Module – 3

AIRCRAFT PROPULSION

Syllabus:

Aircraft Propulsion: Aircraft power plants, classification based on power plant and location and principle of operation. Turboprop, turbojet and turbofan engines; ramjets and scramjets; performance characteristics. Aircraft power plants – basic principles of piston, turboprop and jet engines; Brayton cycle and its application to gas turbine engines; use of propellers and jets for production of thrust; comparative merits and limitations of different types of propulsion engines; principle of thrust augmentation.

1. What is aircraft power plant? Write the classification of aircraft power plant in brief.

Aircraft power plants

The Power Plant may be an Engine and propeller combi-nation or a jet Engine. Engine is mounted in position against a firewall in the front section of the airplane. The firewall provides Seperation of the power plant from the remainder of the fuselage.

The Engine cowling is the metal covering which encases the Engine and its accessories, streamlining the plane and conducting air around the Engine cylinders for cooling. Because the action of the pistons is an up and down movement, this Engine is called a reciprocating Engine or a piston Engine. In multi Engine a/c, the Engines are usually mounted on the leading Edges of the wings.

The jet Engine gives the airplane a thrust because of the jet exhaust gas coming out of the back of the Engine. The moving parts of the Engine is a turbine. Jet Engines may be mounted inside the fuselage as in most military fighters or on the outside of the fuselage or on the wings on most commercial a/c airlines.

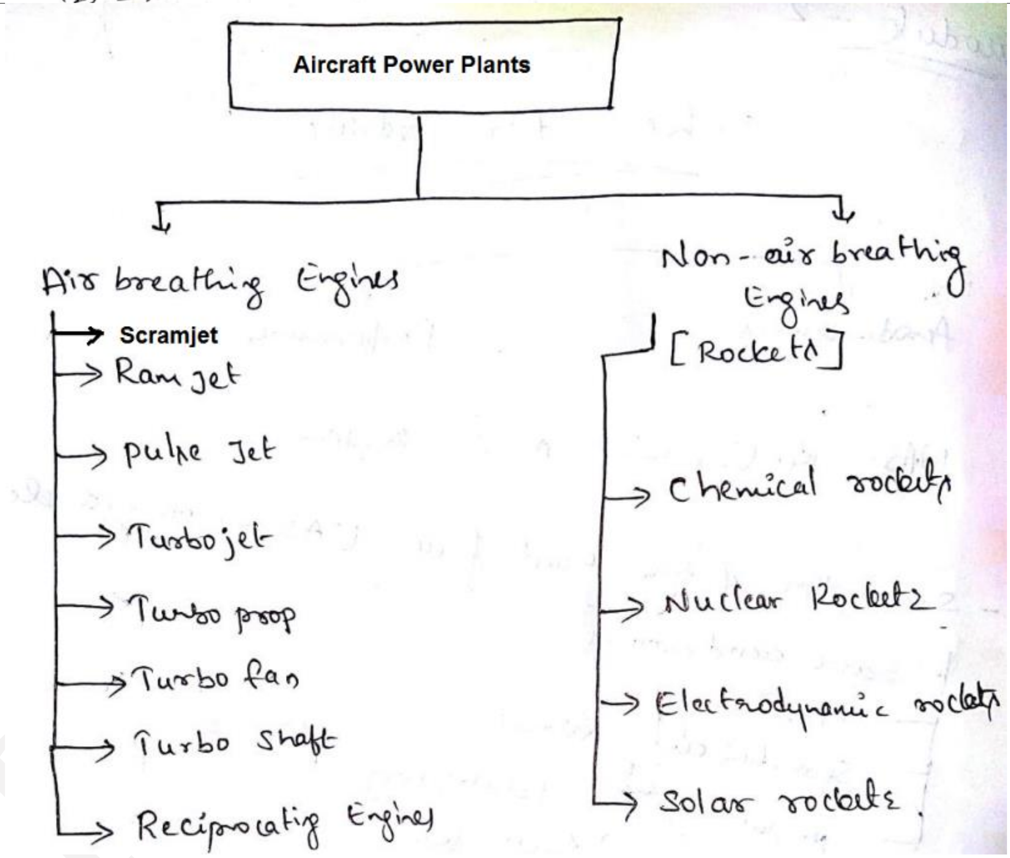
In a propeller driven Aircraft Either a piston Engine (or) a Turbo prop Engine is used to drive the propeller to push the air back.

Where as in jet propulsion there is no propeller so that forward thrust is provided by discharge of high speed gases. There are propulsive Engines which converts the potential Energy in the fuel to the kinetic Energy (or) Mechanical Energy.

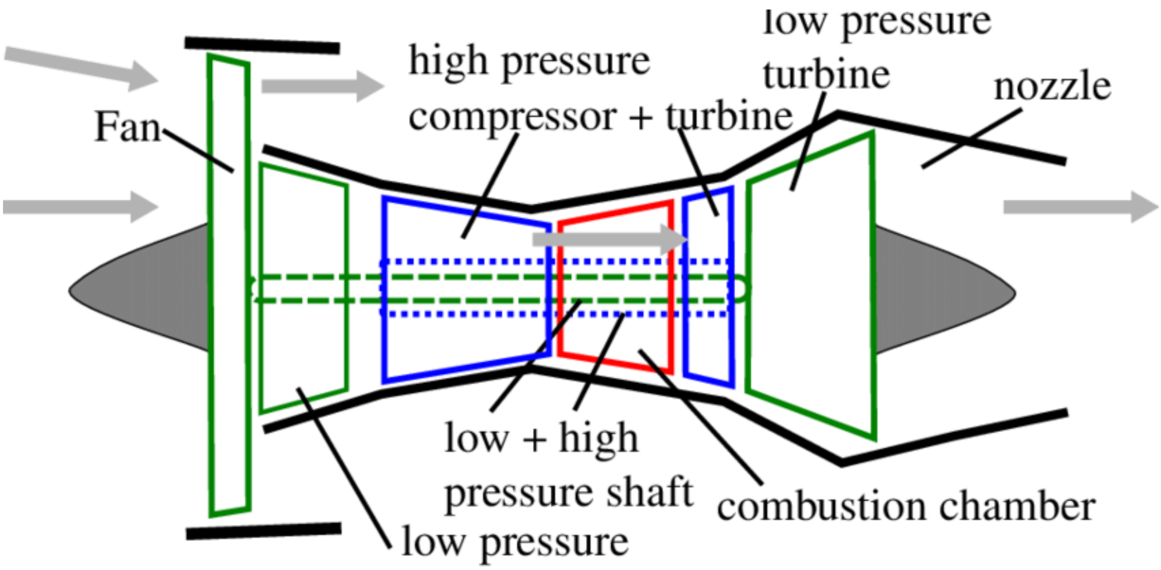
Two basic kinds of Propulsion are given by

(1) Direct Reaction Propulsion

(2) Indirect Reaction Propulsion



2. With a neat diagram, explain Turbofan engine and explain about bypass ratio and its significance.



Working principle:

- A turbofan engine has a large fan at the front, which sucks in air. Most of the air flows around outside of core engine, making it quieter and giving more thrust at low speeds.
- In a turbojet engine, all the air entering the intake passes through the gas generator, which is composed of the compressor, the combustion chamber and the turbine. However, in a turbofan engine only a portion of the incoming air goes into the combustion chamber.
- The remaining air or fan air (or secondary air) either leaves separately from the primary engine air, or ducted back to mix with the primary air through the engine core at the rear.
- The objective of bypass system is to increase thrust without increasing fuel consumption. This is achieved by increasing the total air mass flow and reducing the velocity within the same total energy supply.
- The increased efficiency of a turbofan engine is combined with a substantial noise reduction, typically 10-20%, which is a very important consideration.
- Turbofan engines are generally classified based on the bypass ratio i.e, low bypass (1:1), medium bypass (2-3:1) and high bypass (4:1 or greater).
- In a low bypass engine, the fan and compressor sections handle approximately the same mass of air flow.

- A medium bypass engine produces thrust ratio which is approximately the same as its bypass ratio. The fan of medium bypass ratio engine has a larger diameter compared to that on a low bypass engine of comparable power.
- A high bypass turbofan engine utilizes even wider diameter fan in order to push more air. In this type of engine about 80% of the thrust is provided by the fan and remaining only 20% by the core engine.

Advantages/Merits:

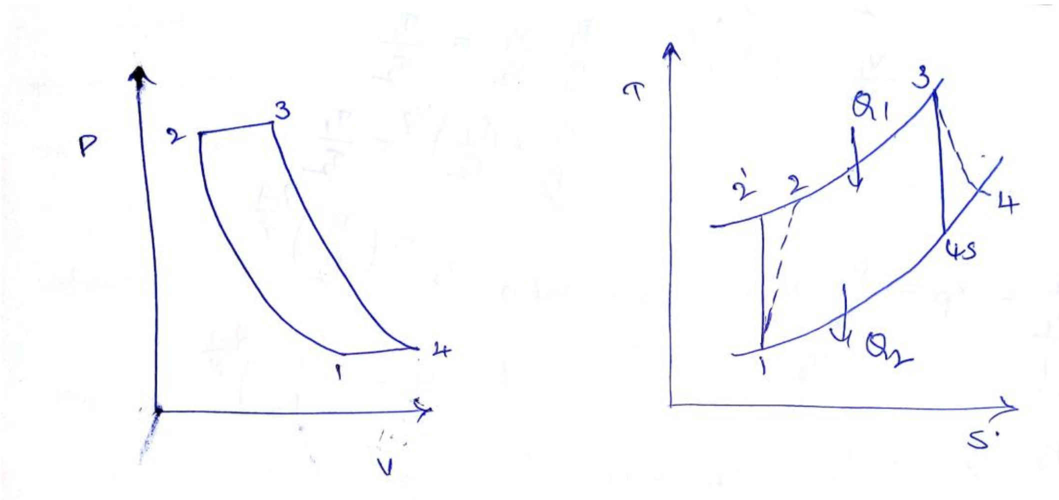
- Higher thrust at lower airspeeds.
- Lower TSFC.
- Shorter takeoff distance.
- Considerable noise reduction.

Disadvantages/Limitations:

- Higher specific weight.
- Larger frontal area.
- Inefficient at high altitudes.

3. With a neat sketch explain Brayton Cycle and its application in jet engines.

Brayton cycle and its application to gas turbine engines



The Brayton cycle is a theoretical cycle for simple gasturbine. This cycle consists of two isentropic and two constant pressure processes on P-V + T-S diagram. The cycle is similar to the Diesel cycle in compression and heat addition. The isentropic Expansion of the Diesel cycle is further Extended followed by constant pressure heat rejection.

The thermal Efficiency:

$$\eta_{th} = \frac{\text{Heat added} - \text{Heat rejected}}{\text{Heat added}}$$

$$= \frac{m_a C_p (T_3 - T_2) - m_a C_p (T_4 - T_1)}{m C_p (T_3 - T_2)}$$

$$= 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

For isentropic process.

$$PV^{\gamma} = const \qquad PV = nRT$$

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma} \qquad \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{\gamma} \qquad \frac{V_1}{V_2} = \left(\frac{P_1}{P_2}\right)^{1/\gamma}$$

$$\frac{P_1}{P_2} \times \frac{V_1}{V_2} = \frac{T_1}{T_2}$$

$$\frac{P_1}{P_2} \times \left(\frac{P_1}{P_2}\right)^{1/\gamma} = \frac{T_1}{T_2}$$

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

$\frac{P_2}{P_1} = r_p = \frac{P_3}{P_4}$ is a pressure ratio.

and $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$ and $\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$

$P_2 = P_3$ and $P_1 = P_4$ then $\frac{T_2}{T_1} = \frac{T_3}{T_4}$

$$\eta_{th} = 1 - \frac{T_4(1 - T_1/T_4)}{T_3(1 - T_2/T_3)} = 1 - \frac{T_4}{T_3} = 1 - \frac{T_1}{T_2}$$

$$\eta_{th} = 1 - \frac{1}{r_p^{\frac{\gamma-1}{\gamma}}}$$

The main difference b/w the actual and theoretical cycle are as follows.

(a) Compression & Expansion are not friction less adiabatic process.

(b) Combustion does not occur Either at Constant volume or at const pressure.

(c) The thermodynamic properties of the gases after combustion are different than those of the fuel-air mixture before combustion.

(d) combustion may be incomplete.

(e) The specific heats of the working fluid are not constant but increases with temperature.

(f) They cylinder pressure during Exhaust process is higher than the atmosphere.

4. What is thrust augmentation? Explain different thrust augmentation methods.

Thrust augmentation

The poor take-off characteristic of the turbojet engine can be improved by augmenting the thrust. The thrust from a turbojet is given by

$$F = \dot{m}_a[(1+f)c_j - c_i]$$

in which the exhaust c_j, is the function of the maximum temperature in the cycle. Higher the maximum temperature higher is the value of c_j. Another method of increasing thrust is to increase the mass flow rate. Improved thrust results in shorter take-off distances, high climb rate and good manoeuvrability at high altitudes. The thrust augmentation can be effected by the following methods:

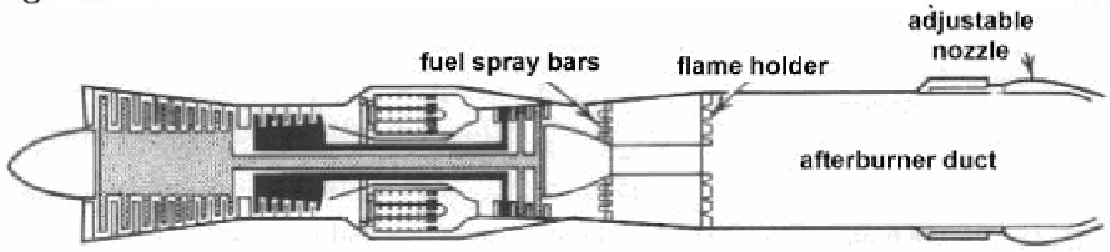
(i) Burning of additional fuel in the tail pipe between the turbine exhaust section and entrance section of the exhaust nozzle. This method of thrust augmentation increases the jet velocity and is known as *afterburning*. The device used is called the afterburner.

(ii) Injecting refrigerants, water or water-alcohol mixture at some point between inlet and exit sections of the air compressor. This method of thrust augmentation increases the mass flow rate and decreases the work of compression.

(iii) Bleeding off air in excess of that required for stoichiometric combustion in the main combustion chamber – at the entrance section of the combustion chamber, and burning it with the stoichiometric fuel-air ratio in a separate one. The combustion products from the latter combustor are expanded in a separate auxiliary exhaust nozzle. The bled air is replaced by water which is injected in the main combustors. This method of thrust augmentation is known as the bleed burn cycle.

7.11.1 The Afterburner

This method of thrust augmentation is being widely applied for obtaining high thrust for short duration. It is known that turbine blade material



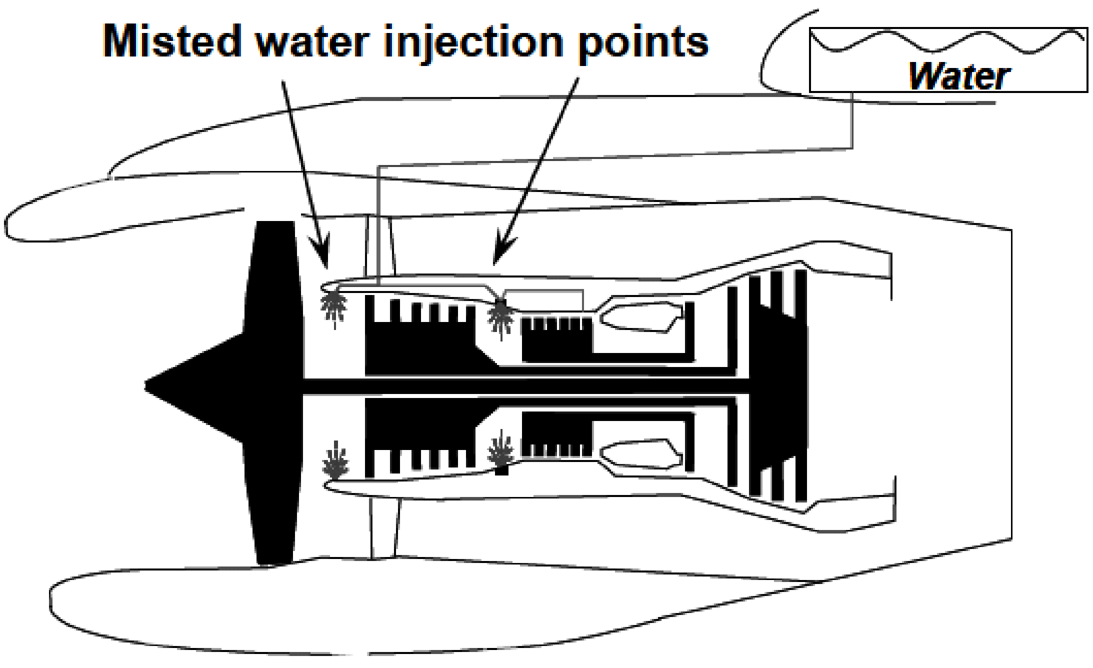
Turbojet with Afterburner

considerations limit the combustion chamber temperature rise. This in turn, limits the basic engine fuel- air ratio to values of about 0.017. As a result, the products of combustion leaving the turbine contain enough unutilized oxygen to support further combustion. Thus if a suitable burner is installed between the turbine and exhaust nozzle, a considerable amount of fuel can be burned in this section to produce temperatures entering the nozzle as high as 2000°C. This increases the gas velocity, and hence provides a thrust increase. A boost of about 30 per cent can be obtained in this manner. However, the fuel consumption increases rapidly. For about 20 per cent thrust increase by use of reheat the overall fuel consumption may be increased by more than 100 per cent and this additional mass of fuel has to be carried by the turbojet. Therefore, it is used only for take-off or for high climbing rates and for a very short duration. Because of the temperature rise in the afterburner, there is a large increase in specific volume of gases, and to keep the pressure drop as small as possible, the tail pipe of the afterburning area is more than that of the normal engine. Furthermore, the afterburning engine must be equipped with a variable exit area exhaust nozzle so that by varying its area with the afterburner operating, the normal conditions at inlet to the afterburner will be unaffected.

7.11.2 Injection of Water-Alcohol Mixture

This method of thrust augmentation is probably the simplest one to achieve. Mixture of water and alcohol or just water is injected at the combustion chamber or compressor inlet section through a series of suitable spray nozzles to produce an increase in thrust.

The effect which produces the greater gain in thrust is the cooling effect within the compressor through water evaporation, which brings about rise in compressor discharge pressure. The rise in pressure can be seen from the

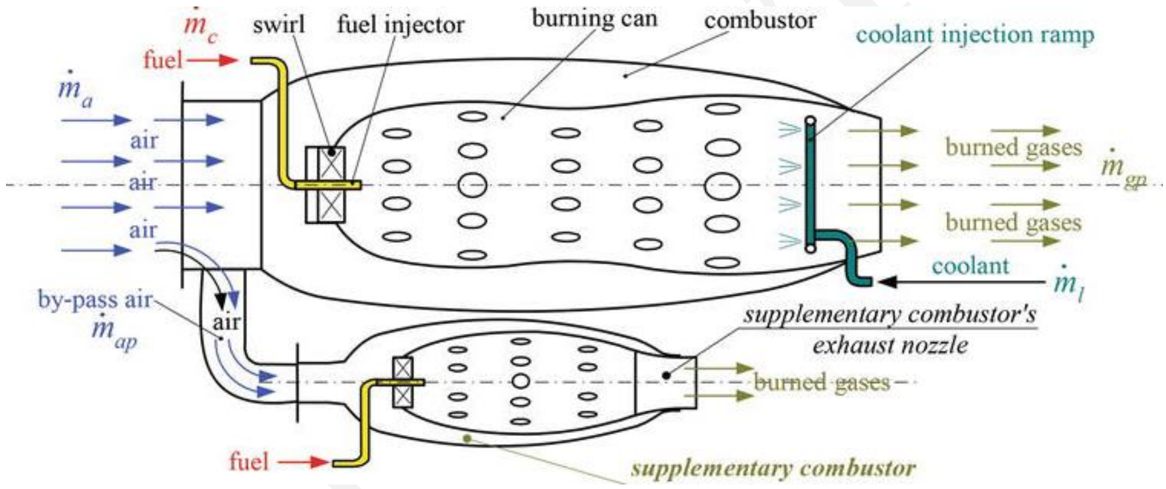


(i) increasing the compressor pressure ratio due to reduced compressor air flow, and

(ii) increasing the total mass flow through turbine and exhaust nozzle. The magnitude of thrust increase is entirely dependent upon compressor operating characteristics.

7.11.3 Bleed Burn Cycle

Since in a turbine excess air is also present, a small percentage of high-pressure air from the compressor is bled to an auxiliary combustion chamber by by-passing the turbine. In auxiliary combustion chamber the bled air is heated by an additional fuel supply to a higher temperature than would be permissible in the main engine on account of the limiting temperature at the turbine blades. The hot gases are then discharged forming an additional jet. A shut off valve is used to bring the engine to normal position. Water is injected into main combustion chamber to replace the mass of the extracted air, thus maintaining the discharge of main jet at the same level. This method is usually used for take-offs only due to high



5. Describe the principle operation of Turboprop engine with neat diagrams.

Turboprop engine

Working principle:

- A turboprop engine is a jet engine attached to a propeller. The turbine at the back is turned by the hot gases and this turns a shaft that drives the propeller.
- Like the turbojet engine, the turboprop engine consists of a compressor, combustion chamber and turbine, which than creates the power to drive the compressor.
- Compared to a turbojet engine, the turboprop engine has better propulsion efficiency. Modern turboprop engines are equipped with propellers that have a smaller diameter but a larger number of blades for efficient operation at much higher flight speeds.

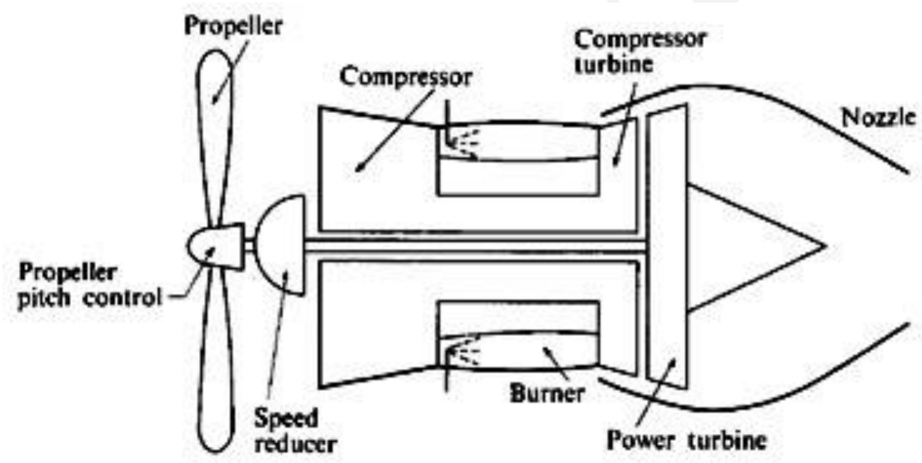


Fig: Turboprop engine

- Turboprop engine drives its propulsion by conversion of gas stream energy into mechanical power to drive the compressor, accessories, etc.
- A free turbine is incorporated in the turboprop engine. The shaft in which the free turbine is mounted drives the propeller through the propeller reduction gear system.
- Approximately 90% of thrust comes from propeller and about only 10% comes from the exhaust gases.

Advantages/Merits:

- Turboprop engines have a higher thrust at takeoff and better fuel economy.
- The frontal area is less than propeller engines so that drag is reduced.

- The turboprop can operate economically over a wide range of speeds ranging from low speeds where pure jet engine is uneconomical to high speeds of about 800 km/h where the propeller engine efficiency is low.
- It is easy to maintain and has lower vibrations and noise.
- The power output is not limited as in the case of propeller engines.
- The multishaft arrangement allows a great flexibility of operation over a wide range of speeds.

Disadvantages/Limitations:

- The main disadvantage is that at high speeds, due to shocks and flow separation. The propeller efficiency decreases rapidly, thereby, putting up a maximum speed limit on the engine.
- It requires a reduction gear which increases the cost and also consumes certain amount of energy developed by the turbine in addition to requiring more space.

6. Describe the principle operation of Turbojet engine with neat diagrams.

Or

Illustrates typical parts of jet engine

Turbojet engine

Working principle:

- The turbojet engine is a reaction engine. In a reaction engine, expanding gases push hard against the front of the engine.
- Turbojet engine derives its thrust by accelerating a mass of air through the core engine.
- The air taken in from an opening in the front of the engine is compressed to about 3-12 times its original pressure in a centrifugal or axial compressor.
- Fuel is added to the air and burned in a combustion chamber to raise the temperature of the mixer to about 1100^0C. The resulting hot air is passed through a turbine, which drives the compressor.

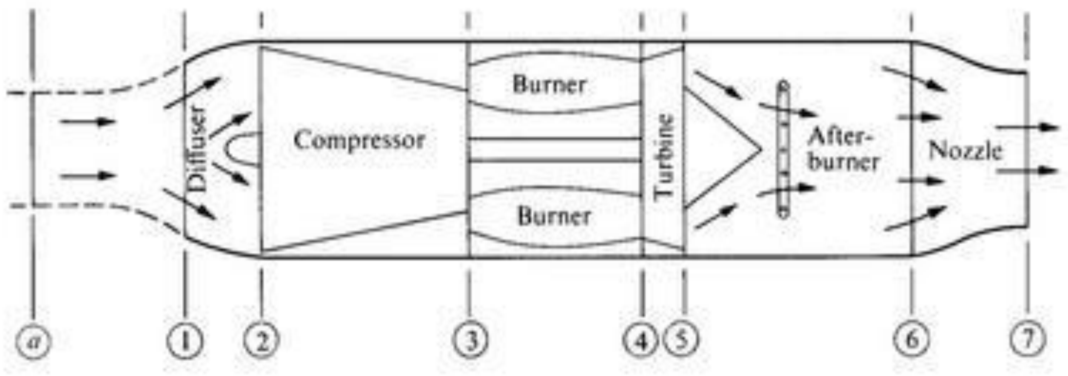


Fig: The turbojet engine

- If the turbine and compressor are efficient, the pressure at the turbine discharge will be nearly twice the atmospheric pressure.
- This excess pressure is sent to the nozzle to produce a high velocity stream of gas which produces the thrust. Thus all the propulsive force produced by a jet engine is derived from exhaust gases.
- An afterburner (or a reheat) is an additional component added to some jet engines. Primarily those on military supersonic aircrafts.

- Its purpose is to provide a temporary increase in thrust at the time of supersonic flight as well as takeoff.
- On military aircraft, the extra thrust is also useful for combat situations. This is achieved by injecting additional fuel into the jet pipe downstream of (after) the turbine.

Advantages/Merits:

- The power to weight ratio of a turbojet engine is about 4 times that of a propeller system having reciprocating engines.
- It is simple, easy to maintain and requires lower lubricating oil consumption. Furthermore, complete absence of liquid cooling results in reduced frontal area.
- There is no limit to the power output which can obtained from a turbojet while the piston engines have reached almost their peak power and further increase will be at the cost of complexity and greater engine weight and frontal area of the aircraft.
- The speed of the turbojet engine is not limited by the propeller and it can attain higher flight speeds than engine propeller aircrafts.

Disadvantages/Limitations:

- The fuel economy at low operational speeds is extremely poor.
- It has low takeoff thrust and hence poor starting characteristics.

7. Give explanation about Ramjet.

Ramjet engine

The fact of obtaining very high pressure ratios of about 8 to 10 by ram compression has made it possible to design a jet engine without a mechanical compressor. A deceleration of the air from Mach number 3 at diffuser inlet to Mach number 0.3 in combustion chamber would cause pressure ratio of more than 30. Due to shock and other losses inevitable at such velocities all of this pressure rise is not available; still whatever we get is more than sufficient for raising the air pressure to the required combustion pressure. This principle of ram pressure rise is used in the ramjet engines. The ram pressure rise can be achieved in diffusers.

It may be noted that the simplest types of air breathing engine is the ramjet engine and a simplified sketch of the engine is illustrated in Fig. 7.1. The engine consists of

(i) supersonic diffuser (1–2),

(ii) subsonic diffuser section (2–3),

(iii) combustion chamber (3–4), and

(iv) discharge nozzle section (4–5).

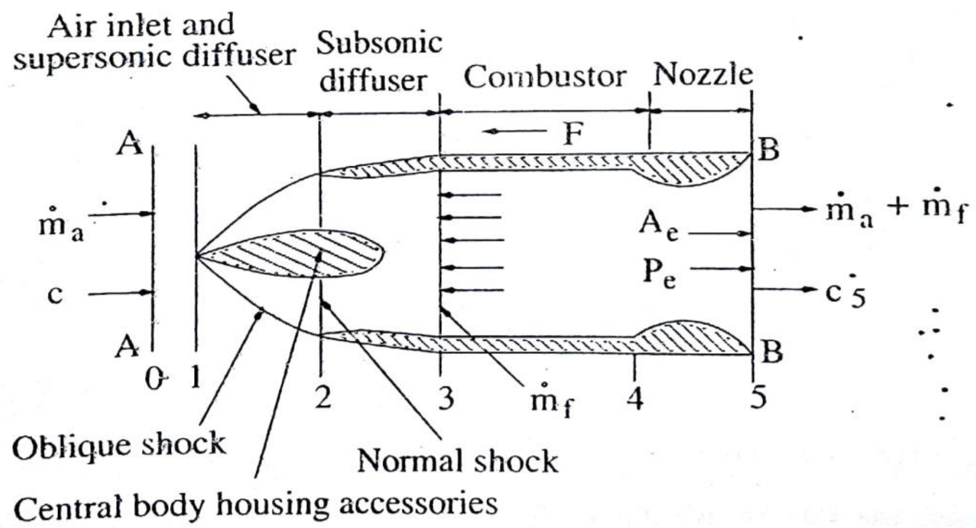


Fig. 7.1 Ramjet engine

Both supersonic and subsonic diffusers convert the kinetic energy of the entering air into pressure rise. This energy transformation is called *ram effect* and the pressure rise is called the *ram pressure*. The principle of operation is as follows:

Air from the atmosphere enters the engine at a very high speed and its velocity gets reduced first in the supersonic diffuser, thereby its static pressure increases. The air then enters the subsonic diffuser wherein it is compressed further. Afterwards the air flows into the combustion chamber, the fuel is injected by suitable injectors and mixed with the unburnt air. The air is heated to a temperature of the order of 1500 – 2000 K by the continuous combustion of fuel. The fresh supply of air to the diffuser builds up pressure at the diffuser end so that these gases cannot expand towards the diffuser. Instead, the gases are made to expand in the combustion chamber towards the tail pipe. Further, they are allowed to expand in the exhaust nozzle section. The products will leave the engine with a speed exceeding that of the entering air. Because of the rate of increase in the momentum of the working fluid, a thrust, F, is developed in the direction of flight.

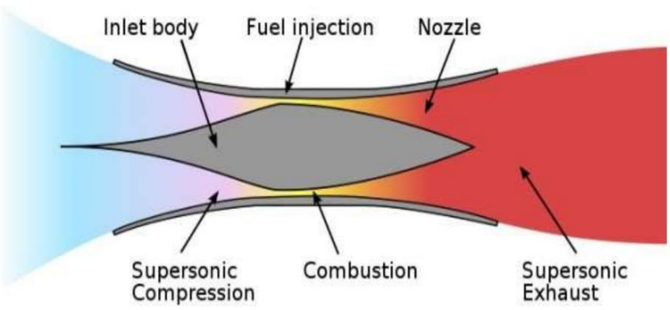
Normally, the air enters the engine with a supersonic speed which must be reduced to a subsonic value. This is necessary to prevent the blow out of the flame in the combustion chamber. The velocity must be small enough to make it possible to add the required quantity of fuel for stable combustion. Both theory and experiment indicate that the speed of the air entering the combustion chamber should not be higher than that corresponding to a local Mach number of 0.2 approximately.

The cycle pressure ratio of a ramjet engine depends upon its flight velocity. The higher the flight velocity the larger is the ram pressure, and consequently larger will be the thrust. This is true until a condition is reached where the discharge nozzle becomes chocked. Thereafter, the nozzle operates with a constant Mach number of 1 at its throat. Therefore, a ramjet having fixed geometry is designed for a specific Mach number and altitude, and at the design point, will give the best performance.

8. Give explanation about Scramjet.

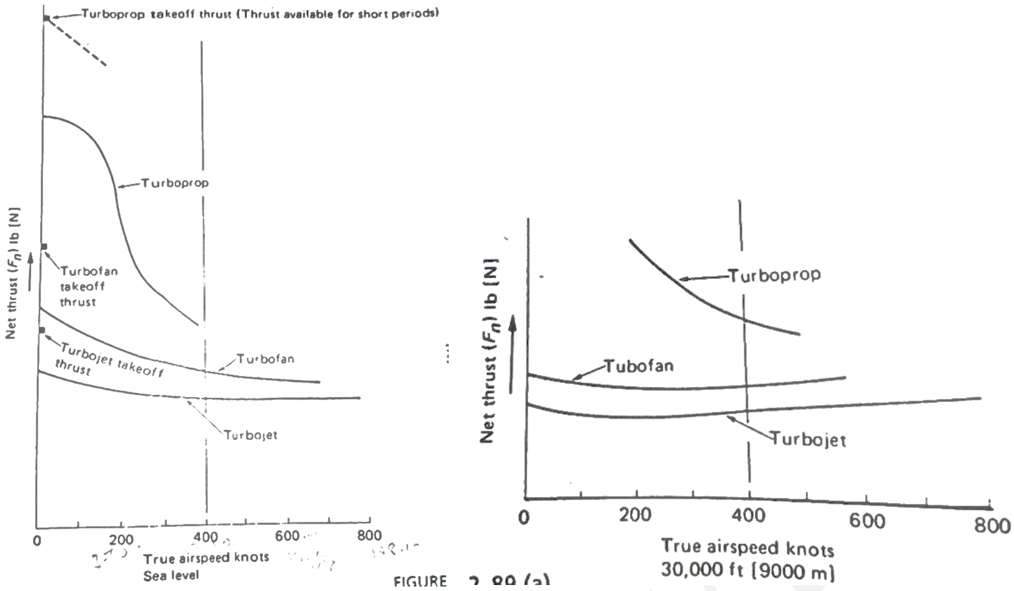
Scramjet

- A Scramjet (supersonic combustion ramjet) is a variant of a ramjet air breathing combustion jet engine in which the combustion process takes place in supersonic airflow.
- As in ramjets, a scramjet relies on high vehicle speed to forcefully compress and decelerates the incoming air before combustion (hence ramjet), but whereas a ramjet decelerates the air to subsonic throughout the entire engine.
- The theoretical projections place top speed of scram between Mach 12 and Mach 24, which is near orbital velocity.
- The Scramjet is composed of three basic components:
    - A CONVERGING INLET, where incoming air is compressed and decelerates.
    - A COMBUSTER, where gaseous fuel is burned with atmospheric oxygen to produce heat.
    - A DIVERGING NOZZLE, where the heated air is accelerated to produce thrust.



9. Discuss about the performance characteristic of Turbojet, Turboprop and Turbofan engines.

Thrust compared to airspeed (Velocity/Mach no) at sea level and at 30,000 ft (9,000m)



- From the above graphs we can say that the turboprop engine is produces more takeoff thrust compared to turbojet and turboprop engines.
- The turboprop engine initially produces more thrust but as speed of the aircraft increase, the thrust will decreases because of the flow separation over a propeller blades.
- In turbojet engine throughout the flight condition constant thrust will produces.
- The turbofan engine lies in between turboprop and turbojet for production of thrust with respect to aircraft speed.

Comparison of thrust and specific fuel consumption

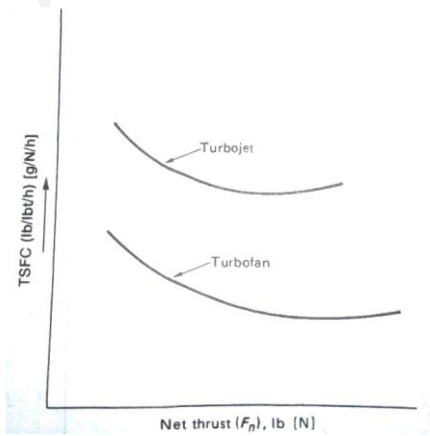


Fig: Comparison of thrust specific fuel consumption (TSFC) with thrust for turbojet and turbofan engines

Thrust specific fuel consumption (TSFC) versus airspeed at sea level and at 30,000 ft (9,000m)

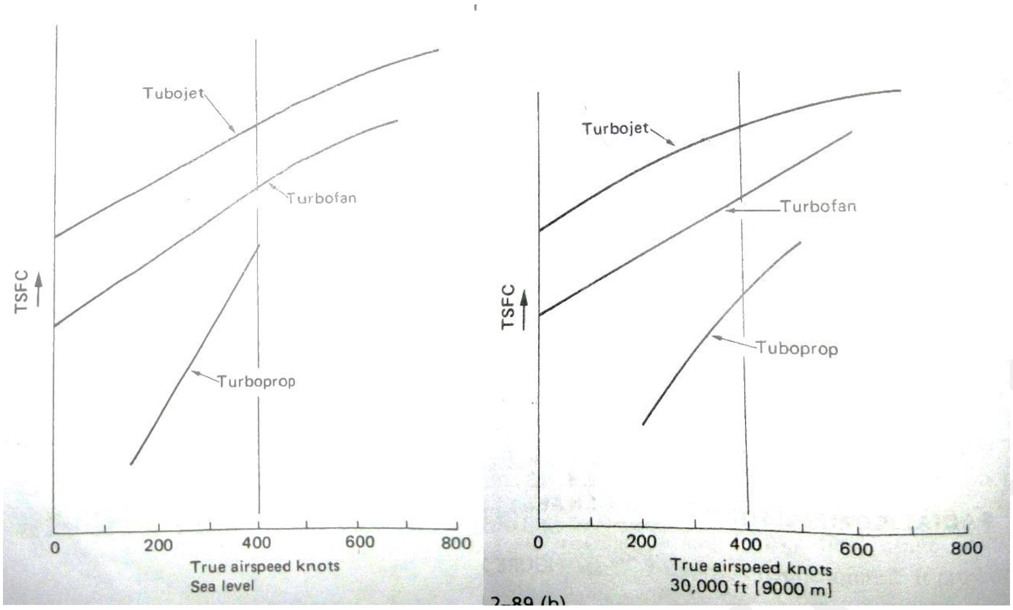


Fig: Thrust specific fuel consumption (TSFC) versus airspeed at sea level and at 30,000 ft (9,000 m)

10. *Problem*

Consider a turbojet-powered airplane flying at a standard altitude of 30,000 ft at a velocity of 500 mi/h. The turbojet engine itself has inlet and exit areas of 7 and 4.5 ft², respectively. The velocity and pressure of the exhaust gas at the exit are 1600 ft/s and 640 lb/ft², respectively. Calculate the thrust of the turbojet.

■ Solution

At a standard altitude of 30,000 ft, from App. B, $p_\infty = 629.66$ lb/ft², and $\rho_\infty = 8.9068 \times 10^{-4}$ slug/ft³. The free-stream velocity is $V_\infty = 500$ mi/h $= 500(88/60) = 733$ ft/s. Thus, the mass flow through the engine is

$$\dot{m}_{air} = \rho_\infty V_\infty A_i = (8.9068 \times 10^{-4})(733)(7) = 4.57 \text{ slugs/s}$$

From Eq. (9.25), the thrust is

$$\begin{aligned} T &= \dot{m}_{air}(V_e - V_\infty) + (p_e - p_\infty)A_e \\ &= 4.57(1600 - 733) + (640 - 629.66)(4.5) \\ &= 3962 + 46.5 = \boxed{4008.5 \text{ lb}} \end{aligned}$$

11. Derive the fundamental thrust equation for jet engine.

The Thrust Equation

Let us consider the control volume of a schematic propulsive device shown in Fig. 7.16. A mass $\dot{m}_i$ of air enters the control volume with a velocity c_i and pressure p_i and the products of combustion of mass $\dot{m}_j$ leaves the control volume with a velocity c_j and pressure p_j. The flow is assumed to be steady and reversible outside the control volume, the pressure and velocity being constant over the entire control volume except that at the exhaust area A_j. Force F is the force necessary to balance the thrust produced due to change in momentum of the fluid as it passes through the control volume.

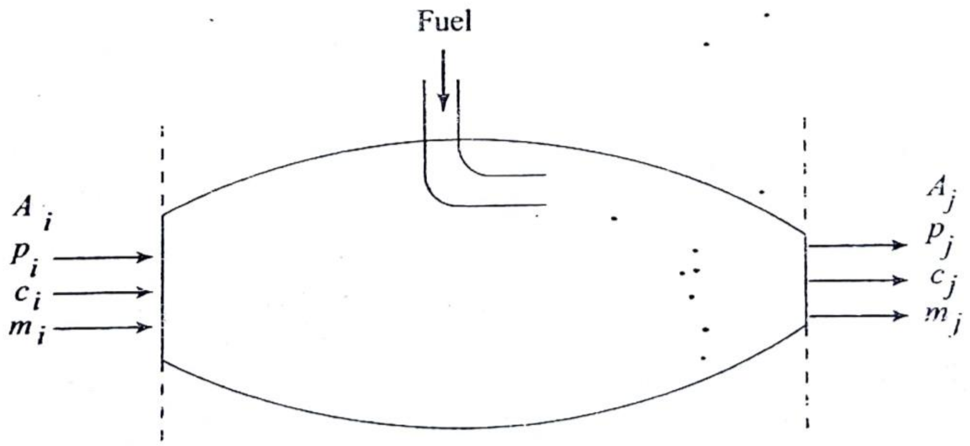


Fig. 7.16 General schematic diagram of a propulsive device

If p_a is the atmospheric pressure, then writing the momentum equation, we get

$$\dot{m}_j c_j - \dot{m}_i c_i = F + (p_i - p_a)A_i - (p_j - p_a)A_j \quad (7.6)$$

or thrust,

$$F = (\dot{m}_j c_j - \dot{m}_i c_i) + (p_j - p_a)A_j - (p_i - p_a)A_i$$

We have by mass balance,

$$\dot{m}_j = \dot{m}_i + \dot{m}_f \quad (7.7)$$

where $\dot{m}_j, \dot{m}_i$ and $\dot{m}_f$ are the mass flow rates of exhaust gases, air, and fuel respectively. If

$$f = \text{Fuel air ratio} = \frac{\dot{m}_f}{\dot{m}_i}$$

$$\dot{m}_j = \dot{m}_i(1 + f)$$

$$\text{Thrust} = \underbrace{\dot{m}_i[(1+f)c_j - c_i]}_{\text{Momentum thrust}} + \underbrace{(p_j - p_a)A_j - (p_i - p_a)A_i}_{\text{Pressure thrust}} \tag{7.8}$$

From Eq. 7.8 it is clear that the net thrust produced is made up two parts, viz., momentum thrust and the pressure thrust . If the exhaust velocity c_j from the control volume is subsonic, then $p_j \approx p_a$ and also $p_i \approx p_a$ so that the pressure thrust is quite small. Similar is the case for propeller engines. For supersonic exhaust velocity the pressure p_j may differ from p_a. However, the pressure thrust developed is so small as compared to the momentum thrust that it can safely be neglected for simple calculations and the net thrust is given by

$$\text{Thrust} = \dot{m}_i[(1+f)c_j - c_i] \tag{7.9}$$