computations (simple computations)

Question:

An aircraft engine has a mass flow rate of air $\dot{m} = 60$ kg/s. The exhaust velocity of the engine is $V_e = 700$ m/s, and the aircraft is flying at $V_0 = 250$ m/s. If the pressure difference term $(p_e - p_0)A_e = 0$, calculate the **thrust** produced by the engine.

Solution:

$$F = 60(700 - 250) + 0$$
$$F = 60 \times 450$$
$$F = 27{,}000 \text{ N}$$

Answer:

$$\mathbf{F = 27,000\ N}$$

Numerical Problem 2: Propulsive Efficiency and Specific Fuel Consumption

Question:

An aircraft engine has the following data:

- Exhaust velocity: $V_e = 800$ m/s
- Aircraft speed: $V_0 = 300$ m/s
- Fuel mass flow rate: $\dot{m}_f = 0.6$ kg/s

- Engine thrust: $F = 30{,}000\ \text{N}$

  (a) Calculate the **propulsive efficiency** η_p

  (b) Calculate the **specific fuel consumption (SFC)**

Solution:

(a) Propulsive Efficiency:

$$\eta_p = \frac{2V_0}{V_e + V_0}$$

$$\eta_p = \frac{2(300)}{800 + 300} = \frac{600}{1100}$$

$$\eta_p \approx 0.545$$

(b) Specific fuel consumption.

$$SFC = \frac{\dot{m}_f}{F}$$

$$= \frac{0.6}{30{,}000}$$

$$= 0.00002\ \text{kg/Ns}$$

Answer:

$$\eta_p \approx 0.545\ (54.5\%)$$

$$SFC = 0.00002\ \text{kg/Ns}$$

7. Applications and Advancements:

1. Commercial Aviation:

- Turbofan engines dominate modern airliners due to high efficiency and low noise.
- Examples: GE90 (General Electric), Rolls-Royce Trent XWB.

2. Defence and Military:

- Turbojets and ramjets are widely used in supersonic aircraft and missiles for high-speed performance.

3. Emerging Technologies:

- Hybrid-electric propulsion: Combines electric motors with traditional turbines for improved efficiency and reduced emissions.

- Scramjets: Supersonic combustion ramjets for hypersonic flight.
- Sustainable Aviation Fuels (SAF): Biofuels and synthetic fuels to reduce carbon footprint.

Conclusion

Aircraft propulsion systems are the heart of modern aviation, enabling flight by converting fuel energy into thrust. Over the years, these systems have evolved from simple piston engines to advanced turbofans, turbojets, and ramjets, meeting the increasing demands for efficiency, speed, and environmental sustainability.

A thorough understanding of propulsion principles, engine types, and performance parameters allows aerospace engineers to design safer, more fuel-efficient, and eco-friendly aircraft. With emerging technologies such as hybrid-electric propulsion, scramjets, and sustainable aviation fuels, the future of aviation promises higher performance, reduced emissions, and innovation in air travel.

In essence, advancements in propulsion systems not only enhance aircraft performance but also play a pivotal role in shaping the next generation of sustainable and high-speed aviation.