Module 1

TYPES, VARIATION AND APPLICATIONS & ENGINE PARTS

Syllabus:

Types, Variation and Applications:

Types of engines showing arrangement of parts. Operating parameters. Energy distribution of turbojet, turboprop and turbofan engines. Comparison of thrust and specific fuel consumption. Thrust, pressure and velocity diagrams.

Engine Parts:

Compressor assembly, types of burners: advantages and disadvantages. Influence of design factors on burner performance. Effect of operating variables on burner performance. Performance requirements of combustion chambers. Construction of nozzles. Impulse turbine and reaction turbine. Exhaust system, sound suppression. Thrust reversal: types, design & systems. Methods of thrust augmentation, afterburner system.

1.1 Types of engines showing arrangement of parts

1.1.1 Turbojet engine

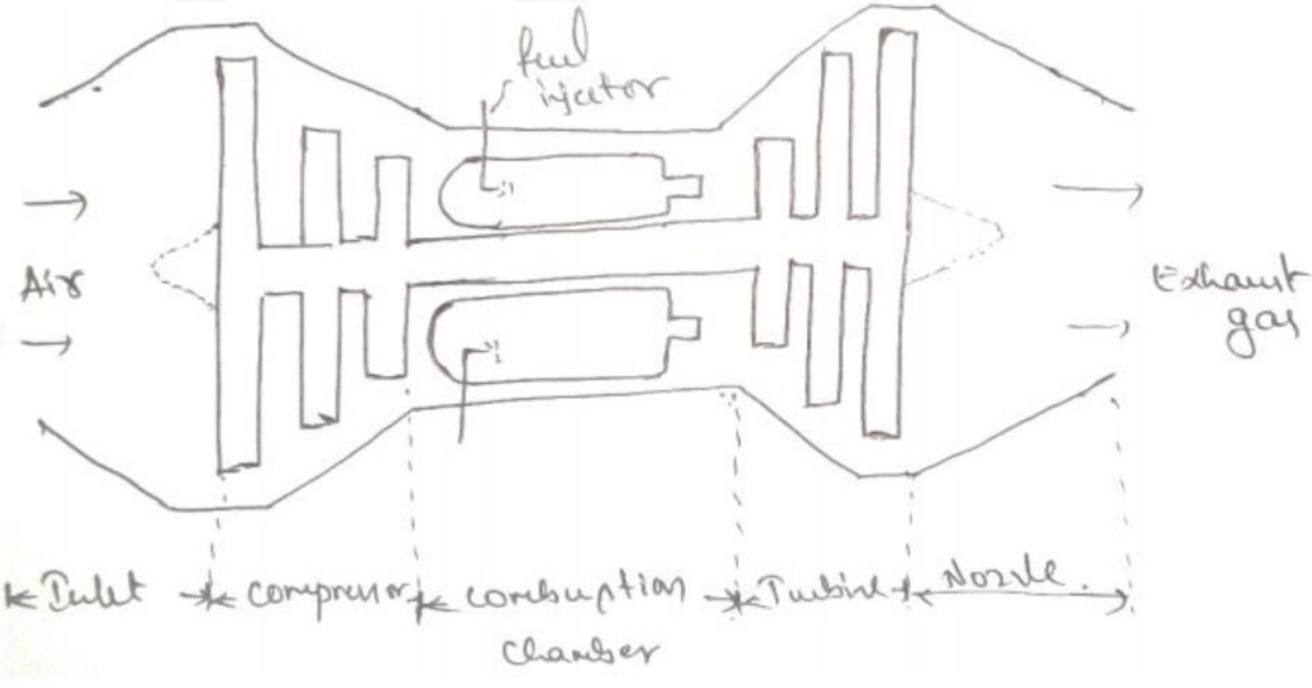


Fig: The turbojet engine

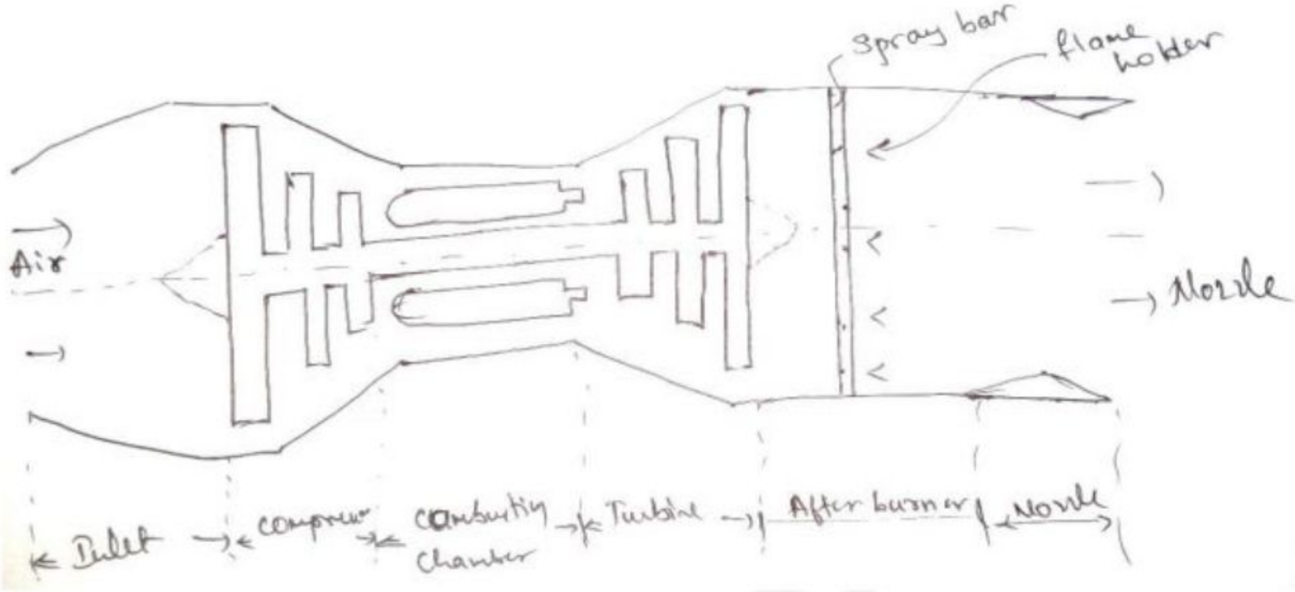


Fig: The turbojet engine with afterburner

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.
- 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.

Characteristics:

- Low thrust at low forward speed.
- Relatively high, thrust specific fuel consumption (TSFC) at low altitude and airspeeds, a disadvantage that decreases as altitude and airspeed increase.
- Long takeoff roll.
- Small frontal area, resulting in low drag and reduced ground clearance problems.
- Lightest specific weight.
- Ability to take advantage of high ram pressure ratios.

Advantages:

- 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:

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

1.1.2 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.

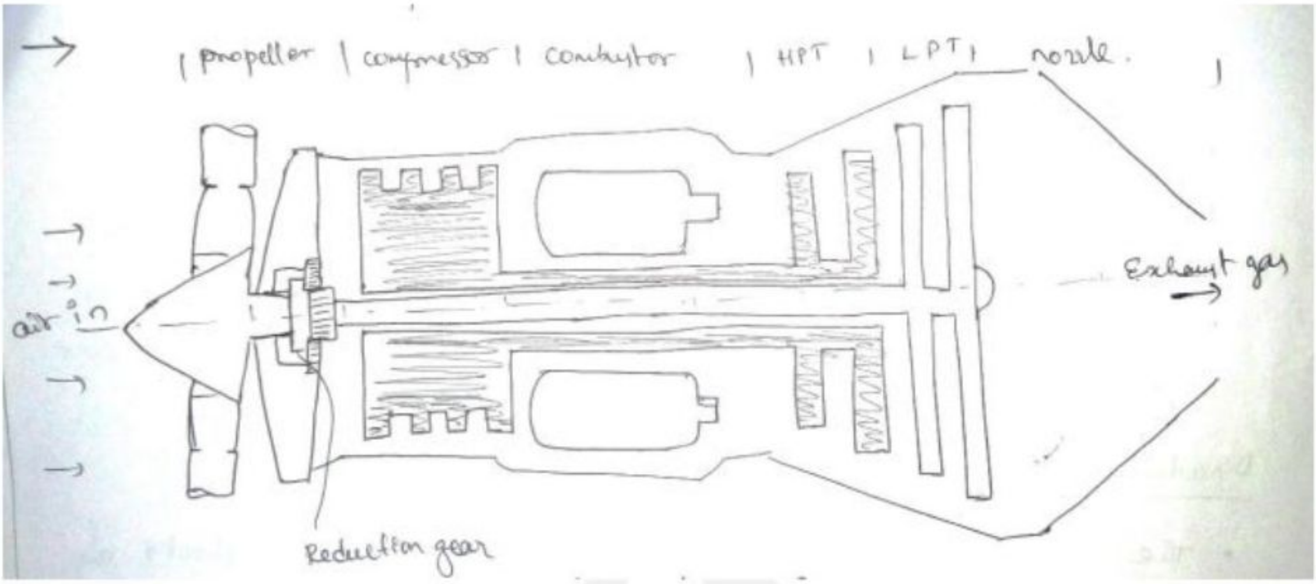


Fig: Turboprop engine

- 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.

Characteristics:

- High propulsive efficiency at low airspeeds, which results in shorter takeoff rolls but fall rapidly as airspeed increases.
- More complicated design and heavier weight than a turbojet.
- Lowest TSFC.
- Large frontal area of propeller and engine combination that necessitates longer landing gears for low wing air planes but does not necessarily increase parasitic drag .
- Possibility of efficient reverse thrust.

Advantages:

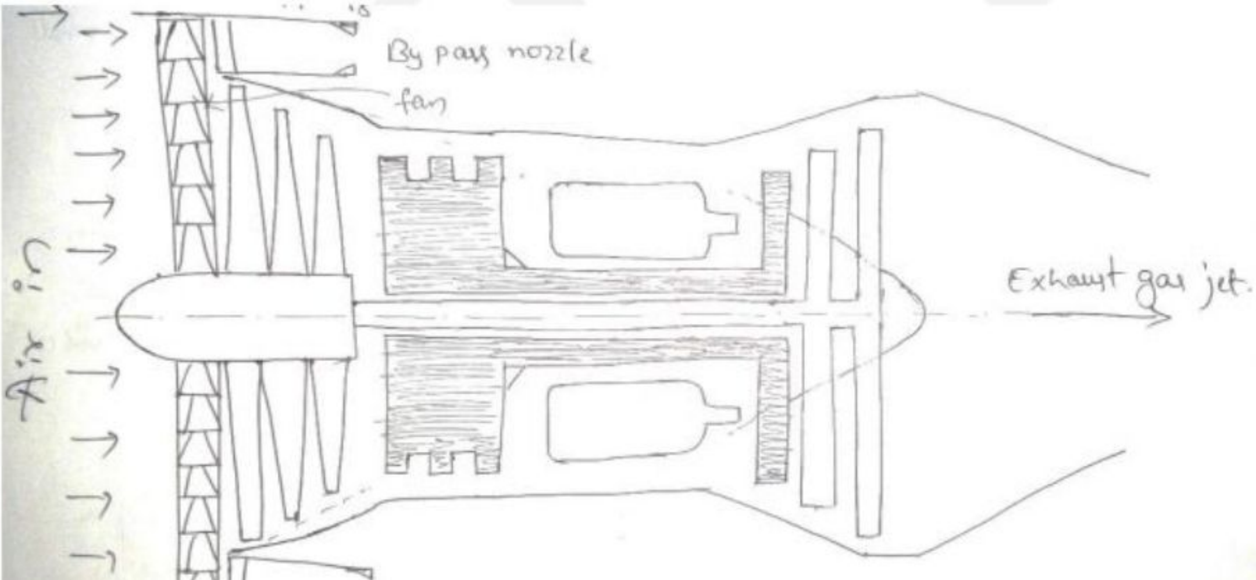
- Turboprop engines have a higher thrust at takeoff and better fuel economy.
- The frontal area is less than propeller engines so that drag is reduced.

- 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:

- 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.

1.1.3 Turbofan engine



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. However, the fan discharge is generally higher than the compressor discharge.
- 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.

Characteristics:

- Increased thrust at forward speeds similar to turboprop results in a relatively short takeoff. However, unlike the turboprop, the turbofan thrust is not penalized with increasing airspeed, up to approximately Mach 1 with current fan designs.
- Weight falls between turbojet and turboprop.
- Ground clearances are less than turboprop but not as good as turbojet.
- TSFC and specific weight falls between turbojet and turboprop, resulting in increased operating economy and aircraft range over the turbojet.
- Considerable noise level reduction of 10 to 20 percent over the turbojet reduces acoustic fatigue in surrounding aircraft parts and is less objectionable to the people on the ground.

Advantages:

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

Disadvantages:

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

1.1.4 Turboshaft engine

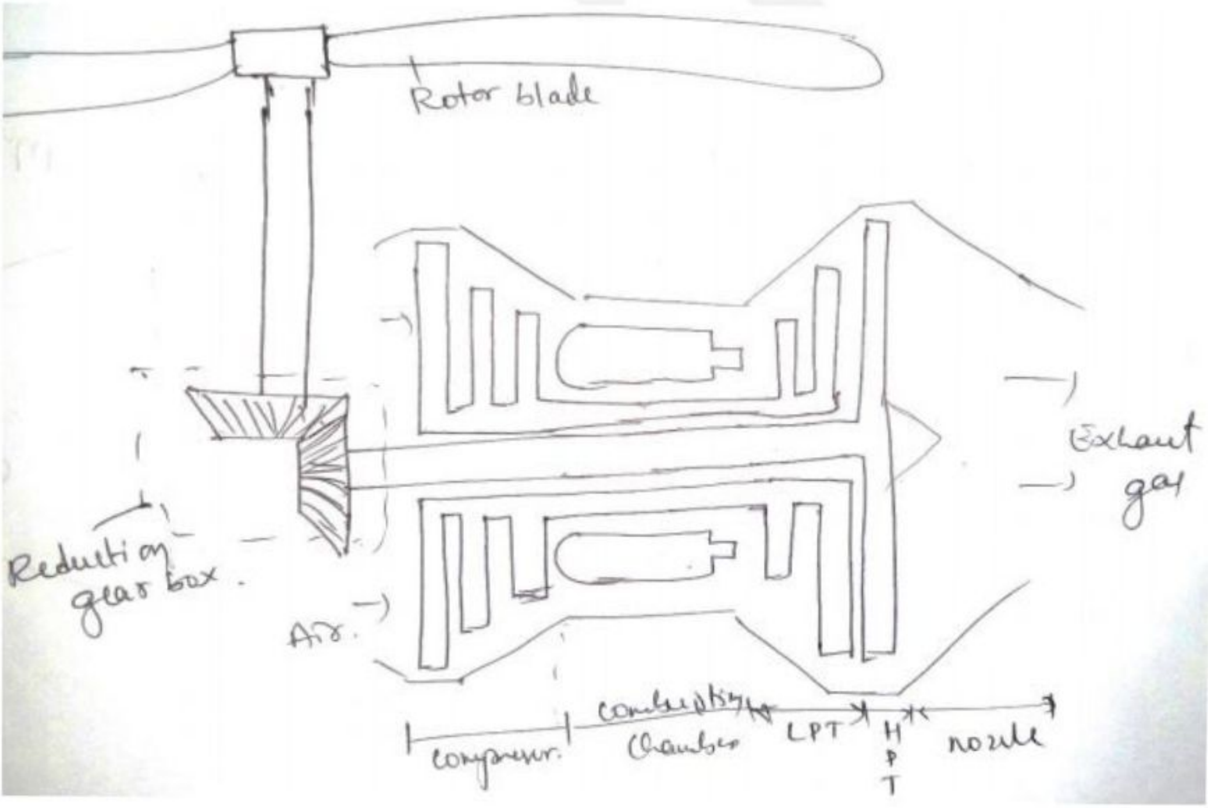


Fig: Turboshaft engine

Working principle:

- This is another form of gas turbine engine that operates similar to a turboprop engine.
- A gas turbine engine that delivers power through a shaft to operate something other than a propeller is referred to as a turboshaft engine. This type of engine is used to power helicopters. It does not drive a propeller.

- The turboshaft engine is designed so that the speed of the helicopter rotor is independent of the rotating speed of the gas generator. This permits the rotor speed to be kept constant even when the speed of the generator is varied to modulate the amount of power produced.
- Turboshaft engine derives its propulsion by conversion of gas stream energy into mechanical power to drive the compressor, accessories, etc. like that of a turboprop engine.
- The shaft, on which the free turbine is mounted, drives the rotor of a helicopter through the reduction gearbox.

Advantages:

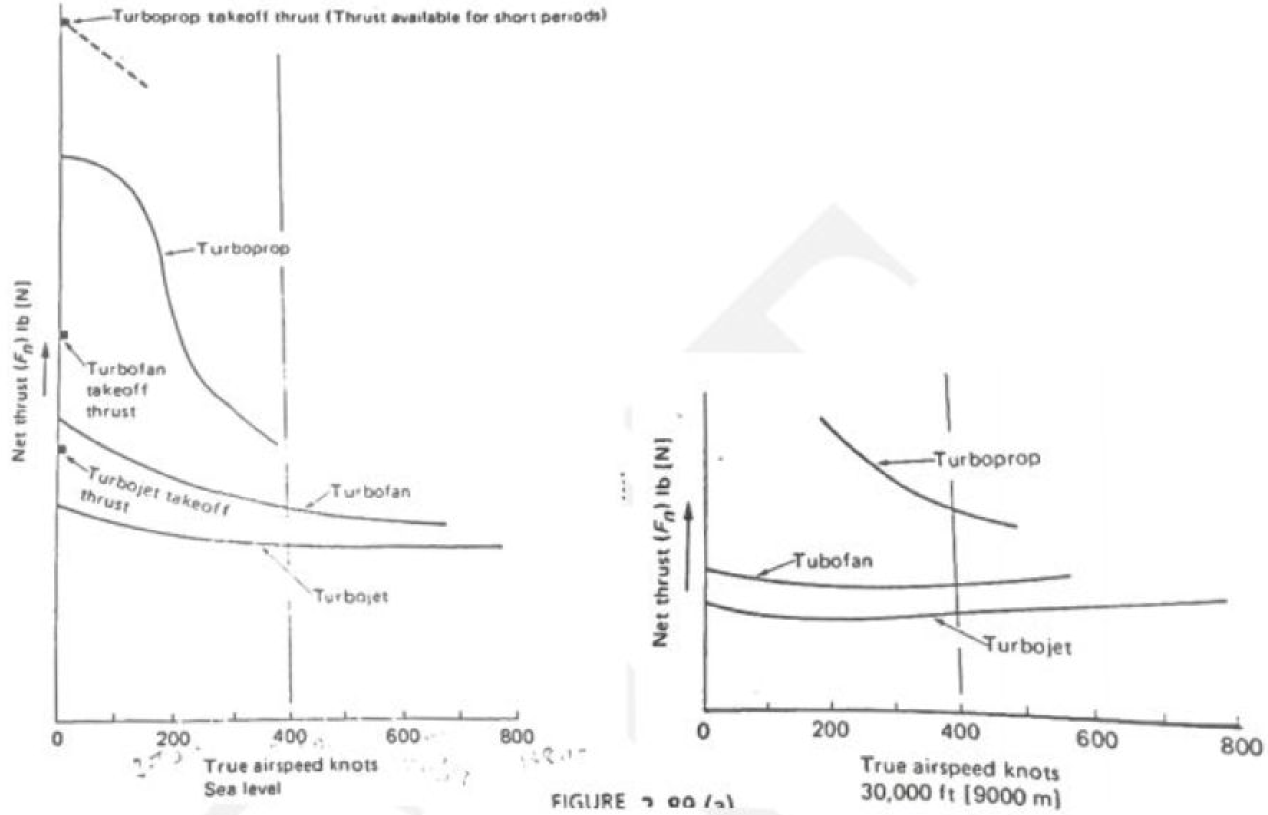
- Freedom from vibration-permits lighter propeller sections and mounting structure.
- Available supply of compressed air.
- Decreased fire hazard – less volatile fuels are used.
- Lower specific weight.
- Lower oil consumption.

Disadvantages:

- High specific fuel consumption at low air speeds – applies chiefly to pure jet engines have performance comparable to reciprocating engines.
- Inefficient operation at low power levels.
- Slow acceleration from minimum to maximum power level – this condition applies chiefly to turbojet engines. Turboprop and turbofan engines are able to accelerate quite rapidly.
- High starting power requirements.
- High cost manufacture.
- Susceptibility to damage by foreign material – such material is readily drawn into the air inlet.

1.2 Operating parameters of the turbojet, turboprop and turbofan engines

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



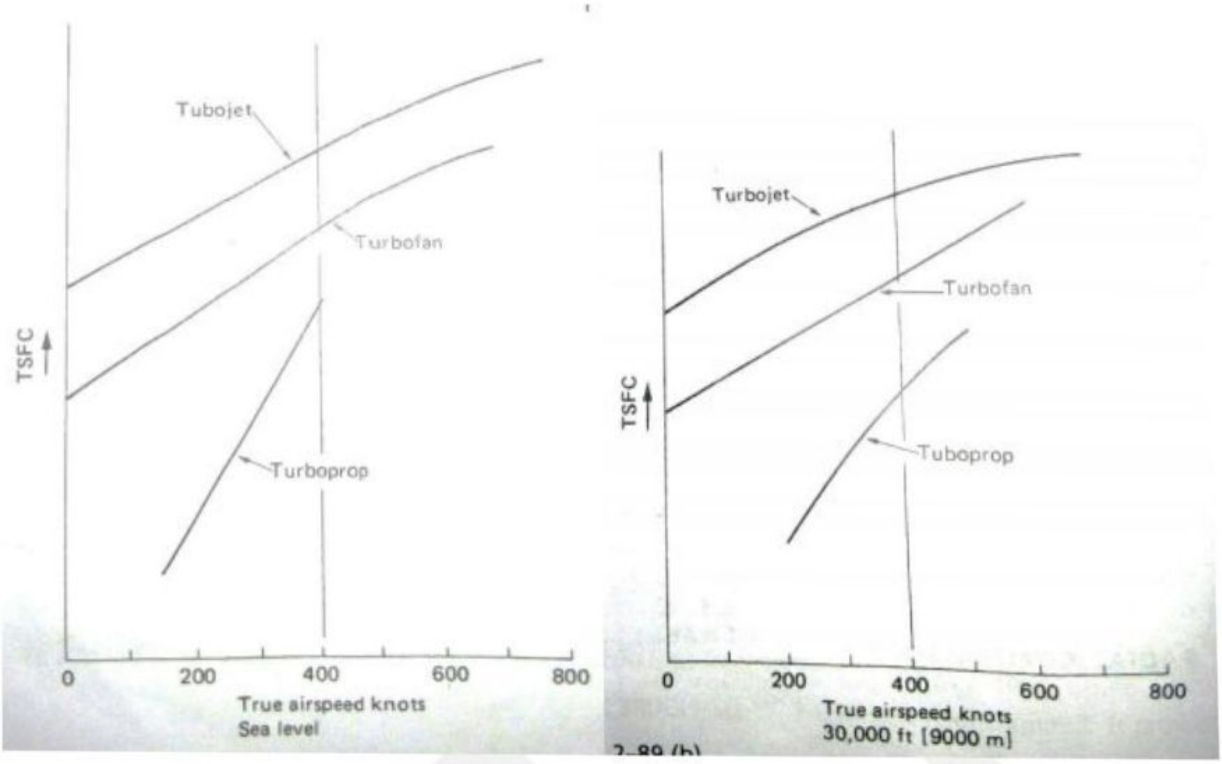
(a) (b)

Fig: Thrust compared to airspeed at sea level and at 30000 ft (9000m)

Note:	1 knot = 0.0015 Mach
	200 knots = 0.3 Mach
	400 knots = 0.6 Mach

- 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.

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



(a) (b)

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

1.3 Comparison of thrust and specific fuel consumption

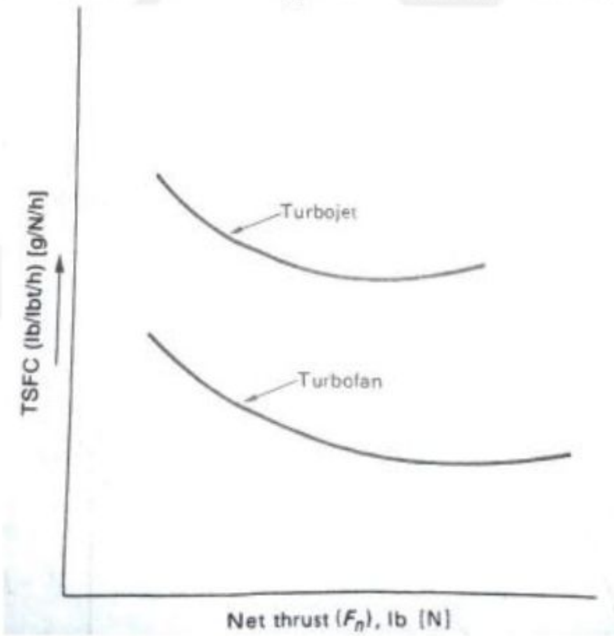


Fig: Comparison of thrust specific fuel consumption (TSFC) with thrust for turbojet and turbofan engines

1.4 Energy distribution of turbojet, turboprop and turbofan engines

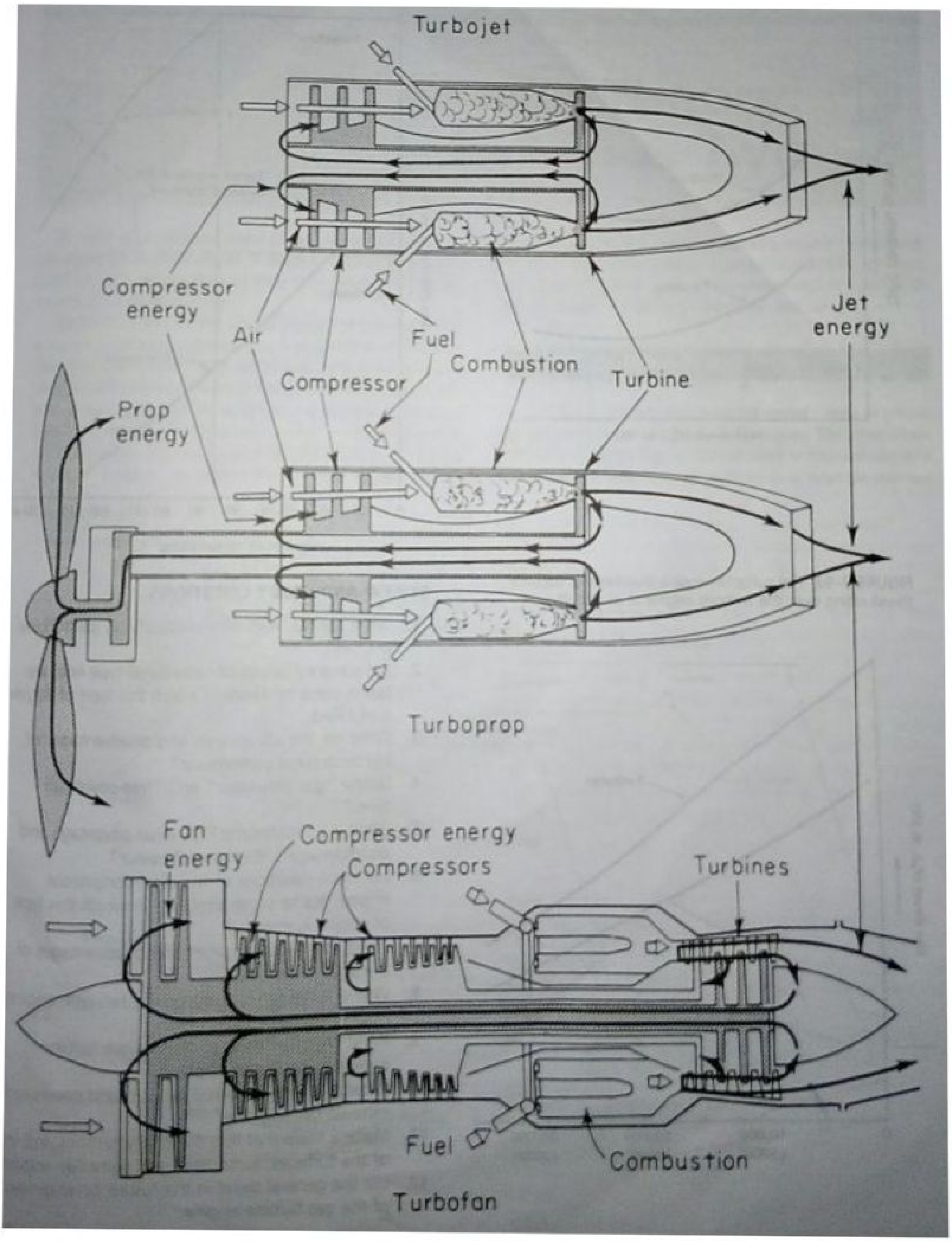


Fig: Energy distribution of the turbojet, turboprop and turbofan engines

- (First need to write the working principle of the respective engine. Afterwards illustrate the energy distribution)
- The fuel is injected in to the combustion chamber and air fuel mixer takes place. After ignition, the heat energy is going to form.

- The heat energy from the combustor is converted into kinetic energy. Some part of KE is than used to rotate the turbine stages and other part is passed to the nozzle section as a jet energy.
- Here turbine section is directly connected with the compressor section. So when turbine rotates, the compressor also rotates using from compressor energy.

1.6 Compressor assembly

The role of the compressor in the gas turbine engine is to provide a maximum of high pressure air that can be heated in the limited volume of the combustion chamber and then expanded through the turbine.

The energy that released in the combustion chamber is proportional to the mass of air consumed; therefore the compressor is one of the most important components of the gas turbine engine since its efficient operation (maximum compression with minimum temperature rise) is the key to high overall engine performance.

Present-day compressors have compression ratios over 25:1, efficiencies over 90%, and airflows up to approximately 158.8 kg/s (350 lb/s). With addition of a fan, total pressure ratios of more than 25:1 and mass airflows of 453.6 kg/s (1000 lb/s) have been achieved.

The importance of the good compressor design can be illustrated by pointing out that for a high bypass ratio turbofan, each 1 percent improvement in the fan efficiency can result in a 0.75 percent improvement in specific fuel consumption, and for each 1 percent improvement in the high pressure compressor, a 0.5 percent change in specific fuel consumption is obtained.

1.6.1 Types of Compressors

All the turbine engines use one of the forms of compressors:

- Centrifugal flow compressor
- Axial flow compressor
- Centrifugal-axial flow compressor

1.6.1.1 Centrifugal flow compressor

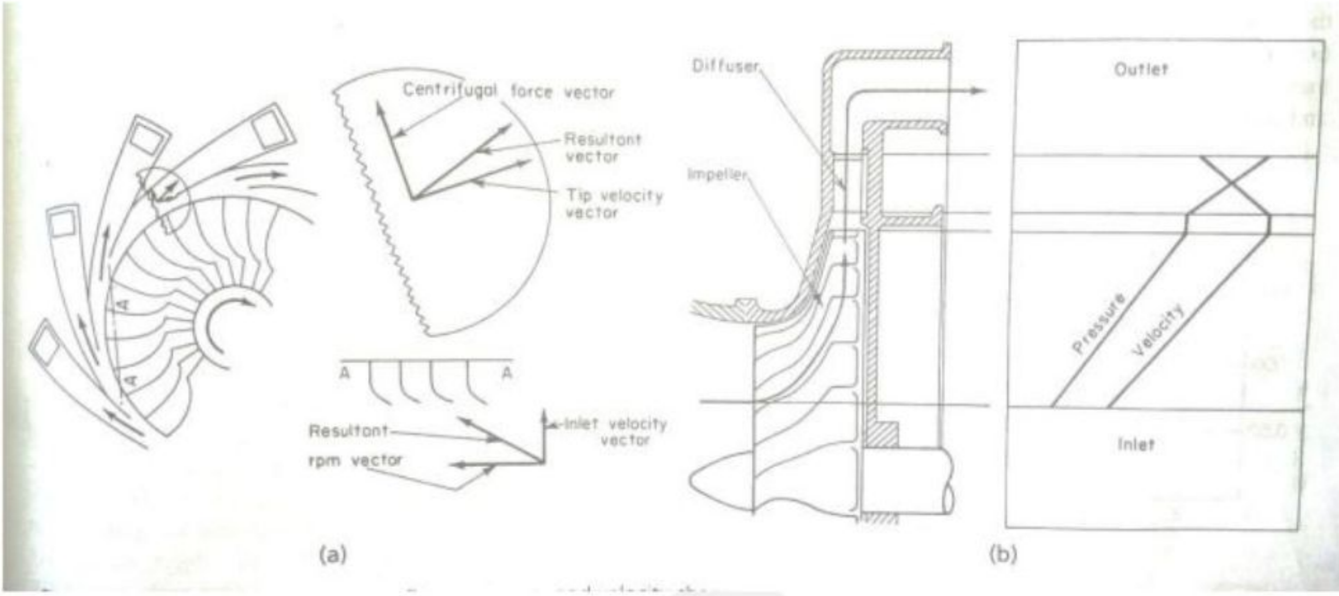


Fig: Centrifugal compressor flow, pressure and velocity changes. (a) Airflow through a typical centrifugal compressor (b) Pressure and velocity changes through a centrifugal compressor

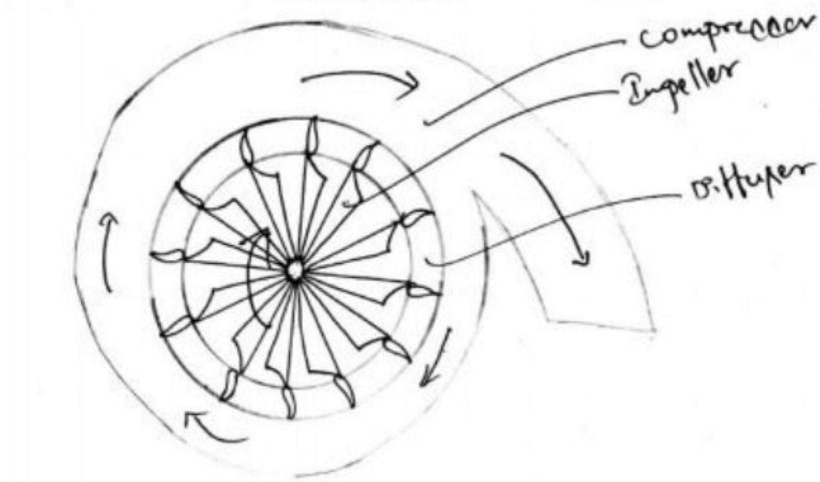


Fig. Schematic diagram of centrifugal compressor.

- The centrifugal compressor consists of basically of an impeller and a diffuse manifold. Other components such as a compressor manifold may be added to direct the compressed air into the combustion chamber.
- As the impeller revolves at high speed, air is drawn in at the eye or inducer.
- Centrifugal force provides high acceleration to this air and causes it to move outward from the axis of rotation toward the rim of the rotor, where it is ejected at high velocity and high kinetic energy of motion into static pressure energy.
- The total compression is shared between the rotor and the diffuser does not work on the air.
- Centrifugal compressors could be manufactured in a variety of designs including single stage, multiple stage and double sided types.

- The centrifugal compressor is capable of relatively high compressor ratio per stage. About 80% efficiency may be reached with a compression ratio of 6 or 7 to 1.
- Above this ratio, efficiency drops off at a rapid rate because of excessively high impeller tip speeds and attending shock wave.

Advantages of centrifugal compressor

- Low weight, easy to design and manufacture.
- Relatively energy efficient.
- Wide range of rotational speed.
- Centrifugal compressors are reliable, low maintenance.
- Generating a higher pressure ratio per stage as compared to axial flow compressor.

Disadvantages of centrifugal compressor

- Large frontal area for a given air flow rate compared to the axial flow compressor.
- Unsuitable for very high compression, limited pressure.
- They work at high speed, sophisticated vibration mounting needed.
- Problem of surging, stalling and choking

1.6.1.2 Axial flow compressor

- The axial flow compressor is made up of a series of rotating airfoils called rotor blades and a stationary set of airfoils called stator vanes.
- As its name implies, the air is being compressed in a direction parallel to the axis of the engine.
- A row of rotating and stationary blades is called a stage.
- The entire compressor is made up of a series of alternating rotor and stator vane stages, with each stage constructed of blades shaped to provide the most lift for the least drag.
- Some axial flow have two or more compressors or spools driven by separate turbines, and the compressors are therefore free to rotate at different speeds.
- Axial compressors have the advantage of being capable of very high compression ratios with relatively very high efficiencies.

- In addition, the small frontal area created by this type of compressor lends to itself to installation in high speed aircraft.

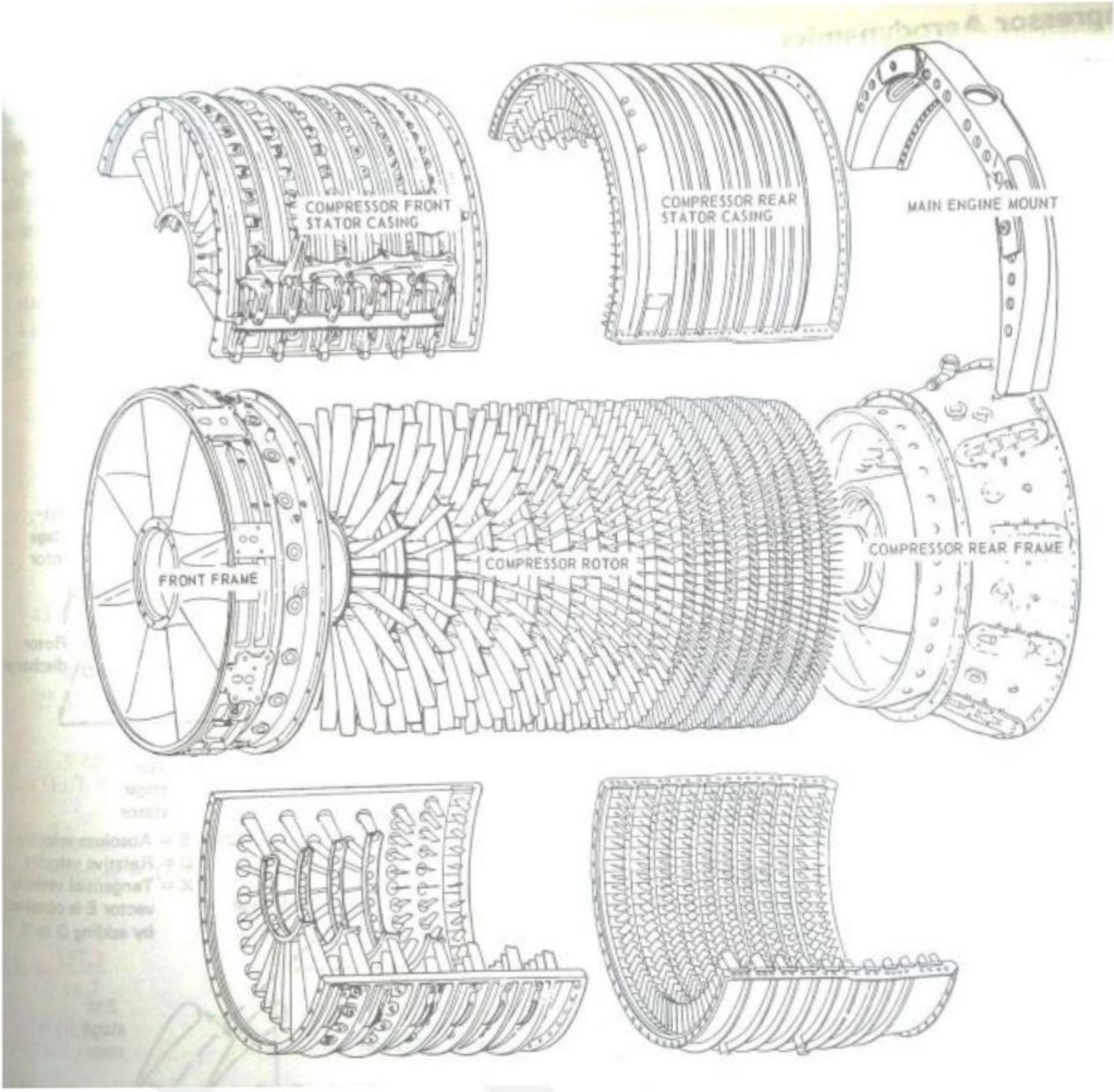
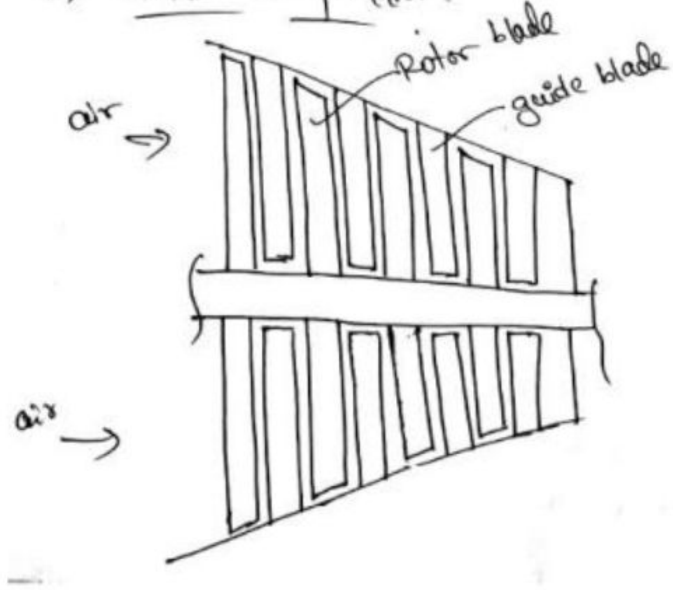


Fig: A modern high performance compressor assembly (General Electric)

(ii) Axial compressor:



- Unfortunately, the delicate blading, especially toward rear, makes this type of air pump especially susceptible to foreign object damage.
- Furthermore, the number of compressor blades and stator vanes (which can exceed 1000 in a large jet engine), the close fits required for efficient air pumping, and the narrow range of possible operating conditions makes this compressor very complex and very expensive to manufacture.

Axial-flow compressors have the following advantages:

- High peak efficiency.
- Small frontal area forgiven airflow.
- Straight-through flow, allowing high ram efficiency.
- Increased pressure rise due to increased number of stages with negligible losses.

They have the following disadvantages:

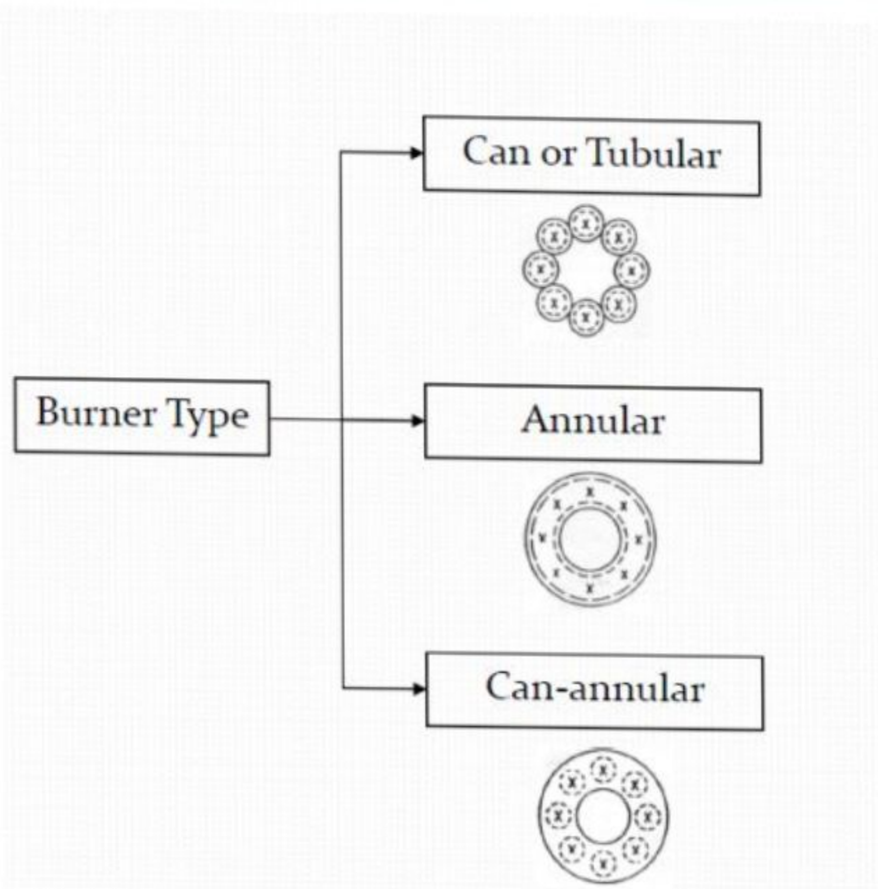
- Good efficiency over narrow rotational speed range.
- Difficulty of manufacture and high cost.
- Relatively high weight.
- High starting power requirements (this has been partially overcome by split compressors).

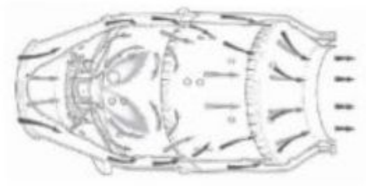
1.7 Combustion chamber

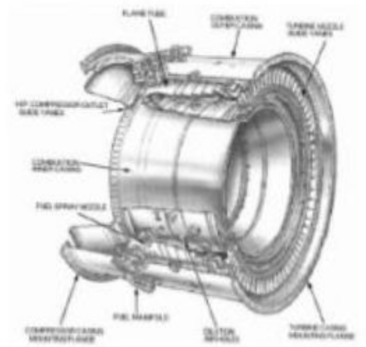
Combustion in the normal, open cycle, gas turbine is a continuous process in which fuel is burned in the air supplied by the compressor, an electric spark is required only for initiating the combustion process, and thereafter the flames must be self-sustaining. Combustion process occurs with the vaporized fuel and air mixed on a molecular scale. The principle requirements for a combustion chamber are:

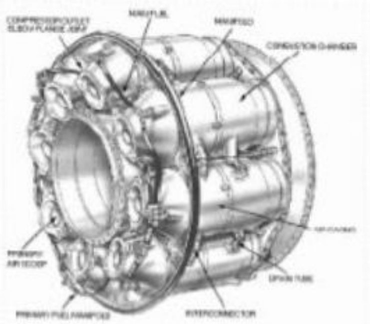
- Low weight and small frontal area
- Low pressure loss
- Stable and efficient combustion over the operating flight altitudes and speeds
- Reliability, serviceability and reasonable life
- Through mixing of hot and cold fluid streams to give a uniform temperature distribution throughout the final mixture arriving at the inlet to the turbine.

Combustion chambers must be designed to ensure stable combustion of the fuel injected and optimum fuel utilization within the limited space available and over a large range of air/fuel ratios. The combustion chamber design depends on the application and requirements in each case.

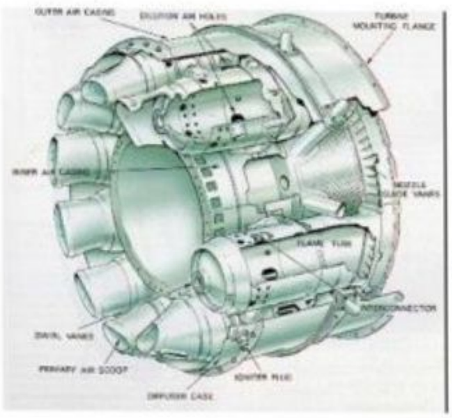


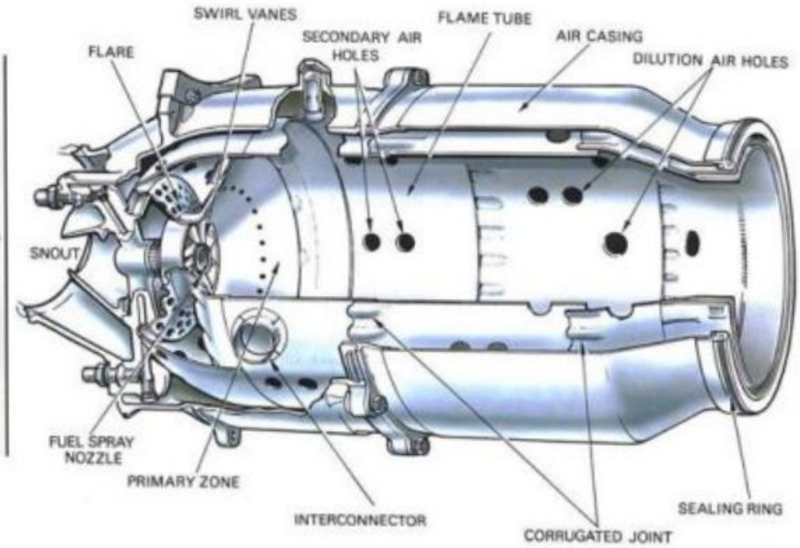






1.7.1 Can type combustor





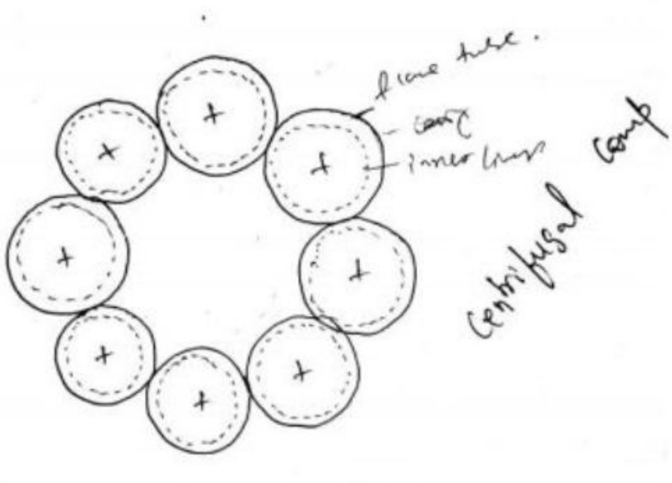


fig: can type combustor.

- Each can has its own fuel injector, ignitor, liner and casing.
- The primary air from the compressor is guided to each individual can, where it is decelerated, Mixed with the fuel and then ignited.
- This types of combustion chamber is used on centrifugal compressor type engines. it has several cans disposed around the engine.
- Each can consists of its own air outer with a flame tube (or burner lines) inside.
- Compressed air is ducted and to pass into the individual chambers. Each can contains its own fuel nozzle.
- The chamber cans are all interconnected. This allows each can to operate at the same pressure and also allows combustion to propagate around the flame tubes during engine starting.

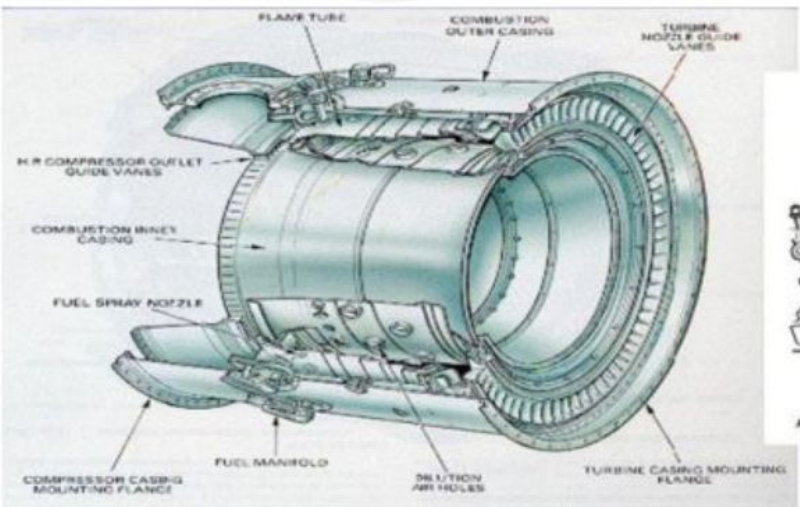
ADVANTAGES:

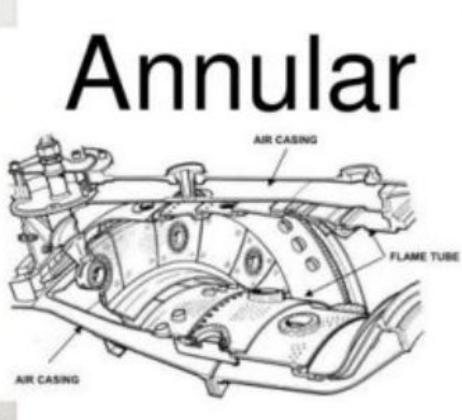
- ➢ The major advantage of can type combustion chambers was that development could be carried out on a single can using only a fraction of the overall air flow and fuel flow.
- ➢ low development cost
- ➢ favorable aerodynamic conditions in the flame tube
- ➢ favorable fuel distribution
- ➢ Good accessibility for servicing.

DISADVANTAGES:

- ➢ In aircraft application, these types of combustion chambers are undesirable because of more weight, more volume and more frontal area.
- ➢ Ignition problems may occur, particularly at high altitudes.
- ➢ A disadvantage of this design consists in the unfavorable inflow/outflow ratios and the associated large size.

1.7.2 Annular type combustor





Annular type combustion chamber:

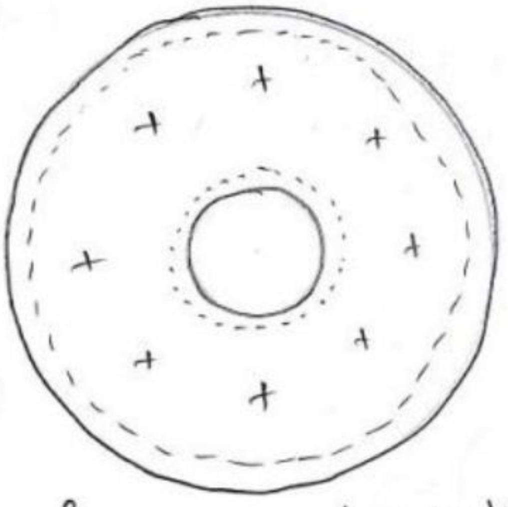


fig:. Annular type combustor.

- Some axial compressor engine have a single annular combustion chamber. This type combustion chamber consists of a single flame tube. Completely annular in form. Which is contained in the annulus of an inner and outer casing.
- Holes in the shrouds allow secondary cooling air to enter the center of the combustion chamber, keeping away from the shrouds.
- In this combustion chamber fuel is introduced through a series of nozzles at the upstream end of the liner.
- This type of combustor has the advantage of being able to use the limited space available most effectively. Permitting better mixing of fuel and air within a relatively simple structure.

ADVANTAGES:

- Low pressure losses
- Small size
- Good ignition behavior
- More number of fuel jets

DISADVANTAGES:

- Maintenance and inspection are difficult.
- The development expenditure for an annular combustion chamber is high and calculations are more complicated than with a can-type combustion chamber since the flow is no longer two-dimensional.
- Improper combustion due to uneven fuel air distribution.
- It is structurally weaker.

1.7.3 Can-annular type

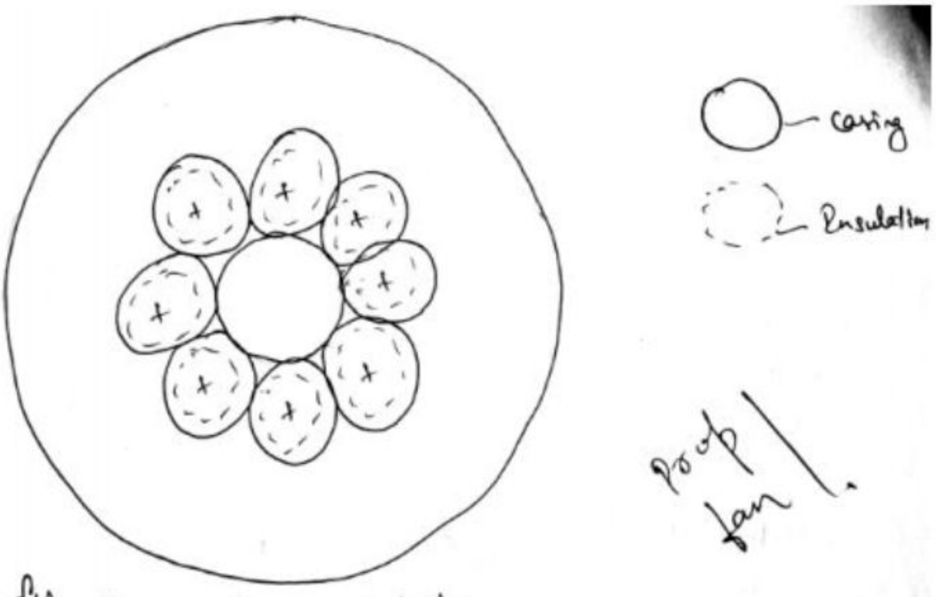


Fig.. Can-annular type combustor.

- This type of combustion chamber design is used on many large turbojet and turbofan engines.
- Individual burner cans are placed side by side to form a circle of cans inside an annular space between outer and inner air casings.
- The cans are essentially individual combustion chamber with concentric rings of perforated holes to admit air for cooling.
- The tube carries additional air, which enters the can through the perforations to provide more air for combustion and cooling.
- The effect is to permit more burning per inch of can length. Several fuel nozzles are placed around the perimeter of the forward end of the can.

ADVANTAGES:

- The use of a reverse flow arrangement allows a significant reduction in the overall length of the compressor-turbine shaft and also permits easy access to the fuel nozzles and combustion cans maintenance.
- They are suitable for large engine and for mechanical reasons, engines with high pressure ratios.
- Development costs are lower and the volume smaller than with a can-type combustion chamber.

DISADVANTAGES:

- The aerodynamic properties are inferior to that of an annular combustor.
- The connectors between the individual flame tubes adversely affect the ignition behavior.

1.7.4 Influence of design factors on burner performance

Methods of air distribution

- Since the quantity of air required for efficient combustion is much less than the total amount pumped through the engine, an important factor in burner design is the correct distribution of air between the combustion zone and the dilution zone.
- As more of the total airflow is used for combustion, a higher overall fuel/air ratio is needed to maintain maximum efficiency.
- The manner in which air is introduced into the burner also has a substantial effect on combustion efficiency.
- Therefore the size, number, shape and location of the air inlet holes has a marked influence on the burner performance.

Physical Dimensions of Burner

- One method is reducing the pressure loss is to increase the diameter or length of the burner.
- The increase allows the more time for the mixing of the hot and cold gases: hence the amount of energy required for mixing that must be supplied by a loss in pressure does not has to be as great.
- If the burner diameter is made too large, the pressure loss may have to be increased in order to produce adequate mixing and provide sufficient cooling for the added liner surface area.

Fuel – air operating range

- There are several ways in which the fuel/air ratio operating range or blowout limit of the burner can be increased.
- One is to cut down the flow velocity through the burner by increasing the diameter.
- Another is to improve fuel atomization and distribution by increasing the pressure drop across the fuel nozzle, or by improving the design of the nozzle metering elements.
- The fuel-air operating range of a burner can also be increased by improving the manner in which combustion air is introduced and distributed.

Fuel nozzle design

- Fuel nozzle design plays a major part in burner performance. Not only must the nozzle atomize and distribute the fuel, but it must also be able to handle a wide range of fuel flows.
- For a given fuel system there is a small pressure drop across the nozzle that must be maintained for good atomization and there is a maximum pressure that a practical fuel pump is able to produce.
- With the swirl type nozzle like those used in many domestic burners, the range of fuel flows that can be handled within these pressure limitations is usually far short of the engine's requirements.

1.7.5 Effect of operating variables on burner performance

Combustion efficiency:

- As the pressure of the air entering the burner increases, the combustion efficiency rises and levels off to a relatively constant value.
- As the inlet air temperature is increased, combustion efficiency rises until it reaches a value of substantially 100%.
- If the fuel/air ratio is increased, combustion efficiency first rises, then levels off when the mixture becomes too rich. An increase In fuel/air ratio will result in increased pressure loss because increase in fuel/air ratios cause higher temperature with a corresponding decrease in gas density.
- Increasing the flow velocity beyond a certain point reduces combustion efficiency, probably because it reduces the time available for mixing and burning.

Stable operating range:

- As the pressure decreases, the stable operating range becomes narrower until a point is reached below which burning will not takes place.
- As the velocity increases, the stable operating range again becomes narrower until a critical velocity is reached, above which combustion will not take place.
- Increasing the temperature of the incoming charge usually increases the fuel/air ratio range for stable operation.
- In addition, as the flow velocity is increased, the burner flow velocity will rise, mainly due to higher expansion losses as the air flows through the restricting or melting holes in the liner.

Temperature distribution:

- The temperature distribution of the burner exit is also affected by changes in the operating variables.
- Reducing the pressure below a set point tends to upset temperature uniformity.
- On the other hand, for a given size burner, more uniform burner may be obtained by better mixing of the hot and cold gases at the expense of an increase in pressure loss.
- If the fuel/air ratio and flow velocity are increased, the exit temperature tend to become less uniform because more heat is released and there is less time for mixing.

Starting:

- Starting is usually easier with high temperature, high pressure and low velocity.
- In addition, there is an optimum fuel/air ratio for starting, above or below which ignition of the fuel/air mixture becomes increasingly difficult.

Carbon deposits:

- The operating variables have some effect upon the accumulation of carbon deposits in the burner, but their effects may vary with different burner types and configurations.
- Generally, deposits gets worse with increasing temperatures and pressures until a point is reached where they begin to burn off.
- Increasing the fuel/air ratio has a tendency to increase deposits, probably because the proportion of oxygen in the combustion zone becomes too low to burn the fuel completely.
- In addition, changes in fuel/air ratio may change the location of carbon deposits within the burner.

Temperature and cooling requirements:

- Changes in the operating variables have a direct bearing on the temperature and cooling requirement of the liner.
- If the pressure and temperature of the incoming charge are increased, more heat is transferred from the burning gases to the liner, partly by radiation through the insulating blanket of cool air and partly by forced convection and the lining temperature goes up.

- If the fuel/air ratio increased combustion temperatures become higher and again the liner temperature increases, mainly due to increased radiation.
- On the other hand, an increase in flow velocity outside the liner tends to increase external convection, thereby reducing temperature of the liner.

1.7.6 Performance requirements of combustion chamber

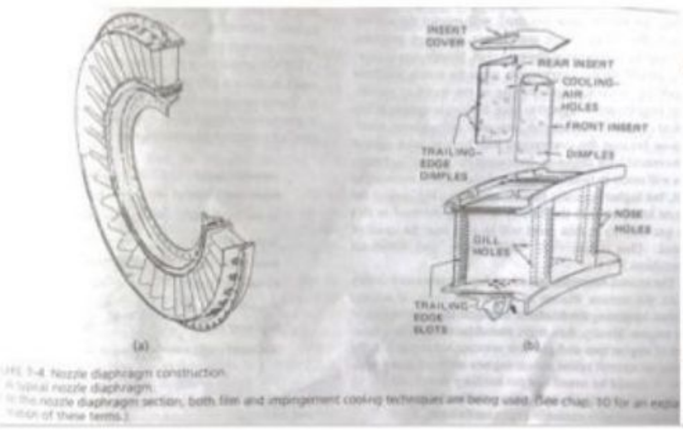
Combustion chambers require the following performance parameters:

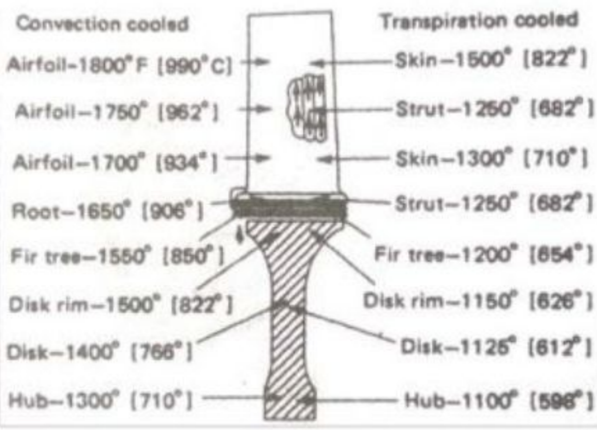
- ***High combustion efficiency*** - This is necessary for long range.
- ***Stable operation*** - Freedom from blowout at airflows ranging from idle to maximum power and at pressures representing the aircraft's entire altitude range is essential
- ***Low pressure loss*** - It is desirable to have as much pressure as possible available in the exhaust nozzle to accelerate the gases rearward. High pressure losses will reduce thrust and increase specific fuel consumption.
- ***Uniform temperature distribution*** - The average temperature of the gases entering the turbine should be as close to the temperature limit of the burner material as possible to obtain maximum engine performance. High local temperatures or hot spots in the gas stream will reduce the allowable average turbine inlet temperature in order to protect the turbine. This will result in a decrease in total gas energy and a corresponding decrease in engine performance.
- ***Easy starting*** - Low pressures and high velocities in the burner make starting difficult; therefore, a poorly designed burner will start within only a small range of flight speeds and altitudes, whereas a well-designed burner will permit easier air restarts.
- ***Small size*** - A large burner requires a large engine housing with a corresponding increase in the airplane's frontal area and an increase in aerodynamic drag. This will result in a decrease in maximum flight speed. Excessive burner size also results in high engine weight and, for a given aircraft, a lower fuel capacity and payload and shorter range. Modern burners release 500 to 1000 times the heat that a domestic oil burner or heavy industrial furnace of equal unit volume does. Without their high heat release the aircraft gas turbine could not have been made practical.
- ***Low-smoke burner*** - Smoke is not only annoying on the ground but may also allow easy tracking of high-flying military aircraft.

- ***Low carbon formation*** - carbon deposits can block critical air passages and disrupt airflow along the liner walls, causing high metal temperatures and low burner life.

1.8 Construction of the nozzle

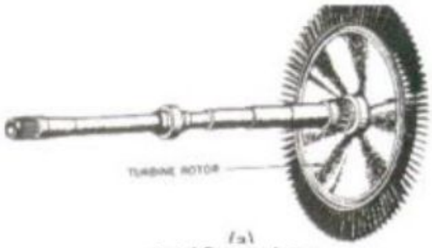
- The nozzle guide vanes have two principal functions
  - They must convert part of the gas heat and pressure energy into dynamic or kinetic energy, so that the gas will strike the turbine blades with some degree of force.
  - The nozzle vanes must turn this gas flow so that it will impinge on the turbine buckets in the proper direction; that is the gases impact on the turbine blade in a direction that will have a large component force in the plane of the rotor.
- Nozzle vanes may be either cast or forged.
- Many vanes made hollow to allow a degree of cooling using compressor bleed air.
- In all cases the turbine assembly is made of very high temperature, high strength steel to withstand the direct impact of the hot, high pressure, high velocity gas flowing from the combustion chamber.
- Several companies are experimenting with transpiration cooled nozzle and turbine blading in which the air flows through thousands of small holes in a porous airfoil made from a sintered wire mesh material.
- Since the performance of the gas turbine is dependent to a large measure on the temperature at the inlet of the turbine, increasing the turbine inlet temperature from the present average limit of about 982^0 to the 1370^0 possible with transpiration cooled blades will result in about a 100 percent increase in specific horsepower.





1.9 Turbines

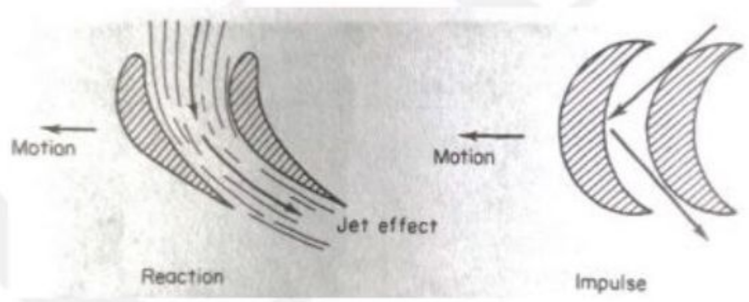
- Types of Turbines
    - Axial flow turbine
    - Radial inflow turbine



Axial flow turbine

Radial inflow turbine

- In radial inflow turbine type, inlet gas flows through peripheral nozzles to enter the wheel passages in an inward radial direction.
- The speeding gas exerts a force on the wheel blades and then exhausts the air in an axial direction to the atmosphere.
- The axial flow turbine comprises two main elements consisting of a set of stationary vanes and one or more turbine rotors.
- The turbine blades themselves are of two types:
    - Impulse
    - Reaction



1.9.1 Impulse turbine

- Impulse machines are those in which there is no change of pressure head of the fluid in the rotor.
- The rotor blade cause only energy transfer and there is no energy transformation.
- The energy transformation from pressure head to kinetic energy or vice versa takes place in fixed blades only.
- To give an example, the transfer of kinetic energy to the rotor in an impulse turbine from a high velocity fluid occurs only due to the impulsive action of the fluid on the rotor.

- From the figure, the rotor blade passages of an impulse turbine there is no acceleration of the fluid, i.e., there is no energy transformation.
- Hence, the chances are greater for separation due to boundary layer growth on the impulse machine suffer greater losses giving lower stage efficiencies.

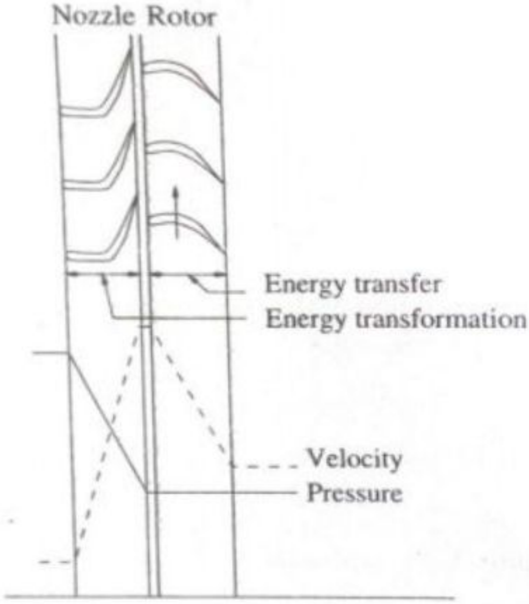


Fig. 11.2 An impulse turbine stage

1.9.2 Reaction turbine

- The reaction machines are those, in which, changes in pressure head occur both in the rotor and stator blade passages.
- Here, the energy transformation occurs both in fixed as well as moving blades.
- The rotor experiences both energy transfer as well as energy transformation. There the reaction turbines are considered to be more efficient. This due to the continuous acceleration of flow with lower losses.

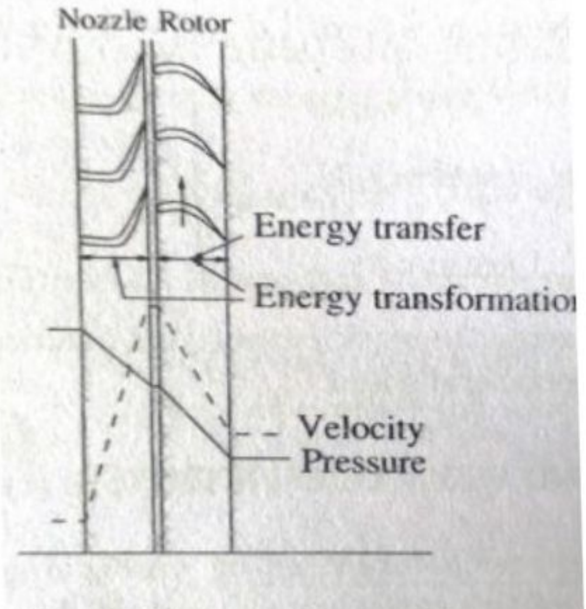


Fig. 11.3 A reaction turbine stage

1.10 Exhaust system

The exhaust duct takes the relatively high-pressure (relative to the exhaust nozzle), low-velocity gas leaving the turbine wheel and accelerates this gas flow to sonic or supersonic speeds through the nozzle at its rear.

It is desirable in a pure jet engine to convert as much of the pressure energy in the gas into kinetic energy in order to increase the gas momentum and therefore the thrust produced. If most of the gas expansion occurs through the turbine section, as, for example, in a turboprop, the duct does little more than conduct the exhaust stream rearward with a minimum energy loss.

However, if the turbine operates against a noticeable back pressure, the nozzle must convert the remaining pressure energy into a high-velocity exhaust. As stated previously, serves to reduce any swirl in the gas as the duct much of an axial leaves the turbine, thereby creating as ow component as possible.

Two types of nozzles in use today are

- the convergent type and
- the convergent-divergent type.

Generally the convergent nozzle will have a fixed area, while the convergent-divergent nozzle area will be variable. The area of the jet nozzle is critical, since it affects the back pressure on the turbine and hence the rpm, thrust, and exhaust gas temperature.

Decreasing the exhaust nozzle area a small amount will sharply increase the exhaust gas temperature, pressure, and velocity, and will also increase thrust. Although rapidly disappearing as a method of nozzle adjustment, on some engines this area is still adjustable by the insertion of small metal tabs called mice. By use of these tabs, the engine can be trimmed to the correct rpm, temperature, and thrust settings.

1.10.1 The Convergent Nozzle

- The typical convergent nozzle is designed to maintain a constant internal total pressure and still produce sonic velocities at the nozzle exit.
- In this type of nozzle the gas flow is subsonic as it leaves the turbine.

- Each individual gas molecule is, in effect, being squeezed by the converging shape and pushed from behind. This three-dimensional squirting action causes the velocity to increase.
- Since this velocity increase is faster than the volume expansion, a converging area is necessary to maintain the pressure or squirting action.
- In the convergent nozzle, the gas velocity cannot exceed the speed of sound because, as the gas velocity increases, the ability of the gas pressure to move the molecules from behind becomes less.
- In fact, the pushing action will drop to zero when the gas moves at the speed of sound. The speed of sound is the speed of a natural pressure wave movement. It is dependent on the natural internal molecular velocity, which is limited by the amount of internal temperature energy of these gas molecules. In other words, the speed of sound, although a pressure wave, is limited by the molecular velocity (or sound-temperature energy).

1.10.2 The Convergent-Divergent Nozzle

- If the pressure at the entrance to a convergent duct becomes approximately twice that at the exit of the duct (exhaust nozzle), the change in velocity through the duct will be enough to cause sonic velocity at the nozzle.
- At high Mach numbers the pressure ratio across the duct will become greater than 2.0, and unless this pressure can be turned into velocity before the gases exit from the nozzle, a loss of efficiency will occur.
- Since the maximum velocity that a gas can attain in a convergent nozzle is the speed of sound, a convergent-divergent nozzle must be used.
- In the diverging section, the gas velocities can be increased above the speed of sound. Since the individual gas molecules cannot be pushed by the pressure of molecules behind them, the gas molecules can be accelerated only by increasing the gas volume outward and rearward.
- The diverging section of the convergent-divergent nozzle allows expansion outward but also holds in the expansion so that most of it is directed rearward off the side wall of the diverging section.
- In other words, the diverging action accelerates the airflow to supersonic velocities by controlling the expansion of the gas so that the expansion (which is only partially

completed in the converging section) will be rearward and not outward to the side and wasted.

- An example of the action that produces an increase in thrust through a diverging nozzle can be shown with the following experiment. If a greased rubber ball were pushed down into a funnel and then released, the ball would shoot out of the funnel. If only the funnel were released, it would move away from the ball.

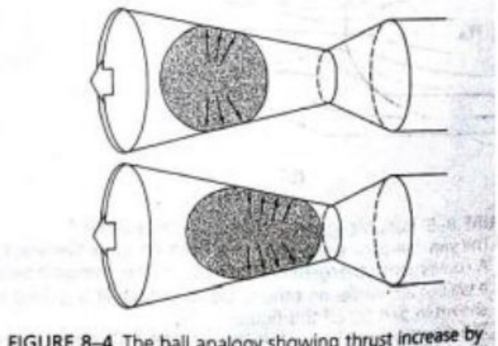


FIGURE 8–4 The ball analogy showing thrust increase by means of a divergent nozzle.

- What is happening is that the ball is partially compressed when it is pushed down into the funnel, increasing the pressure of the air inside the ball. When the funnel is released, the air in the ball expands, returning it to its normal size and pushing the funnel away. This same type of action occurs in the diverging section of a converging-diverging nozzle. As the gases expand against the side of the duct, they produce a pushing effect even though they are decreasing in pressure.

1.11 Sound suppression

The noise problem created by commercial and military jet takeoffs, landings, and ground operations at airports near residential areas has become serious within the last several years. The decibel (dB) is defined as approximately the smallest degree of difference of loudness ordinarily detectable by the human ear, the range of which includes about 130 dB.

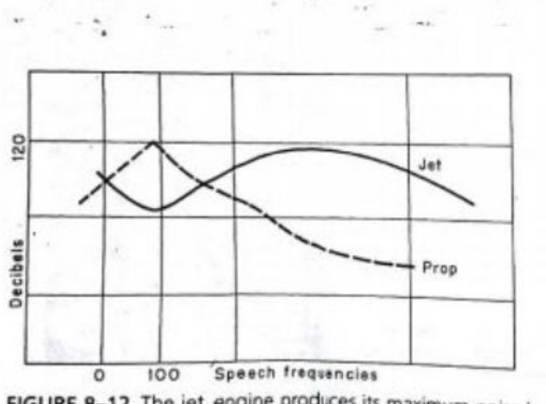


FIGURE 8–12 The jet engine produces its maximum noise in the speech frequency.

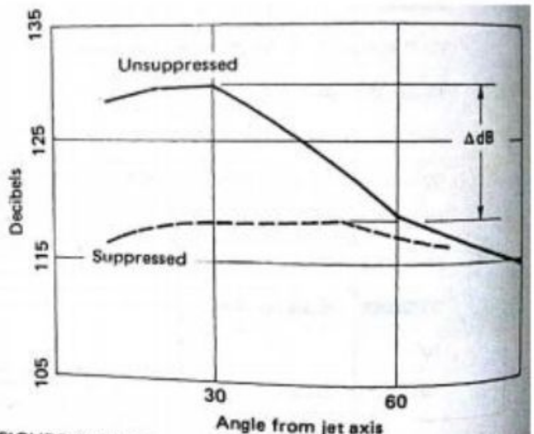


FIGURE 8–13 The sound-level intensities are reduced by means of a noise suppressor.

The pattern of sound from a jet engine makes the noise problem even more bothersome than that coming from other types of engines. For example, the noise from a reciprocating engine rises sharply as the airplane propeller passes an observer on the ground and then drops off almost as quickly. But a jet reaches a peak after the aircraft passes and is at an angle of approximately 45° to the observer. This noise then stays at a relatively high level for a considerable length of time.

The noise from a turbojet is also more annoying because it overlaps the ordinary speech frequencies more than the noise from a reciprocating engine and propeller combination. Since the noise is produced by the high-velocity exhaust gas shearing through the still air, it follows that if the exhaust velocity is slower and the mixing area wider, the exhaust noise levels can be brought down to the point where a sound suppressor is not necessary.

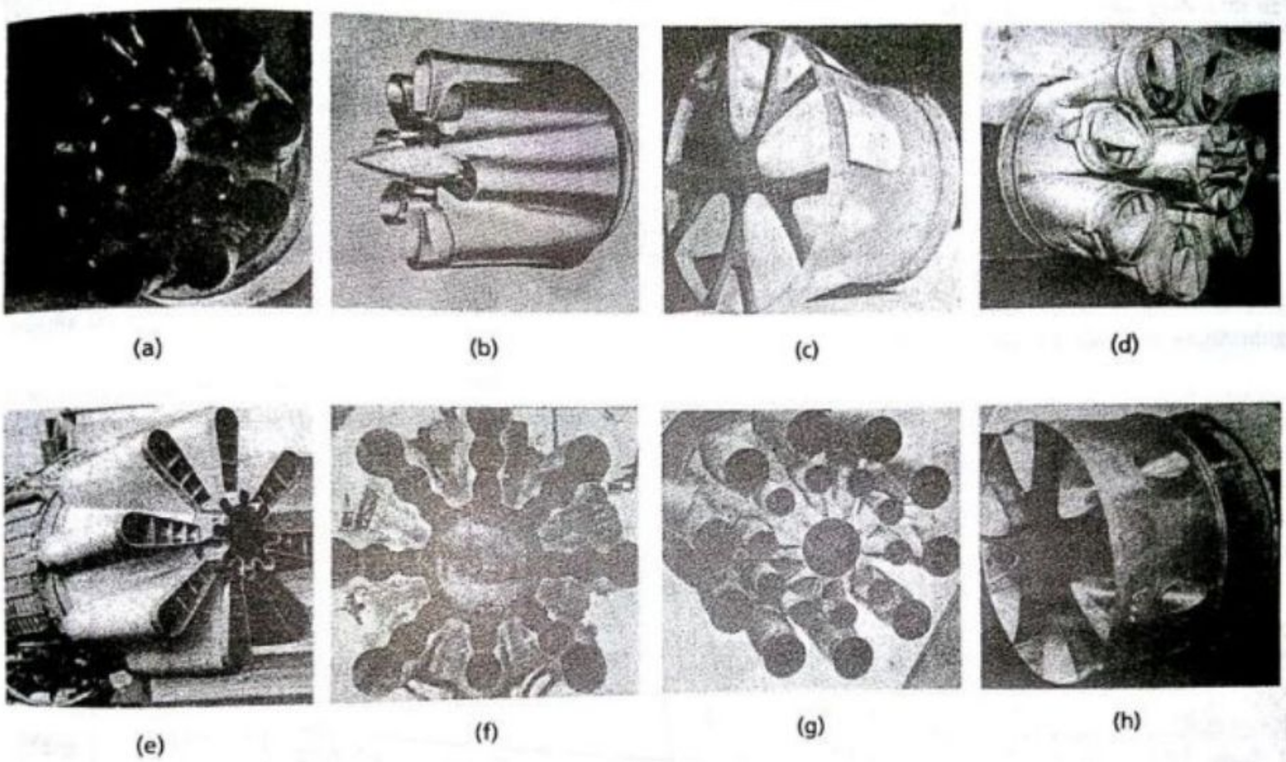


FIGURE 8–14 Typical airborne noise suppressors.

The exhaust gas velocity of a turbofan is slower than a turbojet of comparable size because more energy must be removed by the turbine to drive the fan. The fan exhaust velocity is relatively low and creates less of a noise problem. Noise levels are also lower in the high bypass ratio turbofan engine through the elimination of the inlet guide vanes and the resulting reduction of the "siren" effect. The noise is generated by this effect occurs when the columns of air created by the compressor inlet guide vanes are cut by the rapidly moving compressor blades, generating high frequency pressure fluctuations. Further noise reductions are achieved by lining the fan shroud with acoustical materials, thus dampening the pressure fluctuations by gearing the fan speed down, and spacing the outlet guide vanes further away from the fan. For these reasons, fan engines in general do not need sound suppressors.

The function of the noise suppressor is to lower the level of the sound, about 25 to 30 dB, as well as change its frequency, and to do this with a minimum sacrifice in engine thrust or additional weight.

The two facets of the noise problem, ground operation and airborne operation, lend themselves to two solutions. Noise suppressors can be portable devices for use on the ground by maintenance personal, or they can be an integral part of the aircraft engine installation.

1.12 Thrust Reversers

A jet powered aircraft, during its landing run, lacks the braking action afforded by slow turning propellers, which on larger aircraft are capable of going into reverse pitch, thus giving reverse thrust. The problem is further compounded by the higher landing speeds due to the high streamlined, low drag fuselage and the heavier gross weights common to modern jet airplanes. Standard wheel breaks are no longer adequate under these adverse conditions, and larger breaks would incur a severe weight and space penalty and decrease the useful load of the aircraft. In addition, breaks can be very ineffective on wet or icy runways.

1.12.1 Types of thrust reversers

The two basic types of thrust reversers are as follows:

- Postexit or target type/clamshell
- Preexit using cascades or blocker/deflector doors

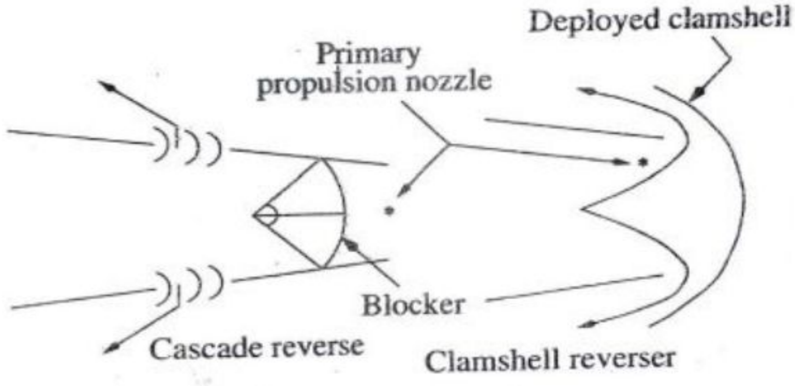


Fig. 13.12 Thrust reversers

Post exit reversing is accomplished simply by placing an obstruction in the jet exhaust stream about one nozzle diameter to the rear of the engine. The gas stream may be deflected in either a horizontal or vertical direction, depending on the engine's placement on the airframe.

In the preexit type, the gases are turned forward by means of doors that are normally stowed or airfoils that are normally blocked during forward thrust operation. During reverse thrust, doors are moved so that they now block the exhaust gas stream. The gas now exits and is directed in a forward direction through turning vanes or by deflector doors.

1.12.2 Thrust Reverser Designs and Systems

A good thrust reverser should do the following:

- Be mechanically strong and constructed of high-temperature metals to take the full force of the high-velocity jet and, at the same time, turn this jet stream through a large angle
- Not affect the basic operation of the engine, whether the reverser is in operation or not.
- Provide approximately 50 percent of the full forward thrust
- Operate with a high standard of fail-safe characteristics
- Not increase drag by increasing engine and nacelle frontal area
- Cause few increased maintenance problems
- Not add an excessive weight penalty
- Not cause the reingestion of the gas stream into the compressor nor cause the gas stream to impinge upon the airframe. That is, the discharge pattern must be correctly established by the placement and shape of the target or vane cascade.
- Allow the pilot complete control of the amount of reverse thrust
- Not affect the aerodynamic characteristics of the airplane adversely.

1.13 Methods thrust augmentation

1.13.1 Water injection

A reduction in atmospheric pressure due to increasing altitude or temperature will therefore cause a reduction in thrust or shaft horsepower. Power under these circumstances can be restored or even boosted as much as 10 to 30 percent for takeoff by the use of water or water-alcohol injection. Engine power ratings during the period water injection is used are called "wet thrust" ratings as opposed to "dry thrust" ratings when water injection is off.

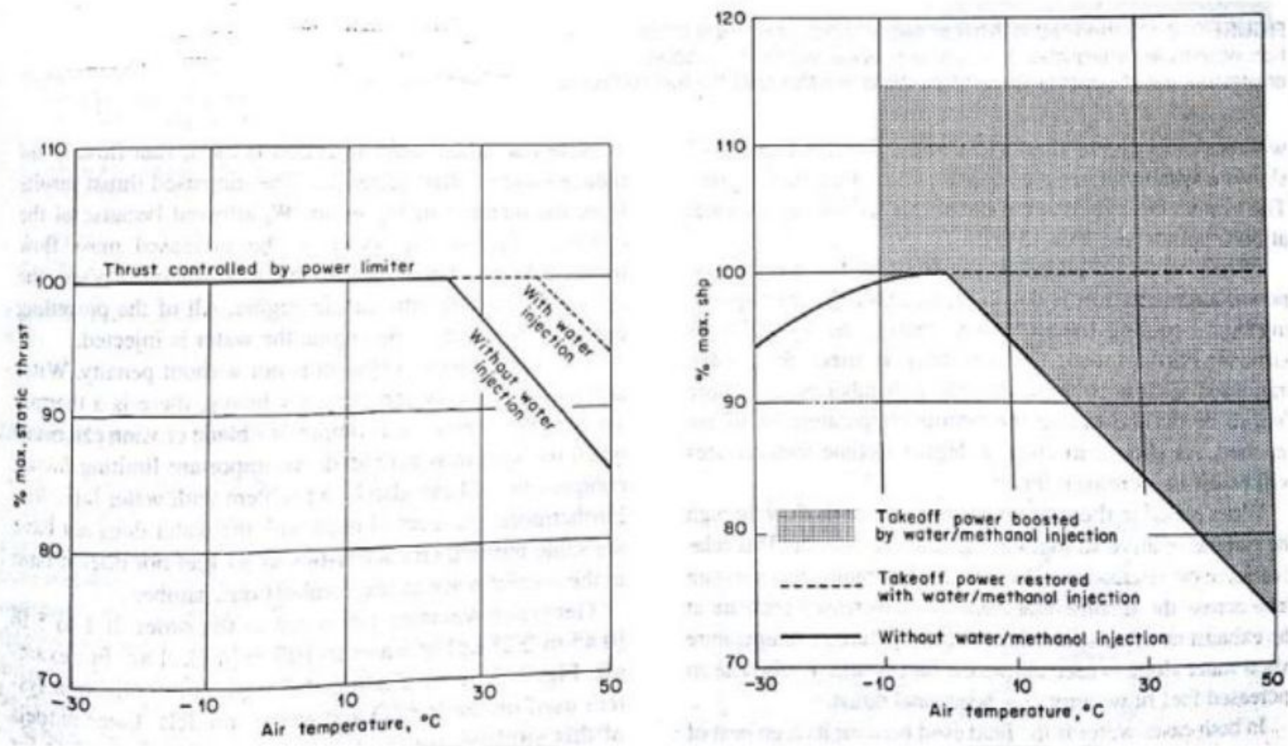


Fig: The effect of water injection on a turbojet and turboprop engine. (a) Turbojet thrust increase with water injection. (b) Turboprop power with water injection.

The alcohol adds to the power by providing an additional source of fuel, but because the alcohol has a low combustion efficiency, being only about half that of gas turbine fuel, and because the alcohol does not pass through the central part of the combustion chamber where temperatures are high enough to efficiently burn the weak alcohol-air mixture, the power added is small. Water alone would provide more thrust per pound than a water-alcohol mixture due to the high latent heat of vaporization and the overall decrease in temperature. The addition of alcohol has two other effects. If only water is injected, it would reduce the turbine inlet temperature, but with the addition of alcohol, the turbine temperature is restored. Thus the power is restored without having to adjust the fuel flow. The alcohol also serves to lower the freezing point of the water.

The water provides additional thrust in one of two ways, depending on where the water is added. Some engines have the coolant sprayed directly into the compressor inlet, whereas others have fluid added at the diffuser system where the water is added at the fuel nozzles.

When water is added at the front of the compressor, power augmentation is obtained principally by the vaporizing liquid cooling the air, thus increasing density and mass airflow. Furthermore, if water only is used, the cooler, increased airflow to the combustion chamber permits more fuel to be burned before the turbine temperature limits are reached. Higher turbine temperatures will result in increased thrust.

Water added to the diffuser increases the mass flow through the turbine relative to that through the compressor. This relative increase results in a decreased temperature and pressure drop across the turbine that leads to an increased pressure at the exhaust nozzle. Again, the reduction in turbine temperature when water alone is used allows the fuel system to schedule an increased fuel flow, providing additional thrust.

In both cases water is the fluid used because its high heat of vaporization results in a fairly large amount of cooling for a given weight of water flow. Demineralized water is generally used to prevent deposit buildup on compressor blades that will lead to deterioration of thrust and more frequent field cleaning of the compressor and engine trimming.

Note that when water injection is used, fuel flow is not reduced and is often increased. The increased thrust results from the increase in W_a and/or W_f allowed because of the cooling effect of the water or the increased mass flow through the fixed area turbine that effectively increases the operating pressure ratio of the engine. All of the preceding depends on where in the engine the water is injected.

The water injection system is not without penalty. Water and the injection system are very heavy; there is a thermal shock to the engine, and compressor blade erosion can occur when the system is activated. An important limiting factor, compressor stall can also be a problem with water injection. Furthermore, the alcohol used with the water does not have the same burning characteristics as jet fuel nor does it burn in the correct place in the combustion chamber.

Generally water/air ratios are in the order of 1 to 5 lb (0.45 to 2.25 kg) of water to 100 lb [45 kgJ air. Later models of this airplane use the fan engine with no provision for water injection. The water tank holds approximately 1200 gallons (gal) [4542 liters (L)], which is usually exhausted during takeoff. About 110 s are required to consume all of the liquid. Any water not used during takeoff is drained overboard.

1.13.2 Afterburning

Afterburning or reheating is one method of periodically augmenting the basic thrust of the turbojet and, more recently, the turbofan engine without having to use a larger engine with its concurrent penalties of increased frontal area, weight, and fuel consumption. The afterburner, whose operation is much like a ramjet, increases thrust by adding fuel to the exhaust gases after they have passed through the turbine section. At this point there is still much uncombined oxygen in the exhaust. The resultant increase in temperature raises the velocity of the exiting gases and therefore boosts engine thrust. Most afterburners will produce an approximate 50 percent thrust increase, but with a corresponding threefold increase in fuel flow. Since the specific and actual fuel consumption is considerably higher during the time the engine is in afterburning or "hot" operation, as compared to the non-afterburning or "cold" mode of operation, reheating is used only for the time-limited operation of takeoff, climb, and maximum bursts of speed. Afterburning rather than water as a method of gaining additional thrust is used extensively in but not limited to, fighter aircraft because of the higher thrust augmentation ratios possible.

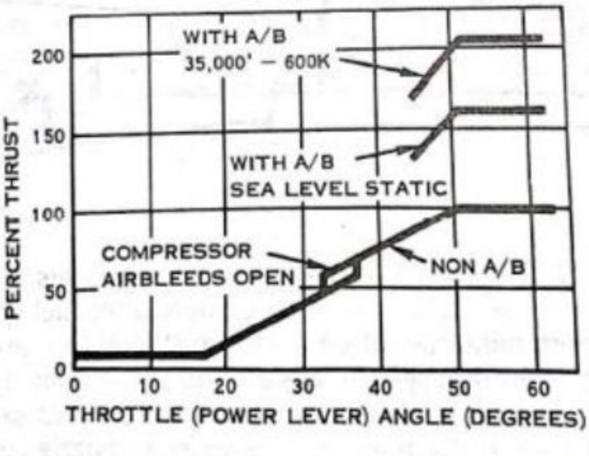


FIGURE 9–4 Typical thrust augmentation due to afterburning. (*Pratt & Whitney, United Technologies Corp.*)

All engines that incorporate an afterburner must, of necessity, also be equipped with a variable-area exhaust nozzle in order to provide for proper operation under a burning and non-afterburning conditions. The nozzle is closed during non-afterburning operation, but when afterburning is selected, the nozzle is automatically opened to provide an exit area suitable for the increased volume of the gas stream. This action prevents any increase in back pressure from occurring that would slow the airflow through the engine and affect the compressor's stall characteristics. A well-designed afterburner and variable-area exhaust nozzle will not influence the operation of the basic turbojet engine.

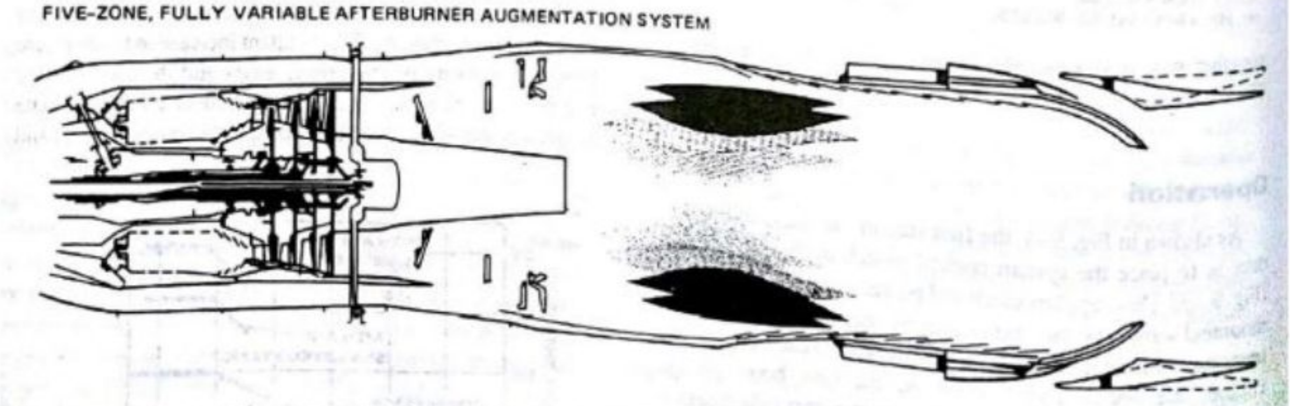


FIGURE 9–5 One of the newer types of afterburners is used on the Pratt & Whitney TF30-P-100 engine. This system uses a multizone afterburner fuel system that provides smooth transient thrust increases from minimum afterburner thrust level to maximum. The five-zone, fully variable afterburner augmentation system uses a 4-joule (see chap. 16) electrical ignition design in place of either hot streak or torch ignition, thus reducing pressure excursions during initial light-off by 30 to 40 percent. Notice the translating, primary iris nozzle combined with an aerodynamically ...

Specific requirements for a reheat augmentation device as follows:

- ***Large temperature rise***-The afterburner does not have the physical and temperature limits of the turbine. The temperature rise is limited by the amount of air that is available.
- ***Low dry loss***-The engine does suffer a very slight penalty in thrust during "cold" operation due principally to the restriction caused by the flame holders fuel spray bars.
- ***Wide temperature modulation***-This is necessary to obtain "degrees" of afterburning for better control of thrust.

1.13.2.1 Construction

The typical afterburner consists of the following components:

- Engine- or turbine-driven afterburner fuel pump
- Afterburner fuel control
- Pressurizing valve--if multistage operation is possible
- Spray nozzles or spray bars
- Torch ignitor and/or ignition system
- Flame holders
- Variable area exhaust nozzle
- Connections (mechanical and pressure) from main fuel control, throttle, and engine
- Screech liner

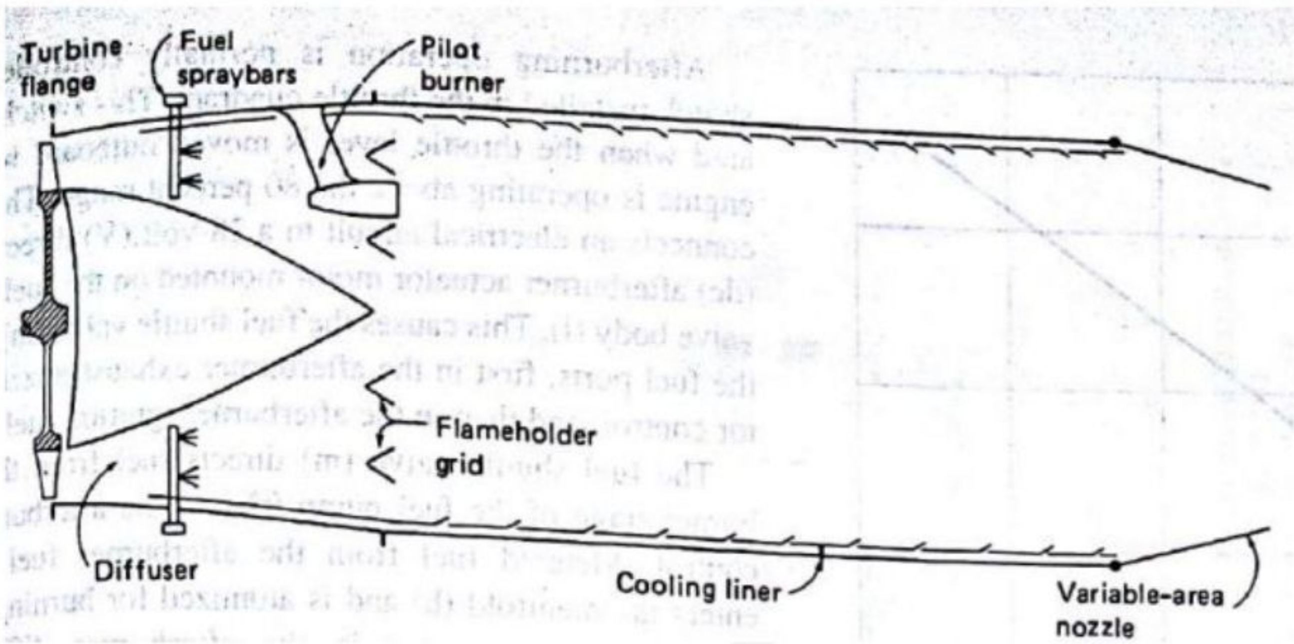


Fig: Simple afterburner schematic

1.13.2.2 Operation

The gases enter the afterburner at the approximate temperature, pressure, and velocity of 1022^0 F, 40 psi, and 2000 ft/s (550^0 C, 276 kPa, and 610 m/s), respectively, and leave at about 2912° F 40 psi, and 3000 ft/s (1600^0 C, 276 kPa, and 914 m/s), respectively. These values can vary widely with different engines, nozzle configurations, and operating conditions. The duct area to the rear of the turbine is larger than a normal exhaust duct would be in order to obtain a reduced velocity gas stream, and thus reduce gas friction This reduced velocity is still too high for stable combustion to place, since the flame propagation rate of only a few per second. It becomes necessary to use a form of flame stabilizer holder located downstream of the fuel spraybars to provide a region in which turbulent eddies are formed, and where the local gas velocity is further reduced. Fuel is fed into the afterburner through a series of nozzles or spraybars. In some engines the afterburner is either on or off, while in others, degrees of afterburning are available. Ignition occurs in one of several ways:

- ***Hot streak ignition*** - In this system an extra quantity of fuel is injected into one of the combustion chambers. The resulting streak of hot gases ignites the afterburner fuel.
- ***Torch ignition*** - A "pilot light" located in the area of the spraybars is fed fuel and ignited with its own ignition system. The system works continuously during afterburner operation.

- ***Electric spark ignition*** **-** A device similar to a spark plug may be used to initiate afterburner ignition.

These systems are used because spontaneous ignition of the afterburner fuel cannot be depended on, especially at high altitudes where the atmospheric pressure is low.

A screech or antihowl liner fits into the inner wall of the duct. The liner is generally corrugated and perforated with thousands of small holes. The liner prevents extreme high frequency and amplitude pressure fluctuations resulting from combustion instability or the unsteady release of heat energy. Screech results in excessive noise, vibration, heat transfer rates, and temperatures that cause rapid physical destruction of the afterburner components. The screech liner tends to absorb and dampen these pressure fluctuations.

The flame holder mentioned above usually takes the form of several concentric rings with a V cross-sectional shape.