Module 1

INTRODUCTION

Syllabus:

Review of thermodynamic principles, Principles of aircraft propulsion, Types of power plants, Working principles of internal combustion engine, Two – stroke and four – stroke piston engines, Gas- turbine engines, Cycle analysis of reciprocating engines and jet engines , advantages and disadvantages.

1.1 Review of thermodynamic principles

INTRODUCTION

Turbines and compressors are usually analyzed using thermodynamic and fluid dynamic equations. The thermodynamic equations relate temperature, pressure and volume whereas the fluid dynamic equations relate force, mass and velocity. The following are the laws that are frequently used in dealing with problems of and operation of these machines:

(i) energy equation in its various forms from the first law of thermodynamics,

(ii) temperature, entropy and gas relations from the second law of thermodynamics,

(iii) continuity relationships from the law of conservation of mass, and

(iv) momentum equation from Newton's second law of motion.

2.1 DEFINITIONS AND LAWS

Before discussing the various aero-thermodynamic aspects of compressors and turbines, let us review some important definitions used in the analysis of compressible flow useful for rotating machines. However, the reader is advised to refer to standard textbooks on thermodynamics and fluid dynamics for more details.

2.1.1 System

A fixed identity with an arbitrary collection of matter is known as a system. The boundary is an imaginary surface which separates the system from its surroundings. Surroundings are those which are outside the system. System can be classified as either an open system or a closed system.

Open System When there is a continuous flow of matter, it is called an open system. Such a system is usually depicted by a control volume. It has a fixed space but does not contain a fixed mass of matter; instead there is a continuous flow of mass through it. The properties of the matter occupying the control volume can vary with time. The surface which encloses a control volume is called control surface.

Closed System When there is a fixed quantity of matter (fluid or gas), it is called a closed system. There is no inflow or outflow of matter to and from a closed system. However, a closed system can interact with its surroundings through work and heat transfers. The boundaries of a closed system containing the fixed mass of matter can change. Expanding gas in a reciprocating internal combustion engine is one such example.

2.1.2 State

Condition of a system, defined by its properties, is known as the state of a system.

2.1.3 Process

A change or a series of changes in the state of a system is known as a process.

2.1.4 Cycle

If the initial and final states of a system experiencing a series of processes are identical, it is said to have executed a cycle.

2.1.5 Pressure

Pressure at a point surrounded by an infinitesimal area, ΔA, is the force per unit area. Pressure is usually designated by Pascal in SI units. It may also be expressed as N/m^2 or bar. In this book, we will follow 'bar' as the unit of pressure.

2.1.6 Density

The density of a medium is the mass of the matter (gas) per unit volume. Density is expressed in kg/m^3.

2.1.7 Temperature

When two systems are in contact with each other and are in thermal equilibrium, the property common to both the systems having the same value is called temperature. Thus temperature is a measure of the thermal potential of a system.

2.1.8 Energy

Energy is the capacity to do work. The state of a system can be changed by adding or removing energy. Heat and work are different forms of energy in transit. They are not contained in any system.

Heat is the form of energy which transfers between two systems by virtue of the temperature difference between them. Heat transfer to or from a system changes its state.

Work is said to be done by a system on its surroundings when they are moved through a distance by the action of a force; this is exerted by the system on the surroundings in the direction of the displacement of the surroundings. The magnitude of mechanical work is given by

$$\text{Work done} = \text{Force} \times \text{Distance in the direction of force}$$

Both heat and work are path functions and they depend on the type of process and therefore, are not properties of a system. In SI units, energy, heat and work are all expressed in joules (J), kilojoules (kJ) or Newton metres (Nm).

2.1.9 First Law of Thermodynamics

It states that when a system executes a cyclic process, the algebraic sum of the work transfers is proportional to the algebraic sum of the heat transfers.

$$\oint \mathrm{d}W \propto \oint \mathrm{d}Q = J \oint \mathrm{d}Q \tag{2.1}$$

When heat and work are expressed in the same units, then

$$\oint \mathrm{d}Q - \oint \mathrm{d}W = 0 \tag{2.2}$$

It can easily be shown that the quantity $(\mathrm{d}Q - \mathrm{d}W)$ is independent of the path of the process and hence it represents a change in the property of the system. This property is referred to as *energy*, denoted here by the symbol E. Thus,

$$\mathrm{d}E = \mathrm{d}Q - \mathrm{d}W \tag{2.3}$$

Equation 2.3 for the two states of a system can be written as

$$E_2 - E_1 = Q - W$$

$$Q = W + (E_2 - E_1) \tag{2.4}$$

$$\text{Heat transfer} = \text{Work done} + \text{Change in energy}$$

2.1.10 Specific Heats of Gases

The specific heat of a gas is the heat carrying capacity in a process. It is the amount of heat that is required to raise the temperature of a unit mass of the gas by one degree.

In thermodynamic analysis two different types of specific heats are used:

(i) Specific heat at constant-volume, and

(ii) Specific heat at constant-pressure.

The specific heat at constant-volume (C_v) is the amount of heat required to raise the temperature of a unit mass of the gas by one degree at constant-volume. It is given by

$$C_v = \left(\frac{\partial q}{\partial T}\right)_v = \left(\frac{\partial U}{\partial T}\right)_v \tag{2.5}$$

The specific heat at constant-pressure (C_p) is the amount of heat required to raise the temperature of a unit mass of the gas by one degree at constant-pressure . It is given by

$$C_p = \left(\frac{\partial q}{\partial T}\right)_p = \left(\frac{\partial h}{\partial T}\right)_p \tag{2.6}$$

The specific heats of actual gases are a function of temperature and vary with temperature

$$C_p, C_v = f(T) \tag{2.7}$$

The ratio of the two specific heats, (γ), is an important parameter in compressible flow problems of turbomachines and is defined as

$$\gamma = \frac{C_p}{C_v} \tag{2.8}$$

2.1.11 Internal Energy

The internal energy of a gas is the energy stored in it by virtue of its molecular motion. If it is assumed that the internal energy of a perfect gas is zero at the absolute zero temperature, its value at a temperature T is given by

$$U = C_vT \tag{2.9}$$

2.1.12 Enthalpy

The heat supplied to or rejected by a system at constant-pressure is the change of enthalpy during the process. The value of enthalpy at a given state is given by

$$h = U + pv = U + \frac{p}{\rho} \tag{2.10}$$

and for an ideal gas

$$h = C_pT \tag{2.11}$$

2.1.19 Irreversible Process

An irreversible process is one which does not satisfy the above conditions of reversibility.

2.1.20 Adiabatic Process

During a process if there is no heat transfer between the system and the surroundings, it is known as an adiabatic process. All the rotating machines discussed in this book are assumed to follow only adiabatic processes.

2.1.21 Isentropic Process

An adiabatic process in which entropy remains constant is known as a reversibly adiabatic or isentropic process. For unit mass, this is governed by the following relations:

$$pv^{\gamma} = \text{constant} \tag{2.28}$$

$$\frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \left(\frac{\rho_1}{\rho_2}\right)^{\gamma-1} \tag{2.29}$$

$$T\mathrm{d}s = \mathrm{d}h - v\mathrm{d}p = \mathrm{d}h - \frac{1}{\rho}\mathrm{d}p = 0 \tag{2.30}$$

2.2 ENERGY EQUATION

The energy equation (Eq. 2.4) is basically derived from the first law of thermodynamics as given in Section 2.1.9. It is written as

$$Q = W + (E_2 - E_1) \tag{2.40}$$

For application in turbomachines, the energy terms will include internal energy, gravitational potential energy and kinetic energy. Other forms of energy which can be included but are not relevant here are strain energy, magnetic energy, etc.,

$$E = U + m(gZ) + \frac{1}{2}mc^2 \tag{2.41}$$

$$dE = dU + mg\,dZ + m\,d\left(\frac{1}{2}c^2\right) \tag{2.42}$$

where U is the internal energy and Z is the potential energy and c is the velocity of the fluid.
The change in the energy in a finite process between two states is given by

$$E_2 - E_1 = (U_2 - U_1) + mg(Z_2 - Z_1) + \frac{1}{2}m(c_2^2 - c_1^2) \tag{2.43}$$

Substituting Eq. 2.43 in Eq. 2.4, a general form of the energy equation can be obtained.

$$Q = W + (U_2 - U_1) + mg(Z_2 - Z_1) + \frac{1}{2}m(c_2^2 - c_1^2) \tag{2.44}$$

Dividing throughout by m

$$q = w + (u_2 - u_1) + g(Z_2 - Z_1) + \frac{1}{2}(c_2^2 - c_1^2) \tag{2.45}$$

2.2.1 Steady-flow Energy Equation

For steady flow processes through turbomachines, the work term in Eqs. 2.44 and 2.45 contains shaft work and flow work. Thus,

$$W = W_s + (p_2V_2 - p_1V_1) \tag{2.46}$$

Substituting Eq. 2.46 in Eq. 2.44 and rearranging, we get

$$Q = W_s + (U_2 + p_2V_2) - (U_1 + p_1V_1) + mg(Z_2 - Z_1) + \frac{1}{2}m\left(c_2^2 - c_1^2\right) \tag{2.47}$$

Writing enthalpy H for the quantity $U + pV$,

$$H_1 + mgZ_1 + \frac{1}{2}mc_1^2 + Q = H_2 + mgZ_2 + \frac{1}{2}mc_2^2 + W_s \tag{2.48}$$

In terms of specific quantities,

$$h_1 + gZ_1 + \frac{1}{2}c_1^2 + q = h_2 + gZ_2 + \frac{1}{2}c_2^2 + W_s \tag{2.49}$$

Equation 2.48 or 2.49 is the steady-flow energy equation for a control volume or an open system. This will now be rewritten for processes in various turbomachines and their components.

2.2.3 Compressible Flow Machines

Most of the compressible flow turbomachines such as turbines and compressors are considered as adiabatic machines, i.e., $q \approx 0$. In these machines, change in potential energy $(Z_1 - Z_2)$ is also negligible as compared to changes in enthalpy $(h_1 - h_2)$ and kinetic energy $\left(\frac{c_1^2}{2} - \frac{c_2^2}{2}\right)$. Therefore, Eq. 2.49 yields

$$h_1 + \frac{1}{2}c_1^2 = h_2 + \frac{1}{2}c_2^2 + W_s \tag{2.52}$$

The shaft work is given by

$$W_s = \left(h_1 + \frac{1}{2}c_1^2\right) - \left(h_2 + \frac{1}{2}c_2^2\right) \tag{2.53}$$

If the entry and exit velocities are small or the difference between them is negligible, then shaft work is given by the difference between the static enthalpies at the two states

$$W_s = h_1 - h_2 \tag{2.54}$$

2.2.4 Energy Transformation

It may be noted that *energy transfer* (shaft work input or output) in a turbomachine stage is possible only in the rotor, whereas *energy transformation* can occur both in moving and fixed blades. An application of the energy equation for stationary components of compressors and turbines such as nozzle blade rings, diffusers and volute casings can be made. The shaft work is absent in these components and the flow is almost adiabatic $(q \approx 0)$. Therefore Eq. 2.52 gives

$$h_1 + \frac{1}{2}c_1^2 = h_2 + \frac{1}{2}c_2^2 = \text{constant} \tag{2.55}$$

2.2.5 Stagnation Enthalpy

In an adiabatic energy transformation process, if the initial state is represented by $h, T, c,$ etc., and the final gas velocity is zero, the resulting value of the enthalpy ($h_2 = h_0$) has a special significance. Under these conditions, Eq. 2.55 yields

$$h_0 = h + \frac{1}{2}c^2 \quad (2.56)$$

Since the gas is stagnant or stationary in the final state, the quantity h_0 in Eq. 2.56 is known as the stagnation enthalpy. Thus, the stagnation enthalpy can be defined as the enthalpy of a gas or vapour when it is adiabatically brought to rest. It may be observed that the definition of stagnation enthalpy in Eq. 2.56 is only another form of the energy equation.

2.2.6 Stagnation Temperature

For a perfect gas, a stagnation temperature is defined through stagnation enthalpy. From Eq. 2.56,

$$C_pT_0 = C_pT + \frac{1}{2}c^2$$

$$T_0 = T + \frac{c^2}{2C_p} \quad (2.57)$$

T_0 is known as the stagnation temperature whereas T is the static temperature and $c^2/2C_p$ is the equivalent of kinetic energy temperature (T_c).

$$T_c = \frac{c^2}{2C_p} \quad (2.58)$$

$$T_0 = T + T_c \quad (2.59)$$

Equation 2.57 can be used to obtain an important relation for compressible flow machines.

$$\frac{T_0}{T} = 1 + \frac{c^2}{2C_pT} \quad (2.60)$$

Using Eq. 2.18,

$$\frac{T_0}{T} = 1 + c^2\left(\frac{\gamma - 1}{2\gamma RT}\right)$$

The velocity of sound in a gas at a local temperature T is given by

$$a = \sqrt{\gamma RT} \quad (2.61)$$

The Mach number of the flow is defined as the ratio of the local velocity of the gas and of sound

$$M = \frac{c}{a} = \frac{c}{\sqrt{\gamma RT}} \quad (2.62)$$

Therefore,

$$\frac{T_0}{T} = 1 + \left(\frac{\gamma - 1}{2}\right)\left(\frac{c^2}{a^2}\right) = 1 + \left(\frac{\gamma - 1}{2}\right) M^2 \quad (2.63)$$

2.2.7 Stagnation Velocity of Sound

Stagnation values of various flow parameters are used as reference values in the analysis of compressible flow machines. Therefore, an expression for the stagnation velocity of sound is derived here. By definition,

$$a_0 = \sqrt{\gamma R T_0} \quad (2.64)$$

Substituting for R,

$$a_0 = \sqrt{(\gamma - 1) C_p T_0} \quad (2.65)$$

Since $C_p T_0 = h_0$

$$a_0 = \sqrt{(\gamma - 1) h_0} \quad (2.66)$$

2.2.8 Stagnation Pressure

The stagnation pressure is the pressure of the gas or fluid when it is brought to rest adiabatically and reversibly (i.e., isentropically). The ratio of the stagnation and static pressures can be obtained from Eq. 2.63

$$\frac{p_0}{p} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \quad (2.67)$$

When the pressure changes are small, the process can be assumed to be incompressible ($\rho \approx$ constant). Then the stagnation pressure can be determined from

$$p_0 = p + \frac{1}{2}\rho c^2 \quad (2.68)$$

2.2.9 Stagnation Density

The density of a stationary gas or vapour is the stagnation density. For an ideal gas, its value at known values of stagnation temperature and pressure is given by

$$\rho_0 = \frac{p_0}{R T_0} \quad (2.69)$$

For an isentropic process from Eq. 2.29,

$$\frac{\rho_0}{\rho} = \left(\frac{T_0}{T}\right)^{\frac{1}{\gamma-1}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{1}{\gamma-1}} \quad (2.70)$$

2.2.10 Stagnation State

The concept of a reference state of the gas in a compressible flow machine is very useful. The stagnation state of a gas is often used as a reference state. A state defined by the stagnation temperature and pressure is the *stagnation state* of the gas. This state is obtained by decelerating a gas isentropically to zero velocity.

It should be observed that it is necessary here to qualify the deceleration process as an isentropic process. This is not necessary in defining stagnation enthalpy and temperature.

1.2 Principles of Aircraft Propulsion

Thrust to propel an aircraft forward is based on the Newton's third law of motion, which states that for every action, there is an equal and opposite reaction. For example, if we inflate a balloon, points it upward and let it go, the high pressure air inside comes out of the open neck with a certain speed (action). The balloon is pushed up until all the air is released (reaction). When all the air has escaped (power has stopped) the balloon returns to the ground. The forward force depends on the mass of air expelled and its velocity (Fig. 20.8). This is the principle of jet engine.

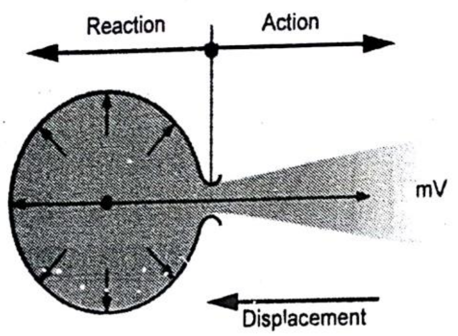
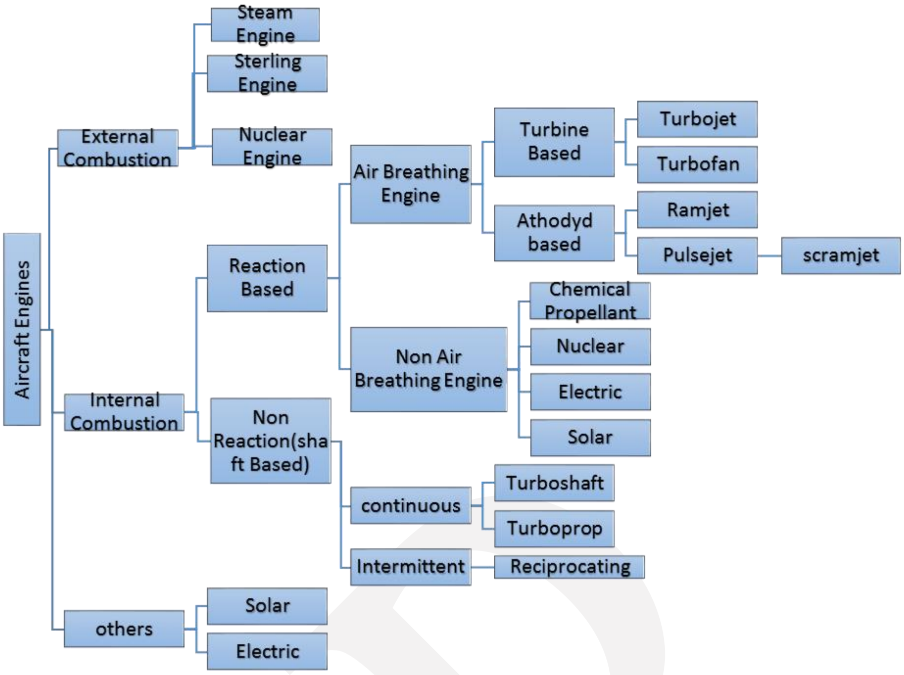


Fig. 20.8

Two basic means are used to provide thrust for an aircraft in flight viz. propeller or jet propulsion. In a propeller driven aircraft either a piston driven engine or a turboprop engine is used to drive a propeller to push air backwards. In jet propulsion, there is no propeller so forward thrust is provided by the discharge of high speed gases through a rear-facing nozzle (just like a balloon).

Aero engines are machines, which transform the potential energy contained in the fuel and air into kinetic energy or mechanical energy. The propulsion system is classified as follows:

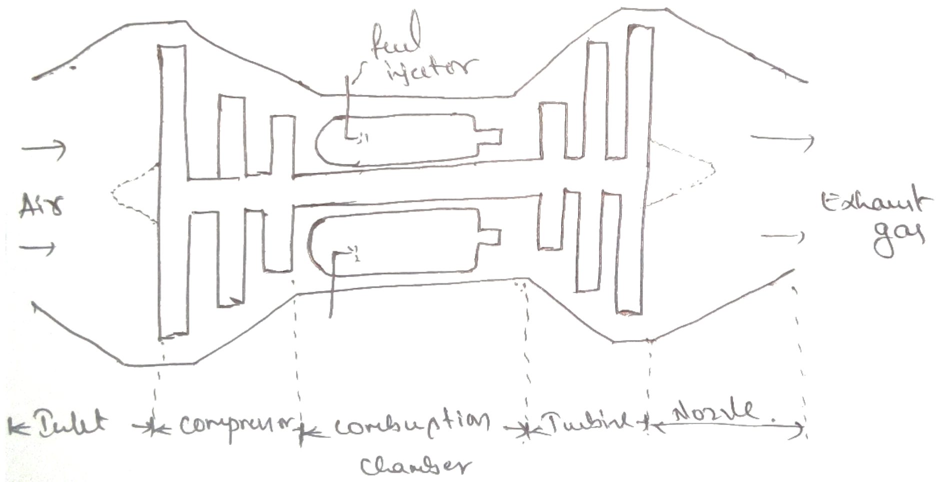


1.3 Gas Turbine Engines

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^{0}C. 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.

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.
- 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.

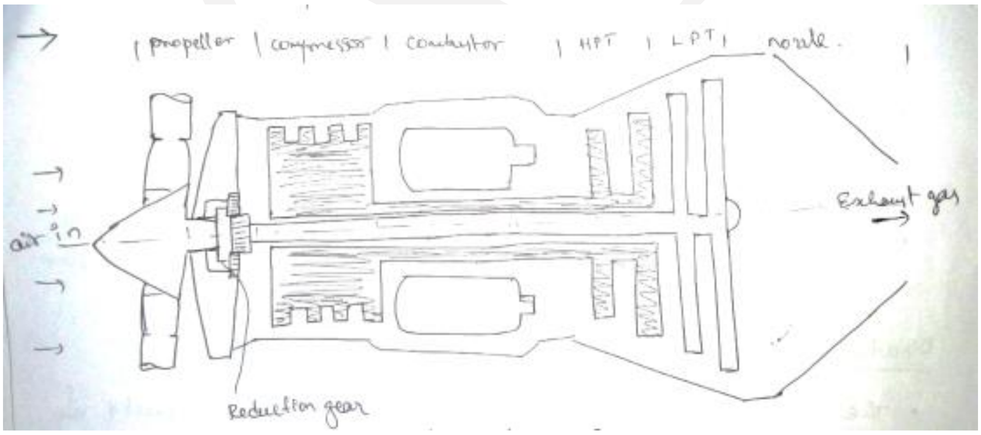


Fig: Turboprop engine

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.

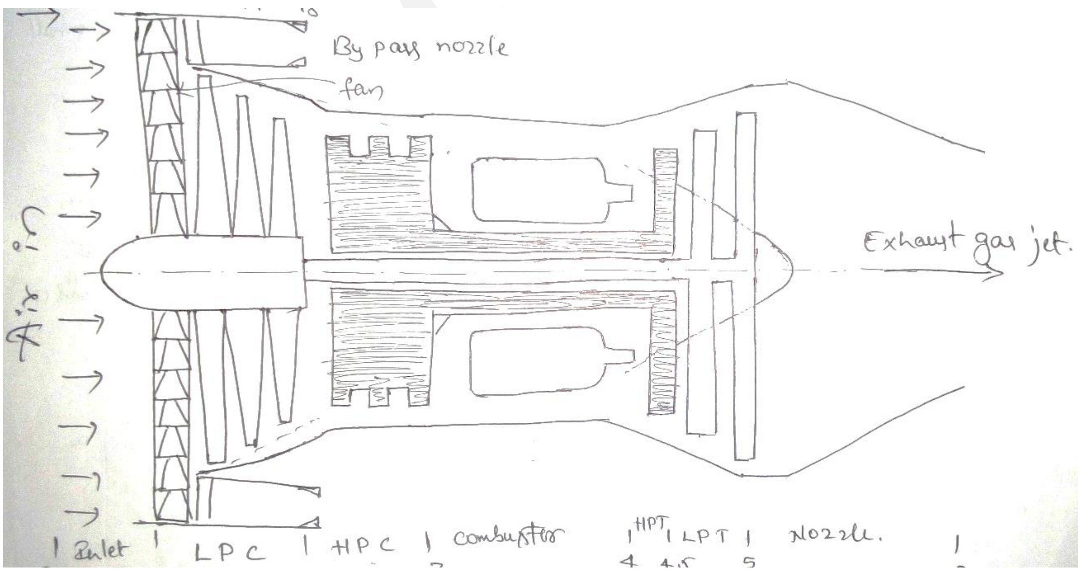
Advantages:

- 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.

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.
- 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.

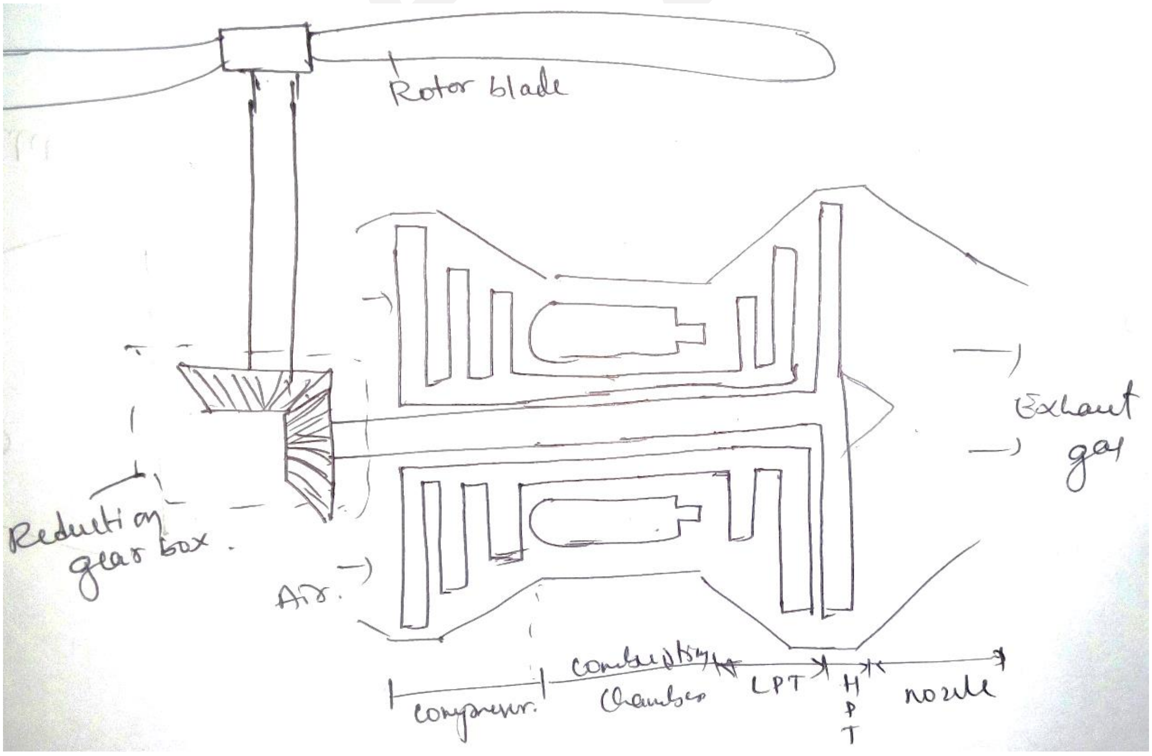
Disadvantages:

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

Turboshaft engine:

Working principle:

- This is another form of gas turbine engine that operates similar to a turboprop engine.



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

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.

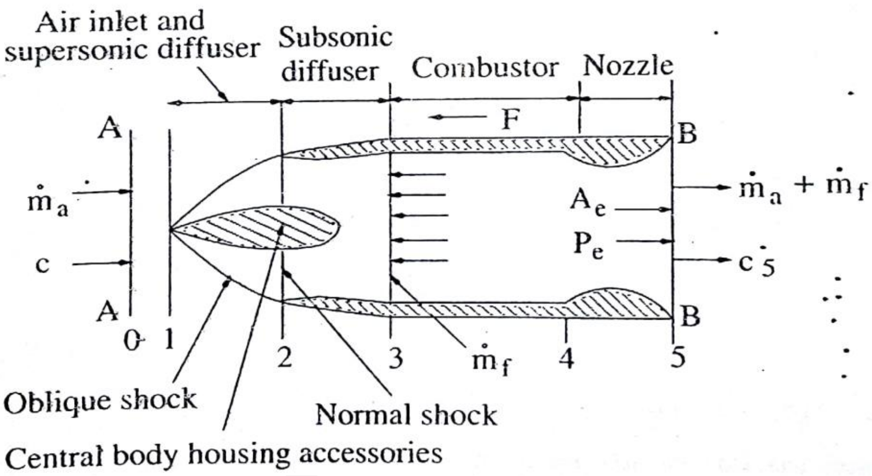
It may be noted that the simplest types of air breathing engine is the ramjet engine and a simplified sketch of the engine is illustrated in Fig. 7.1. The engine consists of

(i) supersonic diffuser (1–2),

(ii) subsonic diffuser section (2–3),

(iii) combustion chamber (3–4), and

(iv) discharge nozzle section (4–5).



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.

Since the ramjet engine cannot operate under static conditions, as there will be no pressure rise in the diffuser, it is not self-propelling at zero flight velocity. To initiate its operation, the ramjet must be either launched from an airplane in flight or be given an initial velocity by some auxiliary means, such as launching rockets. Since the ramjet is an air breathing engine, its maximum altitude is limited. Its field of operations is inherently in speed ranges above those of the other air breathing engines. However, it has a limited use in the high subsonic speed range. Its best performance capabilities, however, are in supersonic speed range of Mach numbers between 2 and 5. The upper speed is limited by the problem of cooling of the outer skin of the engine body at the high flight Mach numbers.

7.3.3 Advantages, Disadvantages and Characteristics

In this section, the various advantages and disadvantages of ramjet are enumerated.

Advantages of ramjet

(i) Ramjet is very simple and does not have any moving part. It is very cheap to produce and requires almost no maintenance.

(ii) Due to the fact that a turbine is not used to drive the mechanical compressor, the maximum temperature which can be allowed in ramjet is very high, about 2000°C as compared to about 900°C in turbojets. This allows a greater thrust to be obtained by burning fuel at air-fuel ratio of about 13:1, which gives higher temperatures.

(iii) The specific fuel consumption is better than other gas turbine power plants at high speed and high altitudes.

(iv) Theoretically there seems to be no upper limit to the flight speed of the ramjet.

Disadvantages of ramjet

(i) Since the compression of air is obtained by virtue of its speed relative to the engine, the take-off thrust is zero and it is not possible to start a ramjet without an external launching device.

(ii) The engine heavily relies on the diffuser and it is very difficult to design a diffuser which will give good pressure recovery over a wide range of speeds.

(iii) Due to high air speed, the combustion chamber requires flame holder to stabilize the combustion.

(iv) At very high temperatures of about 2000°C dissociation of products of combustion occurs which will reduce the efficiency of the plant if not recovered in nozzle during expansion.

7.3.4 Basic Characteristics and Applications

The basic characteristics of the ramjet engine can be summarized as follows:

(i) It is a simple engine and should be adaptable for mass production at relatively low cost.

(ii) It is independent of fuel technology and a wide range of liquid, and even solid fuels can be used.

(iii) Its fuel consumption is comparatively very large for its application in aircraft propulsion or in missiles at low and moderate speeds.

(iv) Its fuel consumption decreases with flight speed and approaches reasonable values when the flight Mach number is between 2 and 5 and therefore, it is suitable for propelling supersonic missiles.

Due to its high thrust at high operational speed, it is widely used in high-speed military aircrafts and missiles. Subsonic ramjets are used in target weapons, in conjunction with turbojets or rockets for getting the starting torque.

Pulse jet engine:

Pulse jet engine (Fig. 7.4) is very similar to ramjet engine in construction except that in addition to the diffuser at intake, combustion chamber and exhaust nozzle, it has mechanically operated flapper valve grids which can allow or stop air flow in the combustion chamber. Thus pulse jet is an intermittent flow, compressorless type of device with minimum number of moving parts. Pulse jet was the power plant of German V-1 bomb popularly known as 'Buzz Bomb' first used in World War II in 1944.

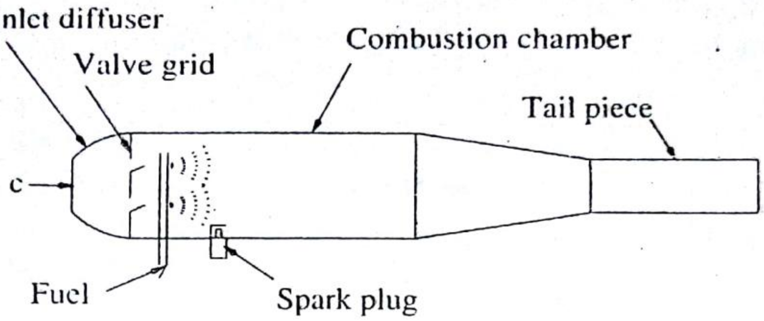


Fig. 7.4 The pulse jet engine

The basic features of the pulse jet engine are illustrated in Fig. 7.4. It consists essentially of the following parts:

(i) a diffuser.

(ii) a valve grid which contains springs that close on their own spring pressure.

(iii) a combustion chamber,

(iv) a spark plug, and

(v) a tail pipe or discharge nozzle.

The theoretical and actual *p-V* diagrams of the pulse jet engine are shown in Fig. 7.5 and Fig. 7.6 respectively.

The operation of the pulse jet is as follows: During starting compressed air is forced into the inlet which opens the spring loaded flapper valve grid; the air enters combustion chamber into which fuel is injected and burnt with the help of a spark plug. Combustion occurs with a sudden explosion process 2–3 in Fig. 7.5, i.e., the combustion is at constant-volume instead of at constant-pressure as in other propulsive devices. The pulse jet cycle is more near to Otto cycle. Ram action can also be used to increase the pressure of the cycle (Fig. 7.5).

The function of the diffuser is to convert the kinetic energy of the entering air into static pressure rise by slowing down the air velocity. When a certain pressure difference builds up across the valve grid, the valves will open. This makes the fresh air to enter the combustion chamber, where fuel is mixed with the air and combustion starts. To start the combustion initially the spark plug is used. Once the combustion starts it proceeds at constant-volume. Thereby, there is a rapid increase in pressure. which causes the valve to close rapidly. The products of combustion surges towards the nozzle. They expand in the nozzle and escape into the atmosphere with a higher velocity so that the exit velocity is much higher than the inlet velocity.

Thus, the rate of momentum of the working fluid is changed so as to cause a propulsive thrust. Since, the combustion process causes the pressure to increase, the engine can operate even at static conditions once it gets started. When the combustion products accelerate from the chamber, they leave a slight vacuum in the combustion chamber. This, in turn, produces sufficient pressure drop across the valve grid, allowing the valves to open again.

A new charge of air enters the combustion chamber which is mixed with fuel that flows continuously. The fresh fuel-air mixture is ignited by the charge leaving and/or by residual charge. New charge need not be ignited with a spark plug again. Proper design allows the duct to fire at a given pulse rate when the fuel flows continuously. The frequency of pulsation is determined by the duct shape and working temperature and may be as high as 500 cycles per second in very small units. The thrust of the pulse jet engine is proportional to the average mass flow rate of gases through the engine multiplied by its increase in velocity.

Like ramjet engines, the maximum operating altitude of the pulsejet is also limited by air density consideration. Unlike the ramjet, the pulse jet engine develops thrust at zero speed. A high initial launching velocity, however, improves its performance. The thrust of the engine, of course, decreases with altitude and does not continue to increase with increasing flight speeds up to supersonic range as is true of ramjet. The maximum flight speed of the pulse jet engine is limited by aerodynamic consideration to below 800 km/h. The pulse jet engine is simple and cheap for subsonic flight and well adapted to pilotless aircraft. The use of the pulse jet engine is restricted to pilotless aircraft due to its severe vibration and high intensity noise.

The pulse jet has low thermal efficiency and limited speed range. In early designs the efficiency obtained was about 2 to 3 percent with a total flight life of 30 to 60 minutes. The maximum operating speed of the pulse jet is seriously limited by two factors:

(i) It is not possible to design a good diffuser at high speeds.

(ii) The flapper valves, the only mechanical part in the pulse jet, also have certain natural frequency and if it coincides with the cycle frequency resonance occurs and the valve may remain open and no compression will take place.

Also, as the speed increases it is difficult for the air to flow back. This reduces the total compression pressure as well as the mass flow of air which results in inefficient combustion and lower thrust. The reduction in thrust and efficiency is quite sharp as the speed increases. At subsonic speeds it might not operate as the speed is not sufficient to raise the air pressure to the required combustion pressure.

Advantages of pulse jet

(i) This is a very simple device next to ramjet and is light in weight. It requires very small and occasional maintenance.

(ii) Unlike ramjet, it has static thrust because of the compressed air starting ; thus it does not need a device for initial propulsion. The static thrust is even more than the cruise thrust.

(iii) It can run on almost any types of liquid fuels without much effect on the performance. It can also operate on gaseous fuel with a little modifications.

(iv) Pulsejet engine is relatively cheap.

Disadvantages of pulse jet

(i) The biggest disadvantage is very short life of flapper valves and high rates of fuel consumption. The specific fuel consumption is as high as that of ramjet.

(ii) The speed of the pulse jet is limited to a very narrow range of about 650–800 km/h because of the limitations in the aerodynamic design of an efficient diffuser suitable for a wide speed range.

(iii) The operational range of the pulse jet is also limited in altitude range.

(iv) The high degree of vibrations due to intermittent nature of the cycle and the buzzing noise has made it suitable for pilotless crafts only.

(v) It has lower propulsive efficiency than turbojet engines.

7.4.2 Applications

Pulse jet is highly suited for bombers like the German V-1 and it has also been used in some helicopters, target aircrafts missiles, etc.

1.4 Gas Turbine Engine Cycle Analysis

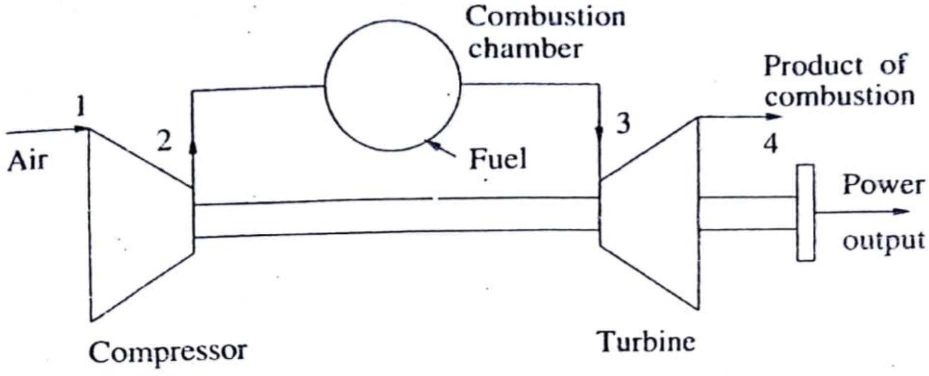


Fig. 5.1 Schematic arrangement of a simple gas turbine

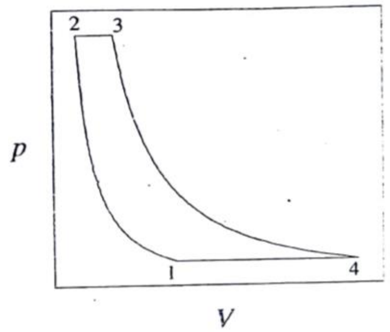


Fig. 5.2 p-V diagram

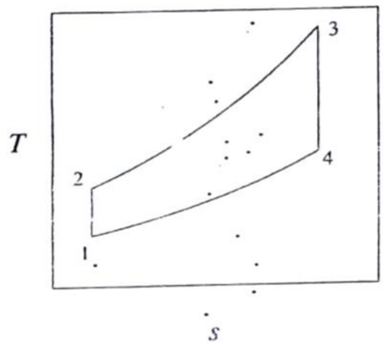


Fig. 5.3 T-s diagram

5.1 ASSUMPTIONS IN IDEAL CYCLE ANALYSIS

The assumption of ideal gas turbine cycle will be taken to imply the following:

(i) The change of kinetic energy of the working fluid between inlet and outlet of each component is negligible.

(ii) Compression and expansion are reversible and adiabatic, i.e., isentropic.

(iii) There are no pressure losses in the inlet ducting, combustion chambers, heat exchangers, intercoolers, exhaust ducting and ducts connecting the components.

(iv) Heat transfer in a heat exchanger is assumed to be perfect (100% effectiveness).

(v) The mass flow of gas is constant throughout the cycle.

(vi) Working fluid has the same composition throughout the cycle and is a perfect gas with constant specific heats.

(vii) Bearing and windage friction, etc., are neglected.

5.2 THE SIMPLE GAS TURBINE CYCLE

The schematic details of a simple gas turbine are shown in Fig. 5.1. Figure 5.2 shows the various processes on a p-V diagram whereas Fig. 5.3 gives the details on a T-s diagram. Figures 5.4 and 5.5 show the performance curves of the cycle.

From the thermodynamic analysis the relevant steady flow energy equation has been shown to be (refer Eq. 2.54)

$$w_s = \Delta h = h_2 - h_1 \tag{5.1}$$

where w_s is the work transfer per unit mass flow, and h stands for enthalpies.

Applying Eq. 5.1 to each component and assuming unit mass flow of the working fluid, we can write the work input to the compressor (process 1→2) as

Compressor work $[W_C]$

$$W_{12} = (h_2 - h_1) = C_p(T_2 - T_1) \tag{5.2}$$

Heat addition $[Q]$

$$Q_{23} = (h_3 - h_2) = C_p(T_3 - T_2) \tag{5.3}$$

Turbine work $[W_T]$

$$W_{34} = (h_3 - h_4) = C_p(T_3 - T_4) \quad (5.4)$$

Net work output $[W_N]$

$$= W_T - W_C$$

$$= C_p(T_3 - T_4) - C_p(T_2 - T_1) \quad (5.5)$$

$$= C_pT_1\left(\frac{T_3}{T_1} - \frac{T_4}{T_1} - \frac{T_2}{T_1} + 1\right) \quad (5.6)$$

Let

$$\frac{T_3}{T_1} = t \text{ and } \frac{p_2}{p_1} = r \quad (5.7)$$

then

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = r^{\frac{\gamma-1}{\gamma}}$$

Let $r^{\frac{\gamma-1}{\gamma}} = c$. From Eq. 5.6

$$\frac{W_N}{C_pT_1} = \frac{T_3}{T_1} - \frac{T_4}{T_3}\frac{T_3}{T_1} - \frac{T_2}{T_1} + 1$$

$$= t - \frac{t}{c} - c + 1 \quad (5.8)$$

$$\frac{W_N}{C_pT_1} = t\left(1 - \frac{1}{c}\right) - (c - 1) \quad (5.9)$$

Equation 5.9 shows that the specific work output $\frac{W_N}{C_p T_1}$, upon which the size of the plant depends is a function of not only the pressure ratio, (r), but also of maximum cycle temperature T_3. Now,

$$\eta = \frac{\text{Net work output}}{\text{Heat input}} = \frac{W_N}{Q} \quad (5.10)$$

$$= \frac{C_pT_1\left[t\left(1 - \frac{1}{c}\right) - (c-1)\right]}{C_p(T_3 - T_2)} \quad (5.11)$$

$$= \frac{C_pT_1\left[(t-c) - \left(\frac{t-c}{c}\right)\right]}{C_pT_1\left[\frac{T_3}{T_1} - \frac{T_2}{T_1}\right]} = \frac{(t-c) - \frac{t-c}{c}}{t-c}$$

$$\eta = 1 - \frac{1}{c} = 1 - \frac{1}{r^{\frac{\gamma-1}{\gamma}}} \quad (5.12)$$

The efficiency of a simple gas turbine thus depends only on the pressure ratio and the nature of the gas, (γ).

1.5 Heat Engines

Heat engine is a machine for converting heat, developed by burning fuel into useful work. It can be said that heat engine is equipment which generates thermal energy and transforms it into mechanical energy.

Classification of Heat Engines

1. Based on combustion of fuel:

- External combustion engine
- Internal combustion engine.

2. Based on fuel used

- **Diesel engine –** Diesel is used as fuel
- **Petrol engine –** Petrol is used as fuel
- **Gas engines** – propane, butane or methane gases are used

3. Based ignition of fuel

- Spark ignition engine (Carburetor type engines)
- Compression ignition engine (injector type engines)

4. Based on working cycle

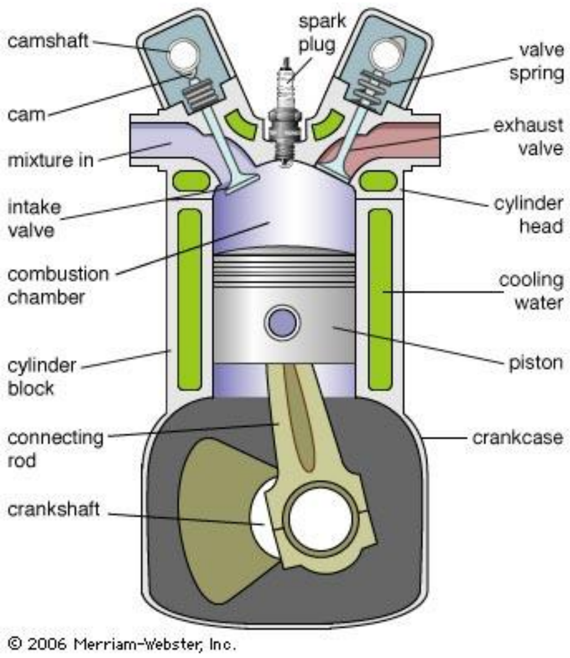
- **Four stroke cycle engine** - When the cycle is completed in two revolutions of the crankshaft, it is called four stroke cycle engine.
- **Two stroke cycle engine.** - When the cycle is completed in one revolution of the crankshaft, it is called two stroke cycle engine

1.6 Working Principle of Internal Combustion Engine

- A mixture of fuel with correct amount of air is exploded in an engine cylinder which is closed at one end.
- As a result of this explosion, heat is released and this heat causes the pressure of the burning gases to increase.
- This pressure forces a close fitting piston to move down the cylinder.
- The movement of piston is transmitted to a crankshaft by a connecting rod so that the crankshaft rotates and turns a flywheel connected to it.
- Power is taken from the rotating crank shaft to do mechanical work.
- To obtain continuous rotation of the crankshaft the explosion has to be repeated continuously.
- Before the explosion to take place, the used gases are expelled from the cylinder, fresh charge of fuel and air are admitted in to the cylinder and the piston moved back to its starting position.

The sequences of events taking place in an engine is called the working cycle of the engine. The sequence of events taking place inside the engine are as follows:

- Admission of air or air-fuel mixture inside the engine cylinder **(suction)**
- Compression of the air or air fuel mixture inside the engine **(compression)**
- Injection of fuel in compressed air for ignition of the fuel or ignition of air-fuel mixture by an electric spark using a spark plug to produce thermal power inside the cylinder **(power)**
- Removal of all the burnt gases from the cylinder to receive fresh charge **(exhaust)**



1.7 Four Stroke Cycle Engine (Diesel/ Petrol Engine)

The events taking place in I.C. engine are as follows:

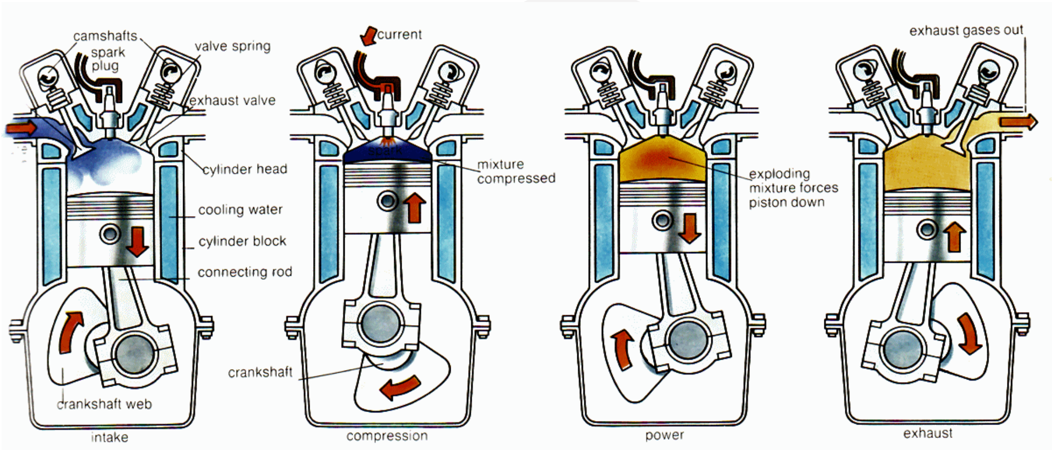
- Suction stroke
- Compression stroke
- Power stroke
- Exhaust stroke

Suction stroke:

- During suction stroke inlet valve opens and the piston moves downward.
- Only air or a mixture of air and fuel are drawn inside the cylinder.
- The exhaust valve remains in closed position during this stroke.
- The pressure in the engine cylinder is less than atmospheric pressure during this stroke.

Compression stroke:

- During this stroke the piston moves upward. Both valves are in closed position.
- The charge taken in the cylinder is compressed by the upward movement of piston.
- If only air is compressed, as in case of diesel engine, diesel is injected at the end of the compression stroke and ignition of fuel takes place due to high pressure and temperature of the compressed air.
- If a mixture of air and fuel is compressed in the cylinder, as in case of petrol engine, the mixture is ignited by a spark plug.

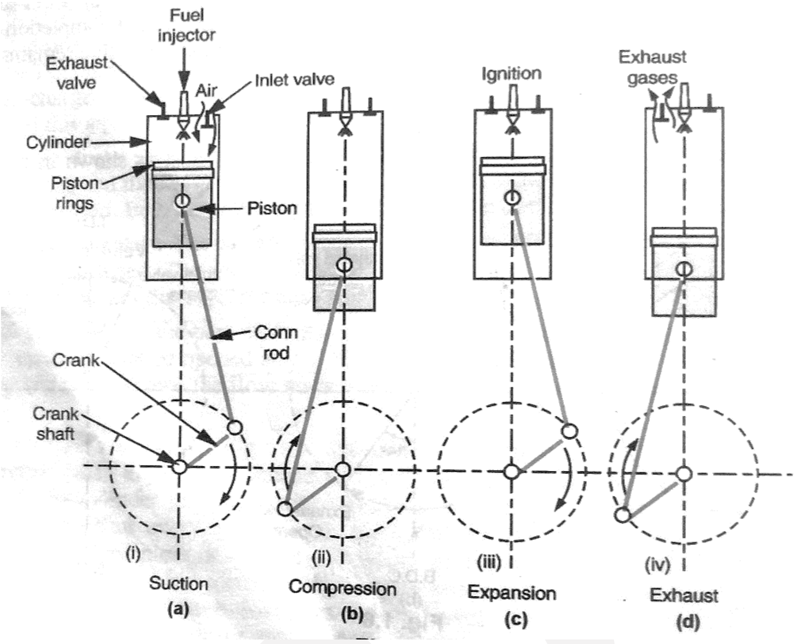


Power stroke:

- After ignition of fuel, tremendous amount of heat is generated, causing very high pressure in the cylinder which pushes the piston downward.
- The downward movement of the piston at this instant is called power stroke.
- The connecting rod transmits the power from piston to the crank shaft and crank shaft rotates.
- Mechanical work can be taped at the rotating crank shaft.
- Both valves remain closed during power stroke.

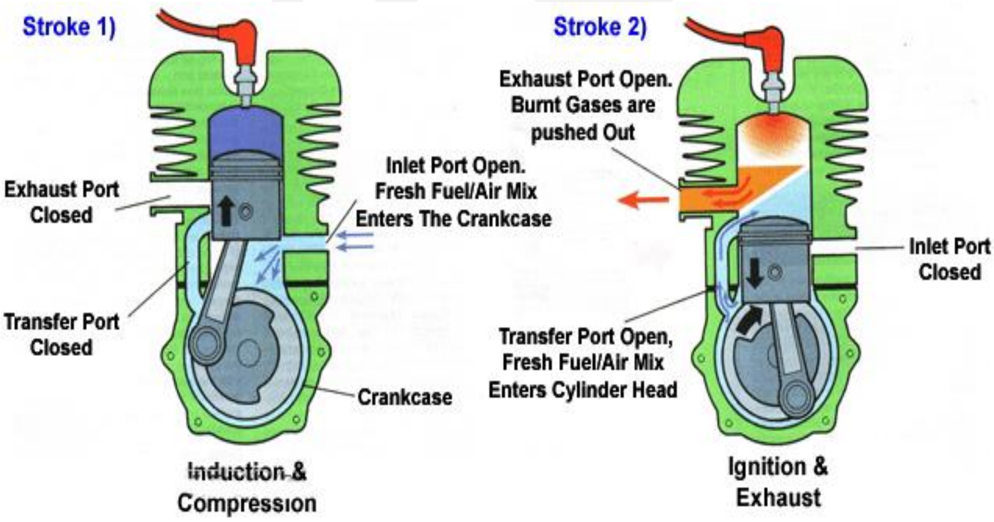
Exhaust stroke

- During this stroke piston moves upward.
- Exhaust valve opens and exhaust gases go out through exhaust valves opening.
- All the burnt gases go out of the engine and the cylinder becomes ready to receive the fresh charge.
- During this stroke inlet valve remains closed.



1.8 Two Stroke Cycle Engine (Petrol Engine)

- In two stroke cycle engines, the whole sequence of events i.e., suction, compression, power and exhaust are completed in two strokes of the piston i.e. one revolution of the crankshaft.
- There is no valve in this type of engine. Gas movement takes place through holes called ports in the cylinder.
- The crankcase of the engine is air tight in which the crankshaft rotates.



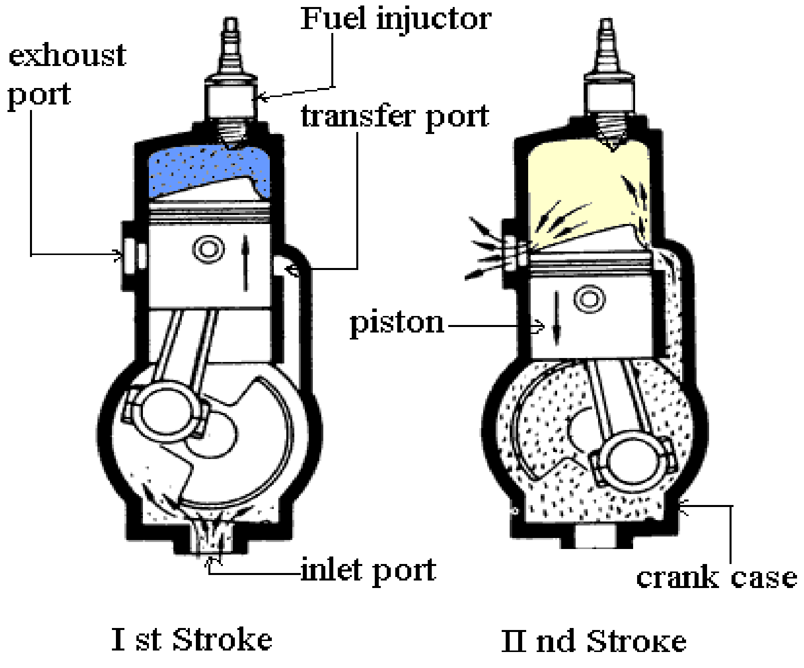
Upward stroke of the piston (Suction + Compression):

- When the piston moves upward it covers two of the ports, the exhaust port and transfer port, which are normally almost opposite to each other.
- This traps the charge of air- fuel mixture drawn already in to the cylinder.

- Further upward movement of the piston compresses the charge and also uncovers the suction port.
- Now fresh mixture is drawn through this port into the crankcase.
- Just before the end of this stroke, the mixture in the cylinder is ignited by a spark plug.
- Thus, during this stroke both suction and compression events are completed.

Downward stroke (Power + Exhaust):

- Burning of the fuel rises the temperature and pressure of the gases which forces the piston to move down the cylinder.
- When the piston moves down, it closes the suction port, trapping the fresh charge drawn into the crankcase during the previous upward stroke.
- Further downward movement of the piston uncovers first the exhaust port and then the transfer port.
- Now fresh charge in the crankcase moves in to the cylinder through the transfer port driving out the burnt gases through the exhaust port.
- Special shaped piston crown deflect the incoming mixture up around the cylinder so that it can help in driving out the exhaust gases.
- During the downward stroke of the piston power and exhaust events are completed.



1.9 Comparison between Two Stroke and Four Stroke

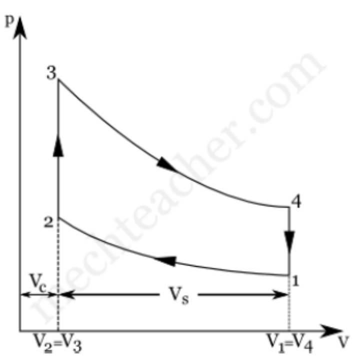
Four stroke engine	Two stroke engine
1. One power stroke for every two revolutions of the crankshaft.	One power stroke for each revolution of the crankshaft.
2. There are inlet and exhaust valves in the engine.	There are inlet and exhaust ports instead of valves.
3. Crankcase is not fully closed and 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.

1.10 Otto Cycle (modern petrol engines)

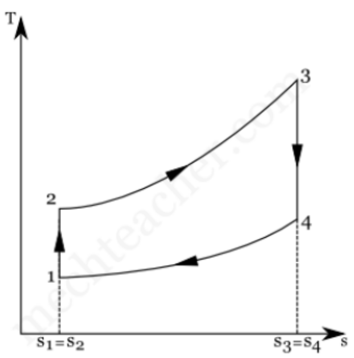
Otto cycle is a gas power cycle that is used in spark ignition internal combustion engines (modern petrol engines). This cycle was introduced by Dr. Nikolaus August Otto, a German Engineer. An Otto cycle consists of four processes:

1. Two isentropic (reversible adiabatic) processes
2. Two isochoric (constant volume) processes

p-V Diagram



T-s Diagram



Processes in Otto Cycle:

As stated earlier, Otto cycle consists of four processes. They are as follows:

Process 1-2: Isentropic compression

In this process, the piston moves from bottom dead centre (BDC) to top dead centre (TDC) position. Air undergoes reversible adiabatic (isentropic) compression. We know that compression is a process in which volume decreases and pressure increases. Hence, in this process, volume of air decreases from V_1 to V_2 and pressure increases from p_1 to p_2. Temperature increases from T_1 to T_2. As this an isentropic process, entropy remains constant (i.e., $s_1 = s_2$).

Process 2-3: Constant Volume Heat Addition

Process 2-3 is isochoric (constant volume) heat addition process. Here, piston remains at top dead centre for a moment. Heat is added at constant volume ($V_2 = V_3$) from an external heat source. Temperature increases from T_2 to T_3, pressure increases from p_2 to p_3 and entropy increases from s_2 to s_3.

In this process,

Heat Supplied = $mC_v (T_3 – T_2)$

Process 3-4: Isentropic expansion

In this process, air undergoes isentropic (reversible adiabatic) expansion. The piston is pushed from top dead centre (TDC) to bottom dead centre (BDC) position. Here, pressure decreases from p_3 to p_4, volume rises from V_3 to V_4, temperature falls from T_3 to T_4 and entropy remains constant ($s_3 = s_4$).

Process 4-1: Constant Volume Heat Rejection

The piston rests at BDC for a moment and heat is rejected at constant volume ($V_4 = V_5$). In this process, pressure falls from p_4 to p_1, temperature decreases from T_4 to T_1 and entropy falls from s_4 to s_1.

In process 4-1,

Heat Rejected = $mC_v (T_4 – T_1)$

Thermal efficiency (air-standard efficiency) of Otto Cycle,

$$\eta_{th} = \frac{\text{Heat Supplied - Heat Rejected}}{\text{Heat Supplied}}$$

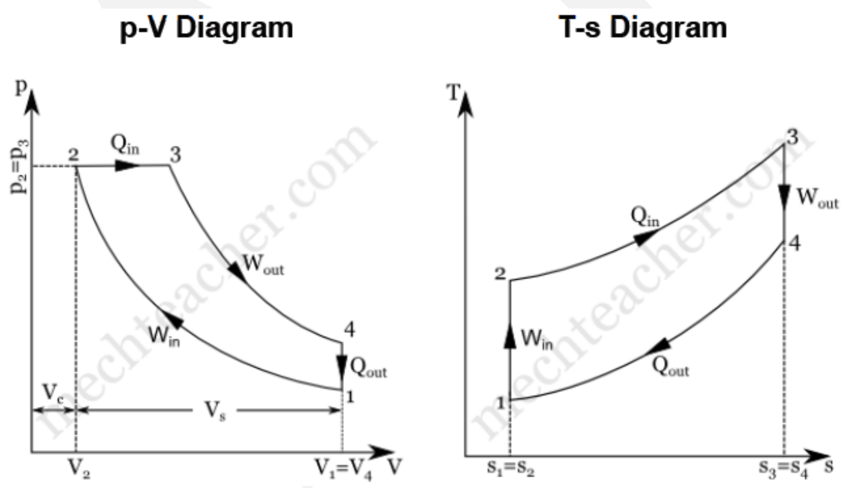
$$\eta_{th} = \frac{mC_v\left(T_3 - T_2\right) - mC_v\left(T_4 - T_1\right)}{mC_v\left(T_3 - T_2\right)}$$

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

1.11 Diesel Cycle (Diesel engines)

Diesel cycle is a gas power cycle invented by Rudolph Diesel in the year 1897. It is widely used in diesel engines.

Diesel cycle is similar to Otto cycle except in the fact that it has one constant pressure process instead of a constant volume process (in Otto cycle).



Processes in Diesel Cycle:

Diesel cycle has four processes. They are:

1. Process 1-2: Isentropic (Reversible adiabatic) Compression
2. Process 2-3: Constant Pressure (Isobaric) Heat Addition
3. Process 3-4: Isentropic Expansion
4. Process 4-1: Constant Volume (Isochoric) Heat Rejection

Process 1-2: Isentropic Compression

In this process, the piston moves from Bottom Dead Centre (BDC) to Top Dead Centre (TDC) position. Air is compressed isentropically inside the cylinder. Pressure of air increases from p_1 to p_2, temperature increases from T_1 to T_2, and volume decreases from V_1 to V_2. Entropy remains constant (i.e., $s_1 = s_2$).

Process 2-3: Constant Pressure Heat Addition

In this process, heat is added at constant pressure from an external heat source. Volume increases from V_2 to V_3, temperature increases from T_2 to T_3 and entropy increases from s_1 to s_3.

Heat added in process 2-3 is given by

$$Q = mC_v(T_3 - T_2)$$

Process 3-4: Isentropic Expansion

Here the compressed and heated air is expanded isentropically inside the cylinder. The piston is forced from TDC to BDC in the cylinder. Pressure of air decreases from p_3 to p_4, temperature decreases from T_3 to T_4, and volume increases from V_3 to V_4. Entropy remains constant (i.e., $s_3 = s_4$).

Process 4-1: Constant Volume Heat Rejection

In this process, heat is rejected at constant volume ($V_4 = V_1$). Pressure decreases from P_4 to P_1, temperature decreases from T_3 to T_4 and entropy decreases from s_4 to s_1.

Heat rejected in process 4-1 is given by

$$Q = mC_v(T_4 - T_1)$$

Air-standard efficiency (or thermal efficiency) of diesel cycle is given by:

$$\eta_{\text{Th}} = \eta_{\text{Diesel}} = \frac{\text{Heat Added} - \text{Heat Rejected}}{\text{Heat Added}} \times 100$$

$$\eta_{\text{Diesel}} = \frac{Q_{in} - Q_{out}}{Q_{in}} \times 100\ \%$$

From equations (i) and (ii)

$$\eta_{\text{Diesel}} = \frac{mC_p\ (T_3 - T_2) - mC_V\ (T_4 - T_1)}{mC_p\ (T_3 - T_2)} \times 100\ \%$$

$$\eta_{\text{Diesel}} = \left(1 - \frac{mC_V\,(T_4 - T_1)}{mC_p\,(T_3 - T_2)}\right) \times 100\,\%$$

$$\eta_{\text{Diesel}} = \left(1 - \frac{C_V\,(T_4 - T_1)}{C_p\,(T_3 - T_2)}\right) \times 100\,\%$$

$$\eta_{\text{Diesel}} = \left(1 - \frac{1}{\gamma}\frac{(T_4 - T_1)}{(T_3 - T_2)}\right) \times 100\,\% \quad (\text{Since, } \frac{C}{C}$$

1.12 Advantages of Reciprocating Engines over Gas Turbines

(i) *Efficiency* The overall efficiency of the turbine is much less than the reciprocating engine since 70% of the output of the turbine is to be fed to the compressor and other accessories and auxiliary parts.

(ii) *Temperature limitation* The maximum temperature in gas turbine cannot exceed 1500 K because of the material consideration of the blade while in reciprocating engines with complete combustion of the fuel the maximum temperature can be raised to 2000 K. This high temperature is permitted since the piston and cylinder head are subjected to this high temperature only for a fraction of a second.

(iii) *Cooling* We can achieve very good results by efficient cooling in reciprocating engine by which the heat of the cylinder walls is taken away, which enables to keep the wall temperature only around 500 K but in gas turbine, cooling is complicated, and, therefore, much higher temperature cannot be allowed to reach.

(iv) *Starting difficulties* It is more difficult to start a gas turbine than a reciprocating engine as it requires compressed air or some suitable starter mechanism which are complicated.

1.13 Advantages of Gas Turbines over Reciprocating Engines

(i) *Mechanical efficiency* Mechanical efficiency of the gas turbine is considerably higher than that of the best reciprocating engine. For simple gas turbine design mechanical efficiency of 90% to 95% has been claimed while for reciprocating engine it is from 85 to 90% under full load conditions. It is due to more frictional losses in reciprocating engines.

(ii) *Balancing* Due to absence of any reciprocating mass in gas turbine engine, balancing can be near perfect. Torsional vibrations are absent because gas turbine is a steady flow machine.

(iii) *Cost* In case of larger output gas turbine units of 2500 kW, it can be built at an appreciably lower cost and in a shorter time than the corresponding multicylinder petrol or diesel engines.

(iv) *Weight* The fuel consumption per kW hour of best available aircraft gas turbine is almost twice that of the normal petrol engine. However, it has much lighter weight per kW so that the total weight of turbine plus fuel does not compare unfavourably with reciprocating type of engine and its fuel. To give quantitative example, the specific weight of (a) steam turbine is about 53 kg/kW, (b) diesel engine is about 115 kg/kW and (c) gas turbine is about 20 kg/kW.

(v) *External shape and size* The basic cylindrical shape of turbine and compressor unit renders the gas turbine more convenient to start, especially in aircraft and locomotives.

(vi) *Fuel* The turbine can be designed to operate with cheaper and more readily available fuels such as benzene, powdered coal, and heavy graded hydrocarbons. Promising results have been obtained using furnace oil and also pulverized coal as fuel.

(vii) *Lubrication* Compared with reciprocating engines the lubrication of gas turbines is comparatively simpler. The requirement is chiefly to lubricate the main bearing, compressor shaft and bearings of auxiliaries.

(viii) *Maintenance* The fact that the gas turbine consists of essentially a single turbine and compressor unit with a common or coupled shaft running in a relatively smaller number of main bearings, only minimum maintenance is necessary as compared to the reciprocating internal combustion engines.

(ix) *Low operating pressures* The gas turbine generally operates at relatively low pressures so that the parts exposed to these pressures can be made light although the effects of thermal expansion and contraction must be taken into account. The maximum combustion pressure is much lower than that in reciprocating engines so that the pressure joints and piping do not pose any difficulty.

(x) *Silent operation* Since the exhaust from a gas turbine occurs under practically constant-pressure conditions unlike the pulsating nature of reciprocating engine exhaust, the turbine and compressor, if dynamically balanced, can run very smoothly. The usual vibrational noises as in the case of reciprocating engine are almost absent.

(xi) *Smokeless exhaust* With the present tendency to use relatively large surplus air for combustion in order to reduce temperature of gases, the exhaust from the turbine is almost smokeless and generally free from pungent odour associated with optimum and rich fuel mixture which is characteristic of reciprocating engines.

(xii) *High operational speed* Turbine can be made lighter than the reciprocating engine of similar output. It can be run at much higher speed than reciprocating engines. The output of any engine varies directly as the product of the driving shaft torque and its rpm. Therefore, for a given output and higher speed the torque will be lower. It may be noted that the torque characteristics of the gas turbine is much better than that of reciprocating engine, since the former gives a high initial torque and its variation with speed is comparatively less.