UNIT-1: IC ENGINES

Heat Engine: Heat Engine is a machine which derives heat energy from the combustion of fuels or from any source and converts this heat energy into mechanical energy.

Classification of Heat Engines:
1.Internal Combustion Engine(IC Engine)
2.External Combustion Engine (EC Engine)

IC Engines: In this, combustion of fuel with oxygen of air occurs within the cylinder of the engine. These are used for driving Automobile, Prime movers for generation of Electrical Power.

Different types of IC Engines are Petrol Engine, Diesel Engine and Gas Engine

EC Engines: In this, the combustion of fuel takes place outside the cylinder as in case of steam engines where the heat of combustion is employed to generate which is used to move a piston in the cylinder. These Engines are used for driving locomotives, generation of Electrical Power.

Advantages of EC Engines over IC Engines:
1.Cheaper fuels can be used i.e Solid fuels.
2. Starting torque is generally high.
3. Due to external combustion, it is possible to have flexibility in arrangements.
4. This units are self starting with working fluids.

Advantages of IC Engines over EC Engines:
1.Overall efficiency is high.
2.Weight-power ratio is generally low.
3.Greater mechanical simplicity.
4.Low initial cost.
5.These units are compact and requires less space.

Applications of IC Engines:

Used in
1.Road Vehicles Eg: Scooter, Buses
2.Air Crafts
3.Locomotives
4.Pumping Sets
5.Hospitals
6.Prime movers

Classification of IC Engines:

IC Engines may be classified as:

1. According to the cycle of operations
   a. Two-Stroke Engine
   b. Four-Stroke Engine

2. According to the cycle of combustion
   a. Otto cycle (constant volume combustion)
   b. Diesel cycle Engine(Combustion at constant pressure)
   c. Dual cycle(combustion partly at constant pressure, partly at constant volume)

3. According to number of cylinders
   a. Single cylinder
   b. Multi cylinder

4. According to arrangement of cylinders
   a. Horizontal Engine
   b. Vertical Engine
   c. V-type Engine
   d. Radial Engine

5. According to their uses
   a. Stationary Engine(used in generators)
   b. Portable Engine
   c. Marine Engine
   d. Auto-mobile Engine
   e. Aero Engine

6. According to fuel used
   a. Oil Engine
   b. Petrol Engine
   c. Gas Engine
   d. Kerosene Engine

7. According to the method of Ignition
   a. Spark Ignition Engines(SI Engine)
   b. Compression Ignition Engines(CI Engine)

8. According to the speed of Engine
   a. Low speed Engines
   b. Medium speed Engines
   c. High speed Engines

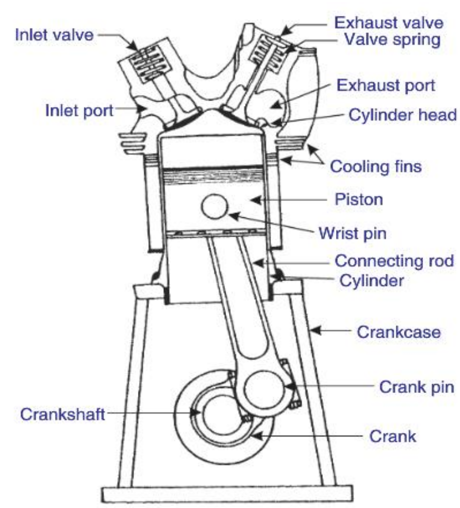
9. According to the method of cooling of Engine
   a. Air cooled Engines
   b. Water cooled Engines

10. According to the method of Governing
   a. Quality governed Engines
   b. Quantity governed Engines
   c. Hit and miss governed Engines

11. According to the Valve Arrangement
   a. Lower head type Engines
   b. Overhead valve Engines
   c. T-Head type Engines
   d. F-Head type Engines

<u>Basic Idea of IC Engines:-</u>

The cylinder which is closed at one end is filled with air-fuel mixture As the crank shaft rotates it pushes the piston upwards as the piston is forced up it compresses the mixture in the top of the cylinder. When the mixture starts igniting it creates a gas pressure on the piston & pushes the piston downwards then the piston pushes the connecting rod which in turn rotates the crank. The flywheel which is mounted on the crank shaft stores the energy and keeps the crank turning steady.



Engine Components

Cylinder &cylinder head:

Cylinder: It is a cylindrical vessel in which the fuel is burnt & the product of combustion gases expand to develop power .The main function of the cylinder is to guide the piston .At the upper end cylinder and cylinder head are connected at the bottom cylinder and crank case are connected .Due to high combustion of fuel high temperatures and high pressures are formed ,so it must be high grade cast iron. It is usually made by casting process .In order to reduce the weight of the engine aluminium alloys are also used

Cylinder head: The top end of the cylinder is closed by means of removable cylinder head. It consists of two valves one for intake and other for exhaust spark plug, fuel inserter etc., The main function of the cylinder head is to seal the cylinder block and not to permit entry and exit of gases.
It is made up of cast iron and aluminium alloys by casting and forging process.

Piston And Piston Rings:

Piston: A piston is fitted in the cylinder in order to receive the gas pressure and transmit the thrust to the connecting rod.
The main function of the piston is to give tight seal to the cylinder through bore &slide freely inside the cylinder.
The piston is made by aluminum and cast iron.

Piston Rings: Piston rings are located between piston and cylinder. They are generally made up of cast iron.
There are two types of ring fitted on the circumferential groove provided on outer surface of piston

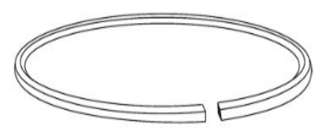
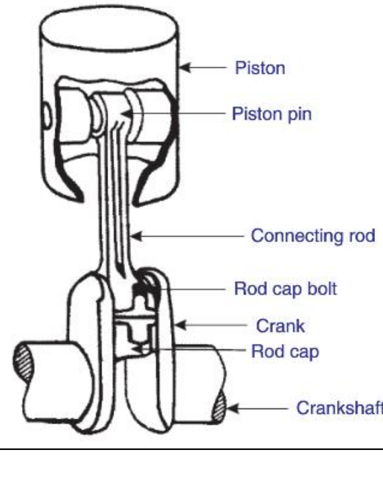


Fig. 23.9. Compression ring.

i)COMPRESSION RING :It maintains a gas tight contact between cylinder and piston.
ii)OIL SCRAPER RING: Lubrication is required in the cylinder sleeve to reduce frictional force. So these rings removes the excessive lubricating oil from cylinder into crank case.

Fig. 23.10. Oil ring.

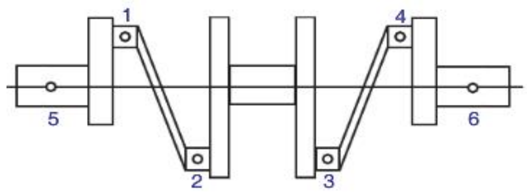
Connecting Rod: Connecting rod transmits the force from piston to crank shaft. It helps in converting reciprocating motion to rotary motion. It has two ends one is small end and other is big end. The smaller end is connected to piston by gudgeon pin. The big end is connected with crank shaft.



Crank, Crank Shaft &Crank Case:

Crank: is lever between connecting rod and crank shaft.

Crank Shaft: receives the thrust from piston to crank shaft and convert reciprocating motion of piston into rotary motion.



. Typical crankshaft layout.

Crank case: supports and covers cylinder and crank shaft. It is used to store lubricating oil.

Cam shaft: It is used in I.C engines to control opening and closing of valves at proper timing .It is driven by the timing belt which drives the crank shaft .Cam shaft rotates half of the speed of the crank shaft.

Flywheel: It is used to control the cyclic variation of engine power produced .It stores excess energy during power stroke & returns the stored energy for use in different stroke. It is made up of cast iron. It is mounted on crank shaft.

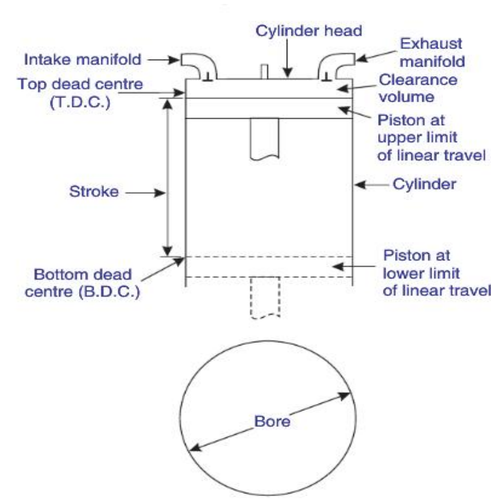
Governor: is a device used to regulate the speed of the engine by operating the supply valve of the fluid according to load requirement in order to maintain constant speed .

When the load on the engine increases it decreases the speed of the engine .In order to maintain constant speed additional amount of may be sent to the cylinder by operating the supply valve and vice versa.

Comparison Between Flywheel And Governor

Flywheel	*Governor*
used because of variation of speed due to variation in the output torque of engine during a cycle.	used because of variation of speed due to variation in the load on the engine.
Limits the inertiable fluctuation of speed during each cycle which arises due to fluctuation of turning moment on crank shaft.	Controls the mean speed of engine by varying the fuel supply which arises due to variation of load.
Stores excess of rotational energy from the power stroke and supply back during non- power strokes of the cycle.	When load on the engine increases, speed decreases, it increases the flow of fuel to keep the mean speed constant.
It controls the speed for one cycle only so it is continuous.	It maintains constant mean speed over a period of time so it is discrete.

TERMS CONNECTED WITH I.C ENGINE



. Terms relating I.C. engines.

BORE:
The inside diameter of the cylinder is called bore.

STROKE:
As the piston reciprocates inside the engine cylinder .It had got limiting upper and lower position beyond which it cannot move and reversal of motion takes places at these limiting position.

The linear distance along the cylinder axis between two limiting position is called stroke.

Top dead center (TDC):
The lowest position of the piston towards the cover end side of the cylinder is called TDC .In case of horizontal engine it is inner a dead center.

Bottom dead center:
The lowest position of the piston towards crank side of the cylinder is called BDC. In case of horizontal engine it is outer dead center.

Clearance volume:
The volume contained in the cylinder above top of the piston ,when the piston is at TDC is called clearance volume.

Swept volume:
The volume swept by the piston in moving TDC ,BDC is called swept volume or piston displacement .
Total volume of the cylinder =Vc+Vs

Compression ratio:
It is the ratio of total cylinder volume to the clearance volume .

$$r = \frac{V_s + V_c}{V_c}$$

In S.I engine compression ratio 7:1 to 9:1
In C.I engine compression ratio 15:1 to 18:1

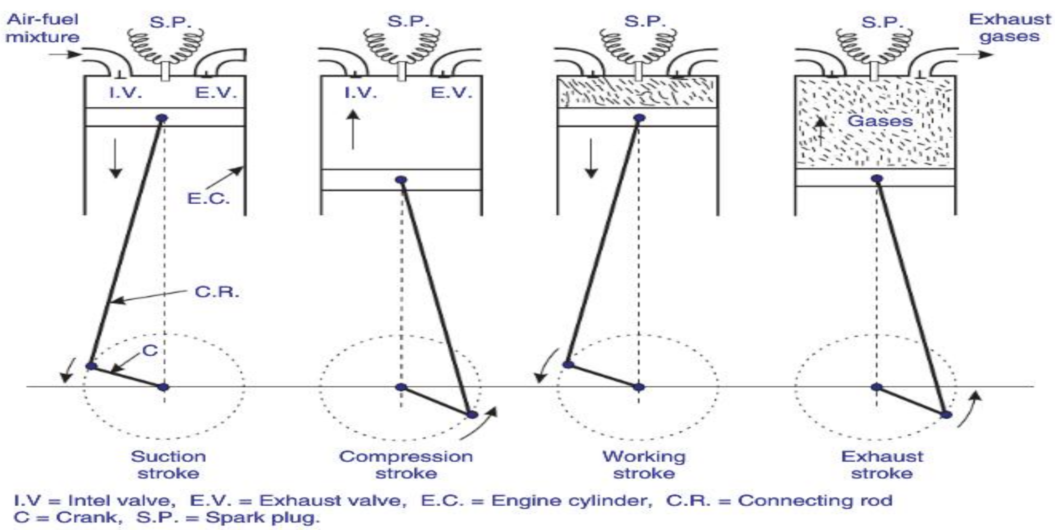
Piston speed : The average speed of the piston is piston speed
piston speed =2 LN
L =length of stroke
N = speed of the engine

Indicator diagram: It is the graph between pressure and volume .Pressure on vertical axis &volume on horizontal axis .This is obtained by an indicator .

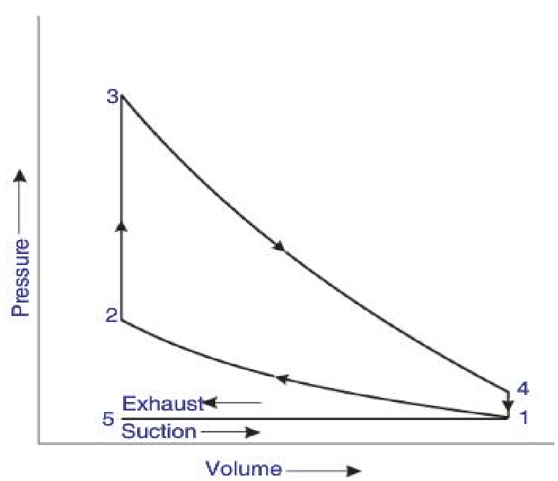
Four Stroke petrol engine

The four stroke petrol engine works on the principle of otto cycle In this the mixture of air and fuel enters into the engine cylinder and the ignition of the engine is due to the spark .It is also known as S.I engine(spark ignition engine).

The various strokes of 4 stroke engines are :
1.Suction stroke
2.Compression stroke
3.Expansion stroke(power stroke)
4.Exhaust stroke



Four-stroke Otto cycle engine.



. Theoretical p-V diagram of a four-stroke Otto cycle engine.

suction stroke:

In this stroke the piston moves from T.D.C to B.D.C the inlet valve opens and air fuel mixture is sucked in the engine cylinder .It is represented by 5-1 .The exhaust valve remain closed throughout the stroke .

Compression Stroke:

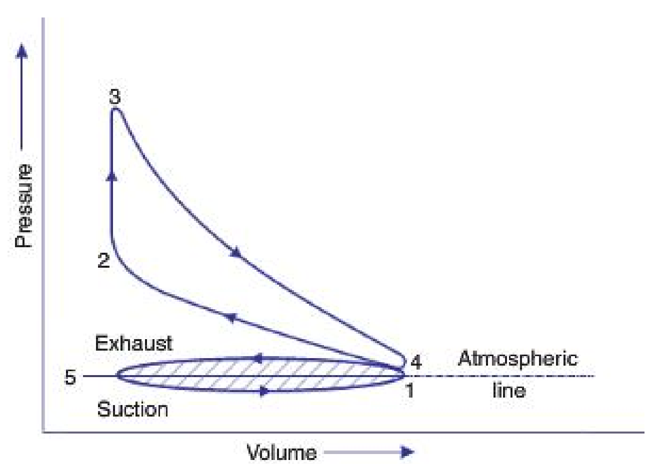
During this stroke the piston moves from B.D.C to T.D.C and compress the enclosed air fuel mixture during this stroke .The pressure of the mixture raises to 8 bar .It is represented by 2-3 line.
Just before the end of the stroke the spark plug initiates the spark plug and ignites the mixture and the combustion takes place at constant volume (2-3).Both inlet and exhaust valve remain closed in this stroke.

Expansion Stroke:

When the mixture is ignited by the spark plug the hot gases are produced which drive or throw the piston from the T.D.C to B.D.C. In this work is obtained from the engine. It is represented by the line 3-4. The flywheel which is mounted on the engine shaft store energy during this stroke & supplies it during other cycles.

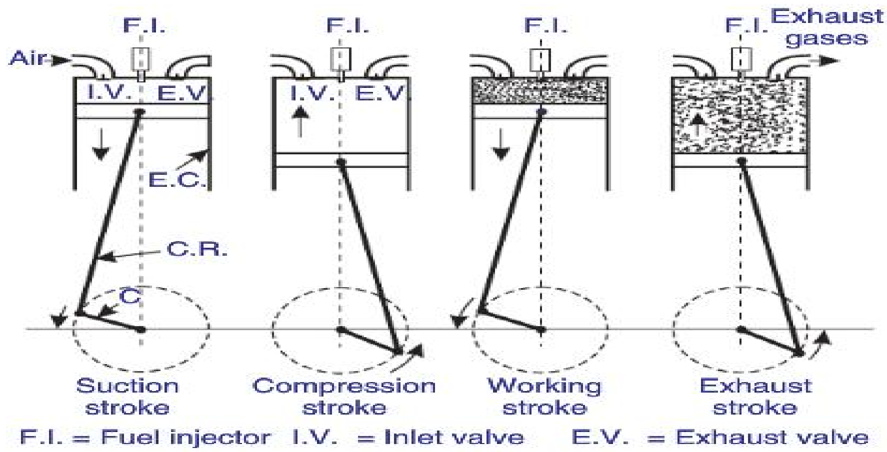
Exhaust Stroke:

The gas from which the work is extracted becomes useless after the completion of expansion stroke and is made to escape through exhaust valve to atmosphere .The piston moves from B.D.C to T.D.C & exhaust gases are driven out of the engine cylinder. This operation is represented by 5-1.



Actual p-V diagram of a four-stroke Otto cycle engine.

Four Stroke Diesel Engine 4-stroke diesel engine works on principle of diesel cycle. In this the air enters into the engine the ignition of engine its due to the compression of air &spraying fuel on compressed air .It is known as compressed ignition engine.



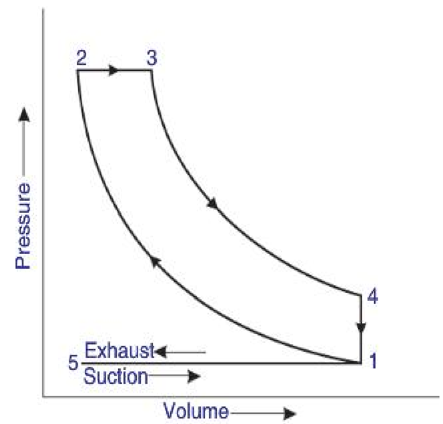
Four-stroke Diesel cycle engine.

Suction Stroke:
With the movement of piston from T.D.C to B.D.C during this stroke the inlet valve opens &air at atmosphere pressure is drawn inside the engine cylinder .Exhaust valve remains closed. This represented by the line 5-1.

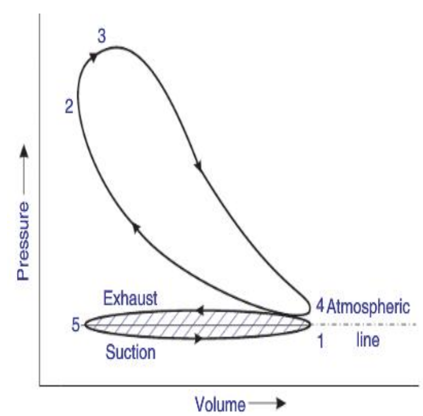
Compression Stroke:
The air drawn at atmosphere pressure during suction stroke is compressed to high pressure &temperature up to 35 bar &600°c respectively. The piston moves from B.D.C to T.D.C. The operation is represented by 1-2.Both inlet valve & exhaust valve don't open during this stroke.

Expansion stroke:
As the piston starts moving from T.D.C a metered quantity of fuel is injected into hot comp air in fine spray by fuel injector and fuel start burning at constant pressure represented by the line 2-3 .The hot gases produced by combustion of fuel expands adiabatic thus produces work it is represented by line 3-4

Exhaust stroke: The piston moves from the B.D.C to T.D.C and exhaust gas try to escape to the atmosphere. It is represented by the line 1-5.

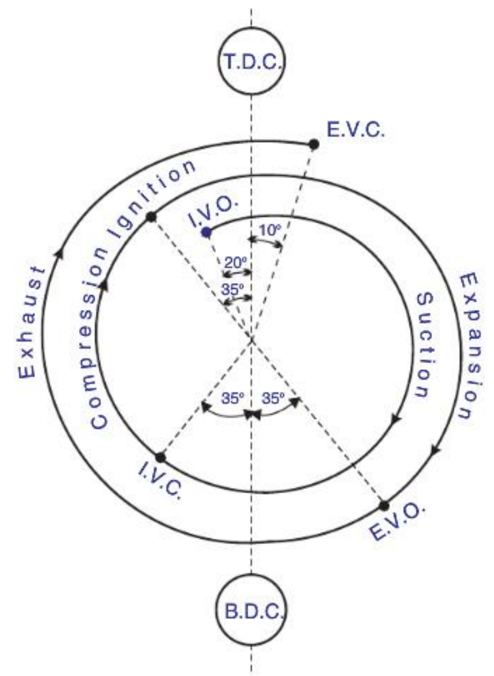


Theoretical p-V diagram of a four-stroke Diesel cycle.

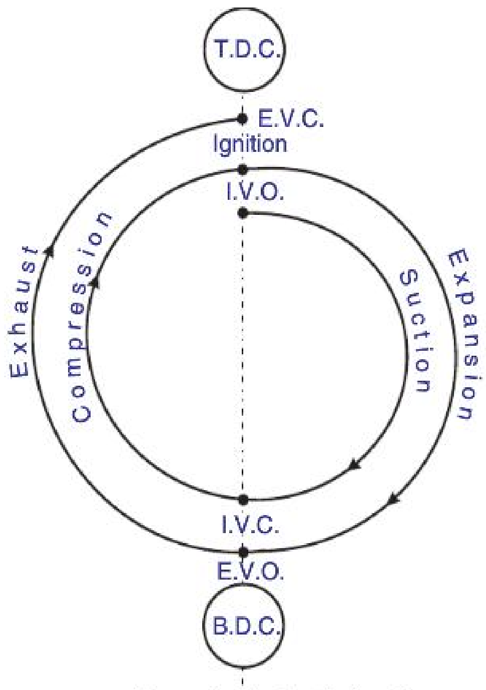


Actual p-V diagram of four-stroke Diesel cycle.

Valve timing diagram:

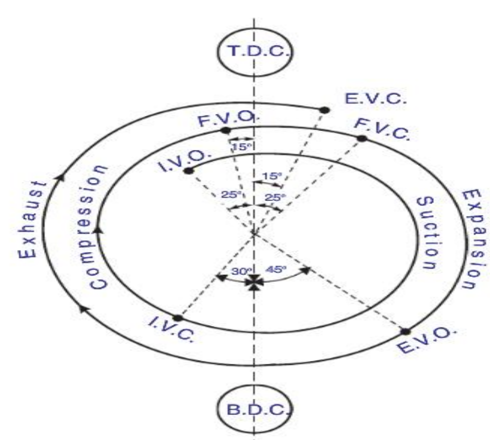


. Actual valve timing diagram (four-stroke Otto cycle engines).



Theoretical valve timing diagram (four-stroke Otto cycle engine).

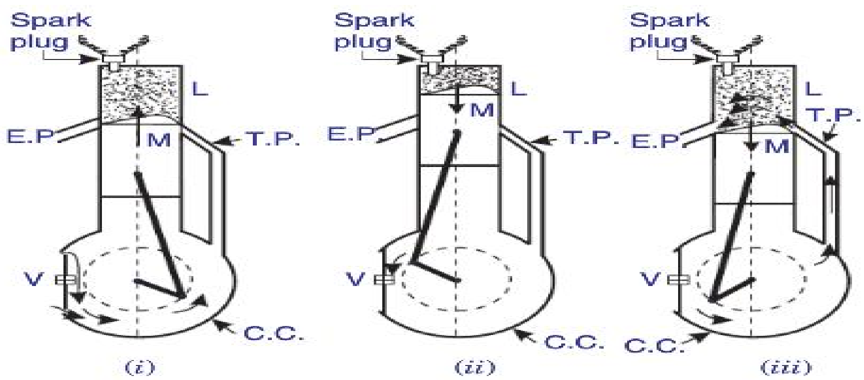
- In actual practice it is difficult to open &close the valve instantaneously so to get better perform of the engine the valve timing diagram are modified.
- The inlet valve open 10°-30°before T.D.C to enable fresh charge into the cylinder & help to sent the burnt gases at the same time.
- The inlet valve closes 30°-40°after B.D.C in order to allow additional time for air-fuel mixture to flow into the cylinder .It increases volumetric efficiency.
- The spark plug produces a spark 30°-40° before T.D.C thus fuel gets more time to burn.
- Exhaust valve opens 30°-60° before T.D.C and closes 10° after T.D.C in order to give more time to start leaving the cylinder.



. Actual valve timing diagram (four-stroke Diesel cycle engines).

Two-stroke cycle engine:

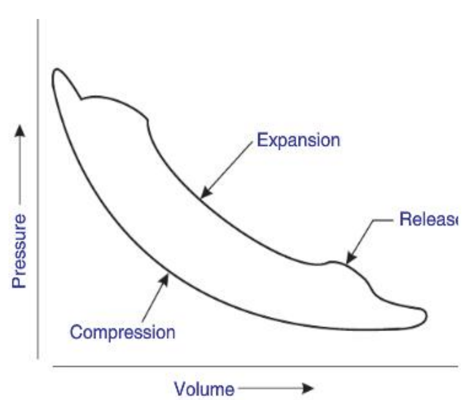
In this two strokes of piston are required to complete the cycle of operations. The engines which uses these cycles are called two-stroke cycle engine.
In this two strokes are eliminated i.e., Suction and Exhaust strokes. In this engine the ports are used instead of Valves. These two stroke engines are used in scooters, Motorcycle etc.



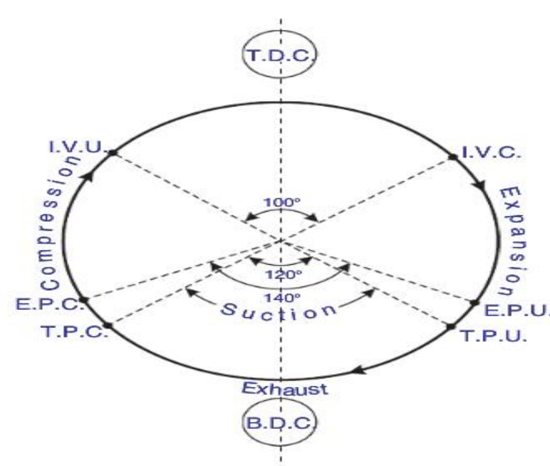
L = Cylinder, E.P. = Exhaust port, T.P. = Transfer port,
V = Valve, C.C = Crank chamber

Two-stroke cycle engine.

- When the piston is moving upwards it compress the charge i.e., air fuel mixture which is previously entered into the cylinder. At the same time inlet port opens the air fuel mixture enters into the crank chamber.
- When the piston reaches the T.D.C the charge will attain high pressures and high temperature. By supplying the spark through spark plug the fuel starts igniting and produces high pressure on piston and pushes the piston downwards and this is expansion stroke.
- In this stroke first exhaust port opens and the burnt gas will flow from this port and next transfer port opens due to this compressed charge from crank chamber enters into the cylinder through the transfer port.
- The fresh charge which is entered into the cylinder will helps in sending the exhaust gas to outside .Due to this the fresh charge may be diluted &efficiency of the engine decreases.
- When the piston moves from B.D.C to T.D.C the transfer port closes &then the exhaust port closes by the piston & completes the cycle.



p-V diagram for a two-stroke cycle engine.



Port timing diagram.

AIR standard cycles: Air-standard analysis is used to perform elementary analyses of IC engine cycles.

Simplifications to the real cycle include:

1) Fixed amount of air (ideal gas) for working fluid

2) Combustion process not considered

3) Intake and exhaust processes not considered

4) Engine friction and heat losses not considered

5) Specific heats independent of temperature

The two types of reciprocating engine cycles analyzed are:

1) Spark ignition – Otto cycle

2) Compression ignition – Diesel cycle

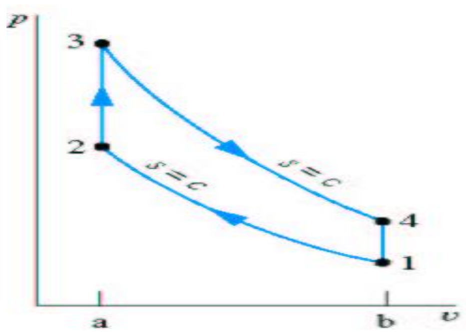
Air-Standard Otto cycle:

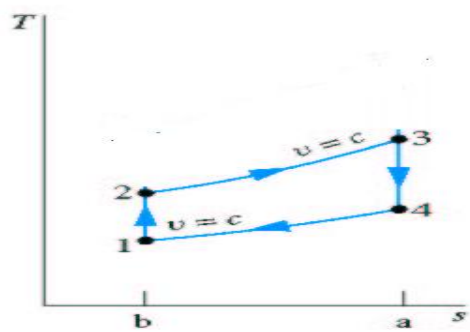
Process 1 → 2 Isentropic compression

Process 2 → 3 Constant volume heat addition

Process 3 → 4 Isentropic expansion

Process 4 → 1 Constant volume heat rejection





Compression ratio:

$$r = \frac{v_1}{v_2} = \frac{v_4}{v_3}$$

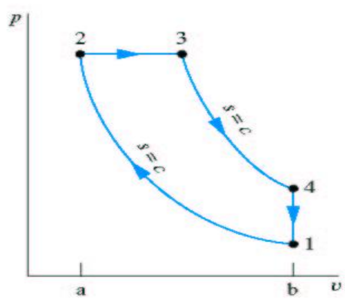
Air-Standard Diesel cycle:

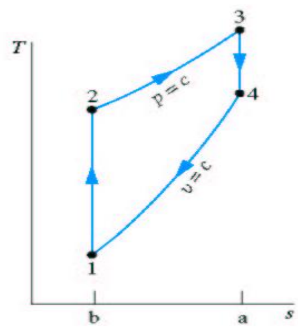
Process 1→ 2 Isentropic compression

Process 2 → 3 Constant pressure heat addition

Process 3 → 4 Isentropic expansion

Process 4 → 1 Constant volume heat rejection





Cut-off ratio:

$$r_c = \frac{v_3}{v_2}$$

Dual Cycle :

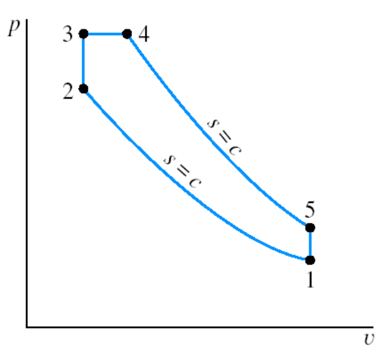
Process 1 → 2 Isentropic compression

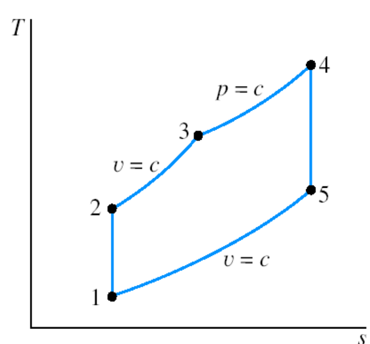
Process 2 → 2.5 Constant volume heat addition

Process 2.5 → 3 Constant pressure heat addition

Process 3 → 4 Isentropic expansion

Process 4 → 1 Constant volume heat rejection





Fuel injection system:

The main function of fuel injection system

1. Filter the fuel
2. Measure the correct quality of air
3. Times the fuel injection
4. Control the rate of fuel injection
5. Atomize or break up the fuel to fine particle
6. Properly distribute the fuel in combustion chamber

In C.I Engine two methods of fuel injections are

1) Air injections
2) Solid or airless injection

Air injections:

In this method of fuel injection air is compressed in compressor to a pressure greater than the pressure which is developed at the end of compression and injected to cylinder through the nozzle. The rate of fuel admittance can be controlled by varying pressure of air

Solid or airless injection

It is also termed as mechanical injection. Here fuel pump is used to supply a measured quantity of fuel to atomizer or injector which injects the fuel at high velocity to the cylinder in the form of spray. The injection o pressure varies from 100 bar t0 145 bar which is produced by the pump

Simple Carburettor:

The process of formation of combustion fuel/air mixture by mixing the proper amount of fuel and air before admission into engine cylinder is known as carburetion. The device which performs the function is known as carburettor.

Functions Of Carburettor:

It must atomise, vaporize and mix the fuel homogeneously with air.
It must supply correct amount of air and fuel mixture in correct proportion under all load conditions and speed of engine.
It must run the engine smoothly by supplying a correct mixture strength.

All modern carburettor are based on Bernoulli's theorem.

$$v^2=2gh$$

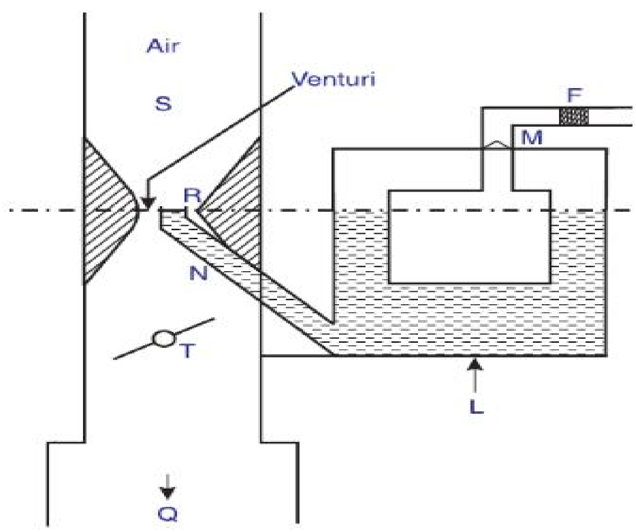
where v=velocity in m/s
g is acceleration due to gravity
h is head causes the flow expressed in meter of height of column of fluid.

Working:

In this float chamber is used for the storage of fuel. The fuel is supplied under gravity action or by fuel pump enters the float chamber through the filter.

The arrangement is such that when the fuel reach the particular the float valve blocks the inlet passage andcuts off the fuel supply.

On the fall of oil level, the float descends down consequently intake passage opens and again the chamber is filled with oil. Thus the float and float valve maintain a constant fuel oil level in the float chamber.



Simple carburettor.

As the piston moves down in the engine cylinder suction is produced in the cylinder as well as in the induction manifold as result of which air flows into the carburettor. When the air flows through the venture there will be an increase in the velocity due to the reduction of area in the venture .As the velocity of air is increased there will be a decrease in the pressure of air due to the conversion of pressure head into kinetic head. Due to the decrease in pressure at venture there will be a virtue of difference in pressure between float chamber and venture .So the jet issue the fuel oil into air stream. As the fuel oil is passed through the nozzle with fine bore the jet is in the form of fine spray it vaporizes quickly and mixes with air .The quality air-fuel mixture can be controlled by the throttle valve.

Limitations Of Simple Carburettor

Theoretically air-fuel ratio supplied by a carburettor is constant for particular throttle opening condition but actually it provides a rich mixture for the same throttle opening condition. It is due to the decrease in density of air. The density of air is decreased due to increase in rate of flow

During idling the throttle valve will causes the reduction in mass of air flowing through venture .At such low rate of flow of air the pressure difference between float chamber and nozzle will be very small. It is insufficient to cause fuel to flow through the jet.

Carburettor does not have any arrangement for providing rich mixture during starting and warming .

In order to correct the above faults

*Idling jet is used which helps in running the engine during idling.

*choke arrangement

AIR-FUEL MIXTURE:

Theoretically correct air- fuel ratio of petrol is 15:1.This uniform supply of such mixture would result in complete combustion of fuel without leaving excess of air of fuel.

Air fuel ratio varies with speed/load

Chemically correct mixture : 15:1

Rich mixture : 10:1

Lean mixture : 17:1

When there is too little air some of fuel goes unburnt when there is too much of air it takes more time to burnt and eventually there will be loss of Power.

Idling /Starting

Engine runs without load produces power only to overcome friction between parts .Rich mixture is required to sustain combustion due to the existing pressure conditions with in the combustion chamber and intake manifold which causes exhaust gas dilution of fresh charge.

Normal Power /Cruising/Medium Load

Engine runs for most of the period .Therefore fuel economy is maintained .Low fuel consumption for maximum economy requires a lean mixture.

Maximum Power Or Acceleration

Overtaking a vehicle (short period) or climbing up a hill (extra load) requires more power. So requires a rich mixture.

Cooling systems:

In I.C engine the temperature of gas in the engine cylinder may vary from 36^o to 275^oc during the cycle. In absence of the cooling system the cylinder walls, cylinder, piston are may be exposed to an average temperature of 1000^oc to 1500^0c

- At these high temperature the metals will loose their characteristic and piston will expand considerably & sieze the liner.
- At these high temperatures the lubricating oil starts to evaporate rapidly both the cylinder &piston may be damaged.
- Though the thermal efficiency of the engine may be decreases due to lubrication but the engine seizes to run .

***Reasons for cooling*:**

1. The expansion of the piston in the cylinder may result in **seizure** of piston.
2. High temperature it may reduce the strength of the piston & cylinder liner.
3. Overheating may results the pre ignition of the charge in SI engine.
4. Physical &chemical charge in lubrication may cause sticking of piston rings & results in excessive wear.
5. Almost 25to35% heat supplied by the fuel is removed by the cooling system &3 to 5% of eat by lubricating oil & radiation.

Types Of Cooling I.C Engine:

1.Air cooling

2.liquid cooling

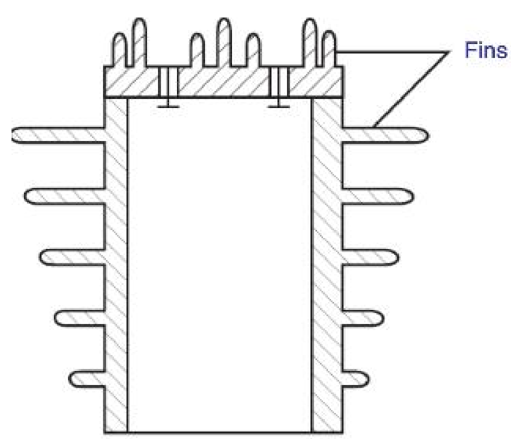
Air cooling :

In this method heat is carried away by the air flowing in and around the engine cylinder

- It is used in motor cycles , scooters etc.
- In this fins are cast on the cylinder head and cylinder Barrel which provides an additional conductive and radiating surface.
- These fins are right angle to the cylinder axis.

Advantages:

- The design of engine is much simple as it does not contain any water jacket.
- Absence of cooling tubes, radiator makes much simpler.
- The engine is not subjected to freezing trouble etc usually encountered danger of engine .
- No leakages of coolant etc.
- Installation of air cooled engine is easer.



Air cooling.

Disadvantages:

- Their movement is noisy
- Non uniform cooling
- The o/p of air cooled engine is less than water cooled engine.
- Maintenance is not easy.

Liquid cooling:

In this cooling of engine the cylinder wall, cylinder head are provided with jackets through which the cooling water circulates.

The heat is transferred from the cylinder wall to the liquid by conduction and convection.

The liquid will be heated in it's passage through the jacket and is cooled by air cooled radiator system. The heat from the liquid in turn is transferred to air.

Various methods in liquid cooling:

1.Thermo syphon cooling.

2.Forced or pump cooling.

3. Thermostat Cooling

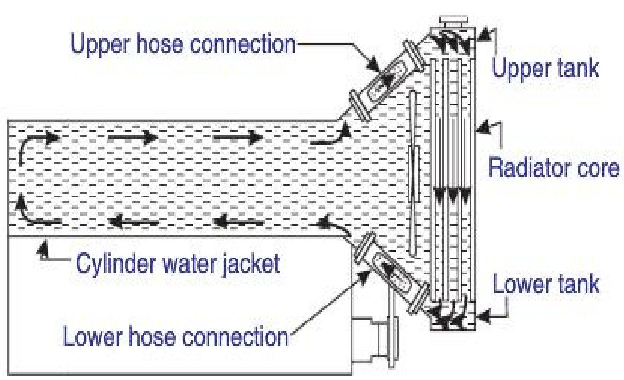
4.Pressurised water cooling.

5.Evaporative cooling.

Thermo syphon cooling system:

It is a method of passive heat exchange, based on natural convection, which circulates the fluid without necessity of mechanical pump. It is used for circulation of coolant in cooling application. As the cylinder, cylinder walls and heads are provided by water jacket in which coolant can circulate .The heat is transferred from cylinder wall to liquids by convection. The top of the radiator is connected to bottom of water jacket.

According to the thermo syphon system principle the liquid is heated it becomes lighter than the cooled water due to specific density. Water travels down the radiator across which air is passed to cool it. The air flow can take place due to vehicle motion or fan can provided for the purpose.



Thermo-syphon cooling.

Advantages:

It is simple, automatic &no pump is required unless there is a leak there is nothing to get out of order.

Disadvantages:

It depends only the temperature& is independent of engine speed.

- The rate of circulation is slow & is insufficient .The circulation of water starts only after the engine has become hot enough to cause thermo siphon action.
- It requires the radiator to above the engine for gravity flow of water engine.
- This thermo syphon system is not widely used at present.

***Forced or pump cooling system*:**

In this pump system is used to circulate the water by using pump. Usually pump is belt driven by engine.

Advantages:

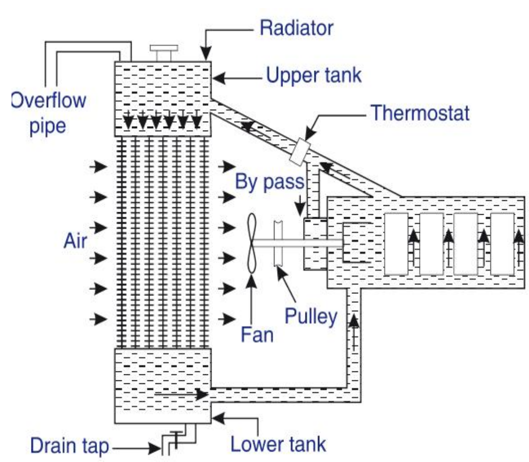
Cooling is ensured under all conditions.

Disadvantages:

- Cooling is independent of temperature. This may result in over cooling in certain condition .
- While moving up hill engine uses high amount of fuel for combustion the cooling requirement will be increased but some amount of cooling is done due to this over heating of engine.
- As soon as the engine is stopped the coolant also ceases. This is undesirable because cooling must continue till the temperature is reduced to normal value.

Thermostat cooling system:

Too lower cylinder barrel temperature may results in severe corrosion damage due to condensation of acids on the cylinder wall. To avoid such a situation there will be a thermostat temperature controlling device to stop flow of coolant before preset cylinder temperature. it prevents the water in the engine jacket from circulating through radiator for cooling until its temperature has reached certain value for suitable operations.



Thermostatically controlled cooling system.

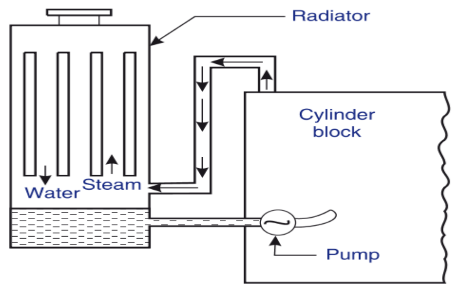
Thermostat contains bellows inn which it is partially filled with volatile liquid ether or methyl alcohol. If temperature increases this liquid vaporizes and crates a pressure to open the main valve and allow the water to flow through the radiator and cool .If temperature is below the set minimum temperature the gas condenses and closes the main valve and by using the by pass the water flows into water jacket without entering into the radiator

Pressurised water cooling:

The boiling point of water can be increased by increasing the pressure .This allows the greater heat transfer to occur in the radiator due to large temperature difference. In this water can be in pressurized condition up to 15bar to 20 bars. A pressure relief valve is provided to relieve the pressure when the engine is stopped

Evaporative cooling:

In this water is allowed to reach a temperature of 100^0c.this method utilizes the latent heat of vaporization of water to obtain a cooling with minimum water .In this cooling circuit is used to convert steam into water and this water will be sent back to the cylinder



Evaporating cooling.

Advantages of liquid Cooling System

- Uniform cooling of cylinder, cylinder head and valves.
- Specific fuel consumption of engine improves by using water cooling system.
- If we employ water cooling system, then engine need not be provided at the front end of moving vehicle.
- Engine is less noisy as compared with air cooled engines, as it has water for damping noise

Disadvantage of liquid Cooling System

- It depends upon the supply of water.
- The water pump which circulates water absorbs considerable power
- If the water cooling system fails then it will result in severe damage of engine.
- The water cooling system is costlier as it has more number of parts. Also it requires more maintenance and care for its parts.

Lubrication system:

Lubrication is the admittance of oil between the surface which are having relative motion

Purpose of lubrication :

- Reduces friction and wear between moving parts
- Transfers heat away from engine parts
- Cleans the inside of the engine
- Seals the spaces between piston rings and cylinder liner
- Cuts power loss and increases fuel economy
- Absorbs shock between moving parts

Parts To Be Lubricated In Ic Engine:

1. Main crank shaft bearings
2. Piston rings and cylinder walls
3. Small end or gudgeon pin bearings
4. Big end bearing
5. Cam shaft cam shaft bearings
6. Timing gears
7. Valve mechanism
8. Valve guides, valve tappets and rocker arm

Properties Of Lubricating Oil:

Viscosity: It is the ability of oil which resists the motion between layers. the high viscosity liquid can carry a greater load.

Flash point: It is the lowest temperature at which a liquid will begin to give off ignitable vapors. so flash point of oil should be high

Fire point: *It is* the lowest temperature at which there are sufficient vapors to support a flame. so fire point of oil should be high

Pour point: It is the lowest temperature at which oil loses its fluidity and will not flow and circulates in the system

Oiliness : It enables the oil to spread and adheres to the surface of bearings

Adhesiveness : It is the property of oil due to which oil particles stick to the metal surfaces

Chemically stable: It should not have any tendency to form oxides

Corrosion: It should not corrode the working substances even in the presence of foreign particles and additives

Physically stable: At lowest temperature it should not become solid and at high temperatures it should not vapourize

Specific gravity: It is the is a comparison of the weight of the substance to the weight of an equal volume of distilled water

The various lubrication system used for IC engine are

1. Mist Lubrication
2. Wet sump Lubrication
3. Dry sump Lubrication

Mist Lubrication System

This system is used where crankcase lubrication is not suitable. In 2-stroke engine as the charge is compressed in the crankcase, it is not possible to have the lubricating oil in the sump .In such engines the lubricating oil is mixed with the fuel, the usual ratio being 3% to 6% .The oil and the fuel induced through the carburettor the fuel is vaporized and the oil is in the form of mist goes via the crankcase in to the cylinder. The oil that impinges the crank case wall lubricates the main and connecting rod bearings and the remaining oil lubricating oil enters into the cylinder and lubricates the piston, piston rings, cylinder liner.

Advantages

Simplicity, low cost (does not required oil pump, filter)

Disadvantages

1. Causes heavy exhaust smoke
2. Get contaminated with acids and result in the corrosion of bearings surface
3. Calls for through mixing for effective lubrication (this requires either separate mixing prior to use of some additive to give the oil good mixing characteristics)
4. The engine will suffer from insufficient lubrication as the supply of fuel is less

Wet Sump lubrication System

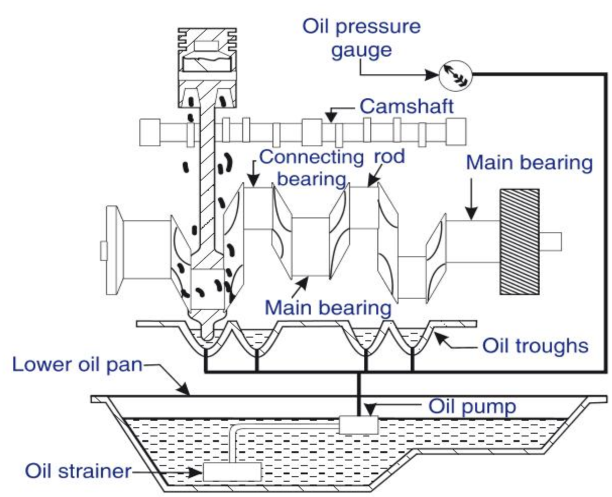
The bottom of the crankcase contains an oil pan or sump from which the lubricating oil is pumped to various components by a pump .After lubricating the parts the oil flows back to the sump by gravity

There are 3 varieties in wet sump lubricating system

1. The splash system 2. The splash and pressure system 3.The pressure feed system

Splash System

This type of lubrication system is used in light duty engines.
The lubricating oil charged in to the bottom of the crankcase and maintained at predetermined level. The oil is drawn by a pump and delivered through a distributing pipe in to the splash troughs
A splasher or dipper is provided under each connecting rod cap .when the connecting rid is in the lowest position just dips into oil trough and directs oil

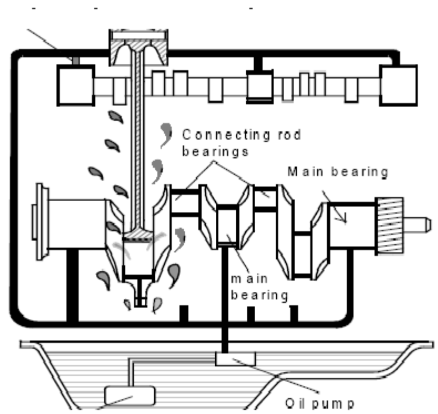


Splash system.

into holes of big end bearing .Due to splash of oil it reaches the lower portion of cylinder wall crankshaft and other parts requiring lubrication. Surplus oil eventually flow to oil sump

Splash & pressure lubrication system

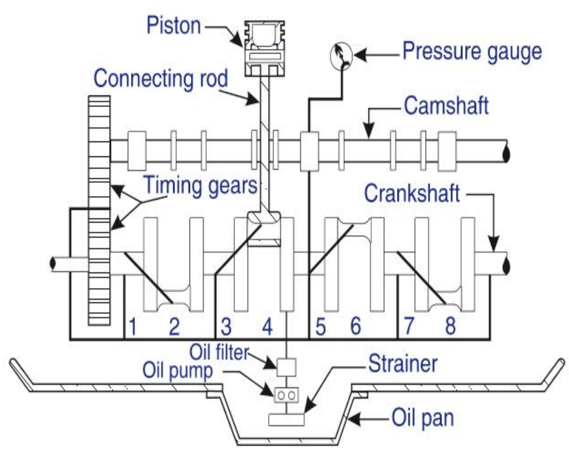
This method uses the combinations of splash and pressure system it has the both advantage.oil is stored in crank case by using gear pump oil is pressurized up to 1 bar to the main bearing. An oil pressure gauge is used to indicate supply of oil .The lubricating oil is supplied under pressure to main and camshaft bearings. The oil is also supplied under pressure to pipes which direct a stream of oil against the dippers on the big end connecting rod bearing cup. The crankpin bearings are lubricated by the splash or spray of oil thrown up by dipper. it enables high bearing load and engine speed as compared to splash system



Splash & pressure lubrication system

Pressure feed system

In this system oil from the sump is pumped under pressure of 1.5 bar to 4 bar to various parts for required lubrication. The oil is forced to all the main bearings of crankshaft. Pressure relief valve is fitted to maintain the predictable pressure values .Oil hole is drilled from the center of each crankpin to the center of an adjacent main journal through which oil can pass from the main bearing to the crankpin .this system is mainly used for high bearing pressure and rubbing speed.



Full pressure system.

Advantages of pressure lubrication system

- Positive introduction of oil to the bearings.
- Cooling effect caused by the large quantities of oil which can be circulated through a bearing.
- Satisfactory lubrication in various attitudes of flight.

Wet-Sump lubrication system

Disadvantages

- Oil supply limited by sump.
- Cooling is difficult.
- Higher operating temperatures.
- Not adaptable to inverted flying

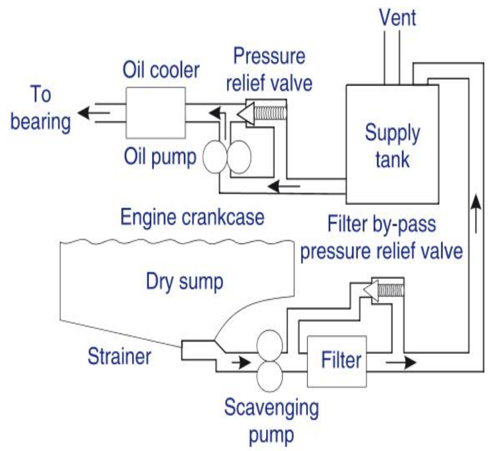
Advantages

- Requires no external parts and fittings to complicate installation.
- No second (scavenge pump) required.
- Can be operated in much cooler temperatures

Dry sump lubrication system

In this system the oil is carried in an external tank. An oil pump draws oil from the supply tank and circulates it under pressure to the various bearings of the engine. Oil dripping from the cylinders and bearings in to the sump is removed by a scavenging pump which in turn the oil is passed through a filter and fed back to the supply tank. The capacity of scavenging pump is always greater than the oil pump. A separate oil cooler provided to remove heat from the oil.

Oil pressure may vary from 3 to8 bar. The primary advantage is that it makes more power by creating extra crank case vacuum which improves ring seal. The lack of oil in crank case improves weight distribution and handling. Used in radial engines and high capacity engines in racing cars



Dry sump lubrication system.

Ignition system: It is a complex electrical system .It function is to produce a spark and initiate the combustion process. The operator of the S.I engines the ignition system to fire thousand cycles in cylinder

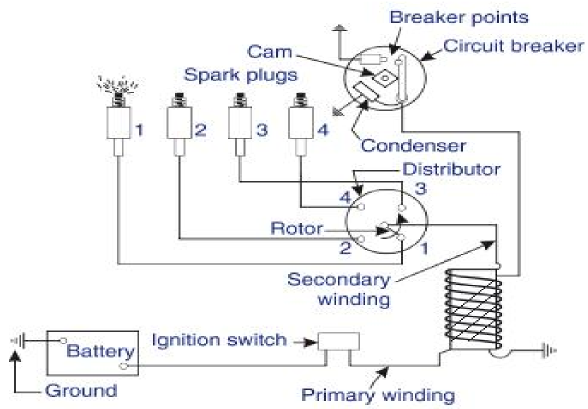
In addition ignition must occur at proper crank angle so that time losses are held at minimum

Requirement of ignition system:

- A source of electric energy must be there
- A means for stepping up the voltage from source to high potential required to produce arc in a spark plug ignites' the combustible mixture
- A mean for timing and distributing the high voltage
- Adjustment of spark advance with speed and load

The two basic ignition system

1. Battery or coil ignition system
2. Magnets ignition system



Battery or coil-ignition system.

Battery or coil ignition system

The essential components are:

- Battery
- Ignited switch
- Ballast resistor
- Ignition coil
- Contact breaker
- Condenser
- Distributor
- Spark plug

Battery:

Rectangular lead acid battery for light duty vehicle or alkaline battery for heavy duty vehicle is used for providing electrical energy for ignition. This battery is charged by dynamo driver by the engine.

Ignition switch:

The battery is connected to the primary winding of ignition core through an ignition switch and ballast resistor with the help of ignition switch and the ignition system can be turned on or off.

***Ballast resistor*:**

A ballast resistor is provided in series with the primary winding to regulate primary current .the objective is to prevent injury to ignition coil by overheating this coil is made by iron wire and iron has as a property that it's electrical resistance increases very rapidly if certain temperature is exceeded.

Ignition coil:

Ignition coil is the source of ignition energy. the purpose of ignition coil is to step up the low voltage to high voltage to induce as electric spark in the spark plug.

Ignition coil consists of magnetic soft iron core and two insulting conducting coil known as primary winding and secondary winding.

Primary winding consist of 200-300 turn with its both ends connected to exterior terminals.

Secondary winding consist of 21000 turns with it's one end connected to high tension wire that goes to the rotor of the distributor and second end is connected to primary winding

***Contact breaker*:**

It is used for making and breaking the primary circuit

It consists of two metal pointer one is fixed and other to movable

The movable one is fixed to spring loaded pivoted arm. spring on the pivot arm keep both the points in contact them by closing the primary circuit

The pivoted arm has heel which rests on cam and breaks the contact point due to action of the cam and the current flow breaks through the contact broker and stop

Condenser:

It is connected in parallel to the contact breaker to prevent the burning of metal Pont and also helps in providing the ignition energy in secondary winding g

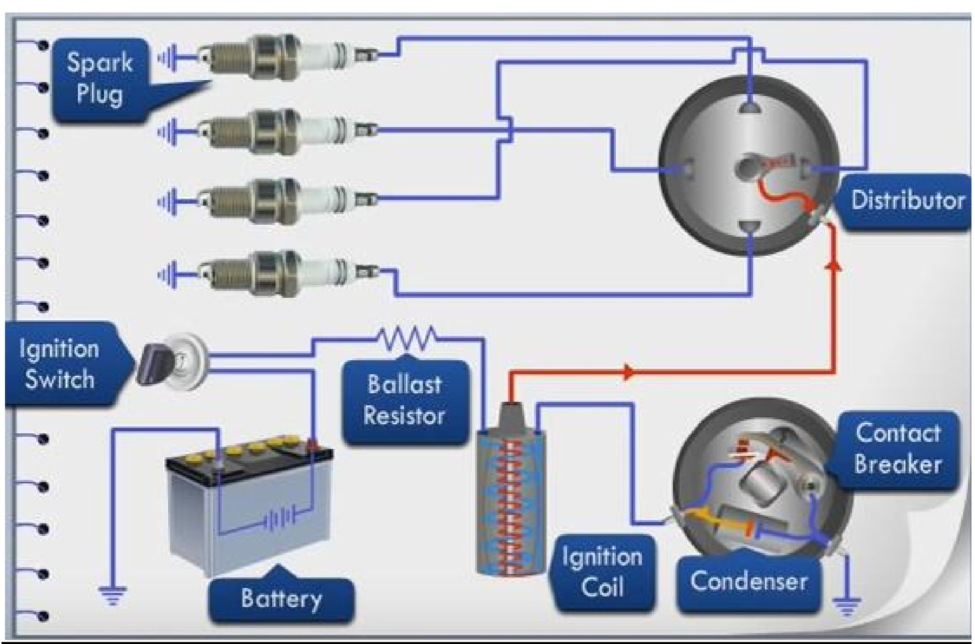
Distributor:

The function of the distributor is to distribute the ignition surges to ignition spark plug in the correct sequence at correct time it consist of rotor in middle and metallic electrodes at the periphery the metallic electrodes are directly connected to spark plug The secondary winding of the ignition coil is connected to distributor rotor which is driver by cam As the rotor rotates it passes the high tension current to the ignition harness and which then Carry these high tension current to spark plug.

Spark plug:

It is the output point of the ignition system it consist of two electrode one attached to the high current carrying users and other is grounded

The potential difference between there electrodes ionizing the gap and thus creates a spark between them which ignites the combustible mixture



Working of ignition system:

- When the ignition switch is turned on the primary circuits get closed and current starts floating through it .This current is known as primary current and it sets up a magnetic field around the iron core of the ignition coil
- When the breaker pt opens by action of the cam, the current which was flowing through contact breaker starts flowing through Condenser
- So the Condenser charges the primary current falls and the magnetic field collapse this change on the magnetic field induces a current in primary winding which flow in the direction of primary current and charges the Condenser to as voltage much higher than battery voltage thus stopping the current flow from battery
- Due to this, the Condenser then discharges into the battery, thus reversing the direction of both primary current and magnetic field Very high voltage in the secondary winding of ignition coil.
- This high voltage is then carried to the distributor rotor where it passes through ignition harnesses in spark plug and produces a spark.

Advantages Of The Coil Ignition System :

1. At the time of starting and idling at low speed good sparkling is available.

2. Initial expenditure is less . Hence, this system is used in cars and commercial vehicles.

3. Maintenance cost is less.

4. Distributor drive is simple and non-complicated.

5. By adjusting spark-timing complete ignition system is not adversely affected

Disadvantage Of Coil Ignition System

1. If the battery is discharged, then it is not possible to start the engine.

2. Battery is to be checked regularly.

3. It occupies more space.

4. Its wiring is complicated.

5. The intensity of spark decreases with increase in speed

Magneto ignition system:

It is similar to the battery ignition system which is used to produce a spark in S.I engine for combustion of fuels. In magneto ignition system the battery and ignition coils are replaced by a magneto. The basic components of magneto ignition system are

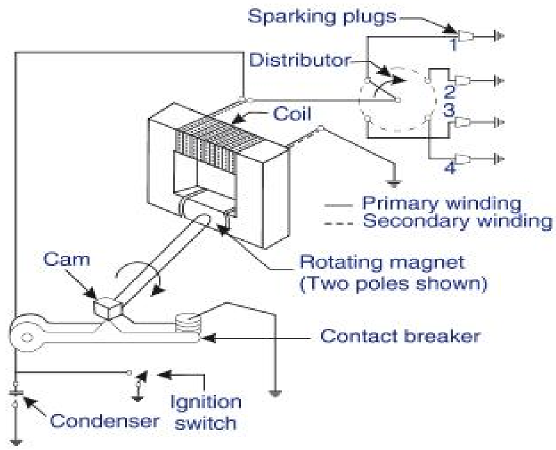
1) Magneto
2) Contact beaker
3) Ignition switch
4) Condenser
5) Distributor
6) Spark plug

Here all the parts except the magneto are same as in battery ignition system.

Magneto:

The function of magneto is to produce current in primary and secondary winding.

- It consists of two pole magnet, a soft iron core on which both primary and secondary winding coil is done.
- When magnet rotates, current is produced in both primary and secondary windings.



Magneto-ignition system.

Working:

When the magnet starts rotating the magnetic field changes through soft iron core.

- This continuous change in magnetic field induces a varying voltage in both primary and secondary winding which produce alternating current.
- The magnet is connected to cam in such a way that the current in primary winding reaches a max value, the beaker point on the contact beaker opens.
- As the beaker points opens then current now flows through condenser which changes the condenser and thus decreases the current in primary winding to zero value thus varying its magnetic field.
- Now the condenser then rapidly discharges into primary circuit which reverses the direction of both primary current and magnetic field.
- The rapid collapse and reversal of magnetic field induces a very high voltage in secondary winding which is then carrier through high tension wire to distributor rotor where it passes to one of the spark plug deads and into the spark plug where the spark is generated.

ADVANTAGES OF MAGNETIC IGNITION SYSTEM:

- Since there is no battery or connecting table, the system is more reliable
- For medium and very high speed engines, the system is more suitable
- The space requires is less, by using cobalt steel and nickel aluminium magnet metals energy.
- This system in fairly reliable with resent development

Disadvantages Of Magneto Ignition System:

- At low speed and during cranking the voltage is very low. Suitable modifications are necessary in the circuit to overcome this.
- Adjustment of the spark timing has determined effect upon the spark voltage or energy.
- The burning of the electrodes will result with powerful sparks at high engine speeds
- More costly. And Starting is troublesome

Performance Of Ic Engine:

Engine performance is an indication of degree of success of conversion of chemical energy contained in fuel into useful mechanical energy

The important parameters are

1)Power and mechanical efficiency 2)Mean effective pressure and torque

3)Specific fuel consumption 4)Volumetric efficiency

5)Air –fuel ratio 6) Thermal efficiency

Power and mechanical efficiency

Indicated power: The total power developed by combustion of fuel in combustion chamber (cylinder)

$$\text{I.P.} = \frac{np_{mi}\, LANk \times 10}{6} \text{ kW}$$

where, n = Number of cylinders,

p_{mi} = Indicated mean effective pressure, bar,

L = Length of stroke, m,

A = Area of piston, m^2, and

$k = \frac{1}{2}$ for 4-stroke engine

= 1 for 2-stroke engine.

Break power: The power developed by the engine at the out put shaft

$$\text{B.P.} = \frac{2\pi NT}{60 \times 1000} \text{ kW}$$

where, N = Speed in r.p.m., and

T = Torque in Nm.

$$\text{B.P.} = \frac{(W - S)\,\pi\,(D_b + d)\,N}{60 \times 1000} \text{ kW}$$

If, W = weight at the end of the rope, N,

S = spring balance reading, N,

N = engine speed, r.p.m.,

D_b = diameter of the brake wheel, m,

d = diameter of the rope, m, and

$(D_b + d)$ = effective diameter of the brake wheel,

Friction power: The difference between IP and B.P

$$\text{F.P.} = \text{I.P.} - \text{B.P.}$$

Mechanical efficiency: It is the ratio of B..P to I.P

$$\eta_{mech.} = \frac{\text{B.P.}}{\text{I.P.}}$$

Mean effective pressure:

It is defined a the average pressure that is assumed to be acting on piston throughout the power stroke of the engine. It is the average pressure inside the engine cylinder based on power output..If it is based on I.P it is called as Indicated mean effective pressure. If it is based on B.P it is called as Break mean effective pressure

Specific fuel consumption:

Fuel consumed per unit time per unit break power .it reflects how good the engine performance

$$\text{s.f.c.} = \frac{\dot{m}_f}{\text{B.P.}} \text{ kg/kWh.}$$

Volumetric efficiency: It is the defined as the ratio of actual volume of charge drawn in during suction stroke to swept volume of the piston

$$\eta_{vol.} = \frac{\text{Actual volume of mixture drawn per stroke at N.T.P.}}{\text{Swept volume of system}}$$

Indicated thermal efficiency:

It is the ratio of indicated power to input fuel energy

$$\eta_{\text{th.}\,(I)} = \frac{\text{I.P.}}{\dot{m}_f \times C}$$

Break thermal efficiency: It is the ratio of break power to input fuel energy

$$\eta_{\text{th.}\,(B)} = \frac{\text{B.P.}}{\dot{m}_f \times C}$$

$\dot{m}_f$ = Mass of fuel used in kg/sec., and

C = Calorific value of fuel (lower),

Relative efficiency: It is the ratio of thermal efficiency of an actual cycle to that ideal cycle

$$\eta_{\text{relative}} = \frac{\eta_{\text{thermal}}}{\eta_{\text{air-standard}}}$$

$$\eta_{\text{air-standard}} = 1 - \frac{1}{(r)^{\gamma-1}}$$

Objective Questions

1. Which of the following is not used in four stroke compression-ignition (CI) engines?
a. Fuel pump
b. Spark plug
c. Fuel injector
d. Inlet and outlet Valves

2. In compression ignition (CI) engine, the compression ratio is
a. Cylinder volume / Clearance volume
b. Swept Volume / Cylinder Volume
c. Clearance volume / Cylinder volume
d. Cylinder volume / Swept volume

3. If the intake air temperature of I.C. engine increases, its efficiency will
(a) increase
(b) decrease
(c) remain same
(d) unpredictable

4. In four stroke engine there is one power stroke in _____ of crankshaft rotation.
a. 180°
b. 360°
c. 540°
d. 720°

5. In four stroke engine which of the following is also known as power stroke
a. Suction stroke
b. Compression stroke
c. Expansion stroke
d. Exhaust stroke

6. The working cycle in case of four stroke engine is completed in following number of revolutions of crankshaft
(a) ½
(b) 1
(c) 2
(d) 4

7. Scavenging air in diesel engine means
(a) air used for combustion sent under pres-sure
(b) forced air for cooling cylinder
(c) burnt air containing products of combustion
(d) air used for forcing burnt gases out of engine's cylinder during the exhaust period

8. Supercharging is the process of
(a) supplying the intake of an engine with air at a density greater than the density of the surrounding atmosphere
(b) providing forced cooling air
(c) injecting excess fuel for raising more load
(d) supplying compressed air to remove combustion products fully.

9. The air standard efficiency of an Otto cycle compared to diesel cycle for the given compression ratio is
(a) same
(b) less
(c) more
(d) more or less depending on power rating.

10. An engine indicator is used to determine the following
(a) speed
(b) temperature
(c) volume of cylinder
(d) m.e.p. and I.H.P.

11. If the compression ratio of an engine working on Otto cycle is increased from 5 to 7, the %age increase in efficiency will be
(a) 2%
(b) 4%
(c) 8%
(d) 14%

12. The maximum temperature in the I.C. engine cylinder is of the order of
(a) 500- 1000°C
(b) 1000- 1500°C
(c) 1500-2000°C
(d) 2000-2500°C

13. Which of the following is not an internal combustion engine
(a) 2-stroke petrol engine
(b) 4-stroke petrol engine
(c) gas turbine
(d) steam turbine.

14. The air-fuel ratio of the petrol engine is controlled by
(a) fuel pump
(b) governor
(c) injector
(d) carburettor

15. A 75 cc engine has following parameter as 75 cc
(a) fuel tank capacity
(b) lub oil capacity
(c) swept volume
(d) cylinder volume

Answers 1(b) 2(a) 3(b) 4(d) 5(c) 6(c) 7(d) 8(a) 9(a) 10(d) 11(d) 12(d) 13(d) 14(d) 15(c)

University Questions:

1. With a neat sketch explain the working principle of a simple carburetor
2. Briefly discuss the air-fuel ratio requirements of a petrol engine from no load to full load.
3. What are the various components to be lubricated in an engine and explain how it is accomplished
4. Compare the wet sump and dry sump lubrication systems
5. With a neat sketch explain Battery ignition system.
6. What is the function of ignition system? Explain the important qualities of a good ignitions system in SI engine
7. With a neat sketch explain the valve timing diagram of a four stroke SI engine
8. Explain the factors that affect the performance of an IC engine.
9. With a neat sketch explain the port timing diagram of a two stroke SI engine
10. With neat sketches explain the working principle of four stroke spark ignition engine
11. What are the different methods used to calculate the frictional power of an IC engine. Explain any one method in detail
12. State the relative advantages and disadvantages of battery and magneto-ignition systems.
13. Explain briefly the following methods of cooling I.C. engines: i) Air cooling ii) Liquid cooling
14. Discuss the differences between theoretical and actual valve timing diagrams of a diesel engine
15. Discuss with suitable sketches Magneto-ignition system used in petrol engines
16. How are IC engines classified?
17. Explain Air standard Otto cycle and derive the expression for its thermal efficiency

Problems:

1. A four-stroke, four cylinder gasoline engine has a bore of 60mm and a stroke of 100 mm. On test it develops a torque of 66.5 Nm when running at 3000 rpm. If the Clear acne volume in each cylinder is 60cc the relative efficiency with respect to brake Thermal efficiency is 0.5 and the calorific value of the fuel is 42MJ/kg, determine the fuel consumption in kg/h and the brake mean effective pressure.
2. A four-stroke gas engine has a bore of 20cm and stroke of 30 cm and runs at 300 rpm firing every cycle. If air-fuel ratio is 4:1 by volume and volumetric efficiency on NTP basis is 80%, determine the volume of gas used per minute. If the calorific value of gas is 8MJ/m3 at NTP and the brake thermal efficiency is 25% determine brake power of the engine

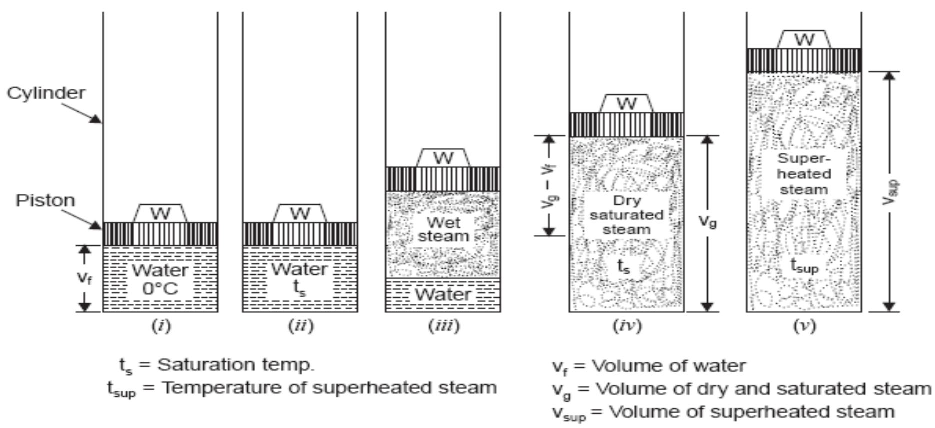
Short Answer Questions;

1. How heat engines are classified. Explain the principle of working of heat engine
2. Compare External combustion engine and Internal combustion engines
3. Discuss the relative advantages and disadvantages of Air cooling and Water cooling systems?
4. Explain about fuel supply system of an IC engine
5. Explain the importance of cooling and lubrication
6. Write a short note on mist lubrication

UNIT:2 PROPERTIES OF STEAM AND VAPOUR POWER CYCLES

FORMATION OF STEAM:

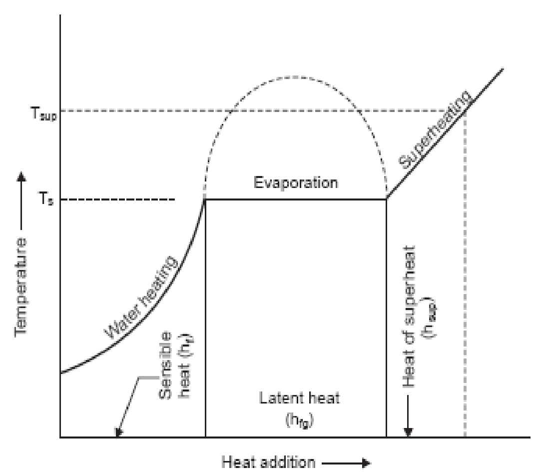
Consider a cylinder fitted with a piston which can move freely upwards and downwards in it. Let, for the sake of simplicity, there be 1 kg of water at 0°C with volume v_f m^3 under the piston. Further let the piston is loaded with load *W* to ensure heating at constant pressure.
Now if the heat is imparted to water, a rise in temperature will be noticed and this rise will Continue till boiling point is reached. The temperature at which water starts boiling depends upon the pressure and as such for *each pressure* (under which water is heated) *there is a different boiling point*. This boiling temperature is known as the temperature of formation of steam or *saturation temperature*



Formation of steam.

It may be noted during heating up to boiling point that there will be slight increase in volume of water due to which piston moves up and hence work is obtained as shown in Fig. (*ii*). This work, however, is so *small* that is can be *neglected*.

Now, if supply of heat to water is continued it will be noticed that rise of temperature after the boiling point is reached *nil* but piston starts moving upwards which indicates that there is increase is volume which is only possible if steam formation occurs. The heat being supplied does not show any rise of temperature but changes water into vapour state (steam) and is known as *latent heat* or *hidden heat*. So long as the steam is in contact with water, it is called *wet steam* [Fig (*iii*)] and if heating of steam is further progressed [as shown in Fig (*iv*)] such that all the water particles associated with steam are evaporated, the steam so obtained is called *dry and saturated steam*. If *vg* m3 is the volume of 1 kg of dry and saturated steam then work done on the piston will be



Graphical representation of formation of steam.

$p(vg - vf)$ where *p* is the constant pressure (due to weight '*W*' on the piston).

Again, if supply of heat to the dry and saturated steam is continued at constant pressure there will be increase in temperature and volume of steam. The steam so obtained is called *superheated steam* and *behaves like a perfect gas.*

IMPORTANT TERMS RELATING STEAM FORMATION:

1. **Sensible heat of water (h_f).** *It is defined as the quantity of heat absorbed by 1 kg of water when it is heated from 0°C (freezing point) to boiling point*. It is also called total heat (or enthalpy) of water or liquid heat invariably

2. **Latent heat or hidden heat (hfg).** *It is the amount of heat required to convert water at a given temperature and pressure into steam at the same temperature and pressure*. It is expressed by the symbol *hfg*

3. **Dryness fraction (x).** The term dryness fraction is related with wet steam. *It is defined as the ratio of the mass of actual dry steam to the mass of steam containing it*. It is usually expressed by the symbol '*x*'

$$\textbf{Dryness fraction, } x = \frac{\text{Mass of dry steam}}{\text{Mass of dry steam + mass of water in suspension}}$$

$$= \frac{m_s}{m_s + m_w}$$

4. **Total heat or enthalpy of wet steam (h).** *It is defined as the quantity of heat required to convert 1 kg of water at 0°C into wet steam at constant pressure*. It is the sum of total heat of water and the latent heat and this sum is also called **enthalpy.**

   In other words, $h = hf + xhfg$

   If steam is dry and saturated, then $x = 1$ and $hg = hf + hfg$.

5. **Superheated steam.** When steam is heated after it has become dry and saturated, it is called superheated steam and the process of heating is called *superheating. Superheating is always carried out at constant pressure*.

If *Tsup*., *Ts* are the temperatures of superheated steam in *K* and wet or dry steam, then (*Tsup – Ts*) is called '*degree of superheat*

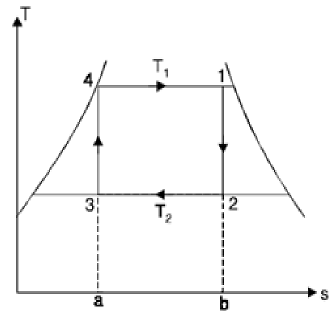
The total heat of superheated steam is given by

$$hsup = hf + hfg + cps\,(Tsup - Ts)$$

Carnot Cycle:

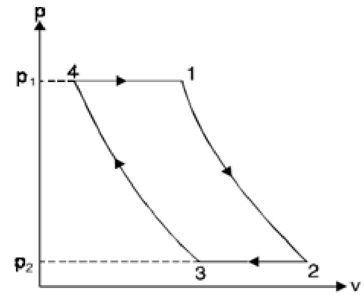
It consists of

1. Constant Pressure Heat Addition
2. Reversible Adiabatic Expansions
3. Constant Pressure Heat Rejection
4. Reversible Adiabatic Compression



Operation (4-1). 1 kg of boiling water at temperature T_1 is heated to form wet steam of dryness fraction x_1. Thus heat is absorbed at constant temperature T_1 and pressure p_1 during this operation.

Operation (1-2). During this operation steam is expanded isentropically to temperature T_2 and pressure p_2. The point '2' represents the condition of steam after expansion.



Operation (2-3). During this operation heat is rejected at constant pressure p_2 and temperature T_2. As the steam is exhausted it becomes wetter and cooled from 2 to 3.

Operation (3-4). In this operation the wet steam at '3' is compressed isentropically till the steam regains its original state of temperature T_1 and pressure p_1. Thus cycle is completed

Heat supplied at constant temperature T_1 [operation (4-1)] = area 4-1-*b*-*a* = $T_1\,(s_1 - s_4) = T_1\,(s_2 - s_3)$.
Heat rejected at constant temperature T_2 (operation 2-3) = area 2-3-*a*-*b* = $T_2\,(s_2 - s_3)$.
Since there is no exchange of heat during isentropic operations (1-2) and (3-4)

$$\begin{aligned} \text{Net work done} &= \text{Heat supplied} - \text{heat rejected} \\ &= T_1\,(s_2 - s_3) - T_2\,(s_2 - s_3) \\ &= (T_1 - T_2)\,(s_2 - s_3) \end{aligned}$$

$$\begin{aligned} \text{Carnot cycle } \eta &= \frac{\text{Work done}}{\text{Heat supplied}} \\ &= \frac{(T_1 - T_2)\,(s_2 - s_3)}{T_1\,(s_2 - s_3)} = \frac{T_1 - T_2}{T_1} \end{aligned}$$

Limitations Of Carnot Cycle :

1. It is difficult to compress a wet vapour isentropically to the saturated state as required by the process 3-4.

2. It is difficult to control the quality of the condensate coming out of the condenser so that the state '3' is exactly obtained.

3. The efficiency of the Carnot cycle is greatly affected by the temperature T_1 at which heat is transferred to the working fluid. Since the critical temperature for steam is only 374°C, therefore, if the cycle is to be operated in the *wet region*, the maximum possible temperature is severely limited.

4. The cycle is still more difficult to operate in practice with superheated steam due to the necessity of supplying the superheat at constant temperature instead of constant pressure

Rankine Cycle:

Rankine cycle is the idealized cycle for steam power plants. In this cycle heat energy is converted into mechanical work while undergoing phase change. The heat is supplied externally to a closed loop, which usually uses water as the fluid. This cycle is represented on p-v, T-v, h-s, diagram.

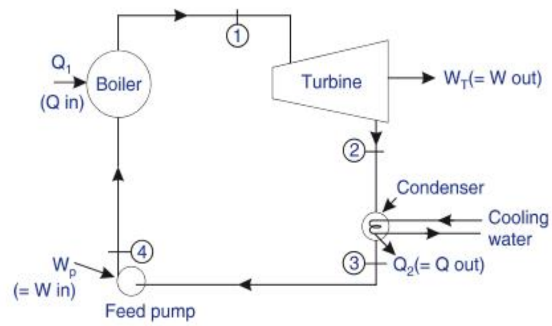
It consists of following process

Process 4-1: Water is converted into steam at constant pressure by the addition of heat in the boiler.

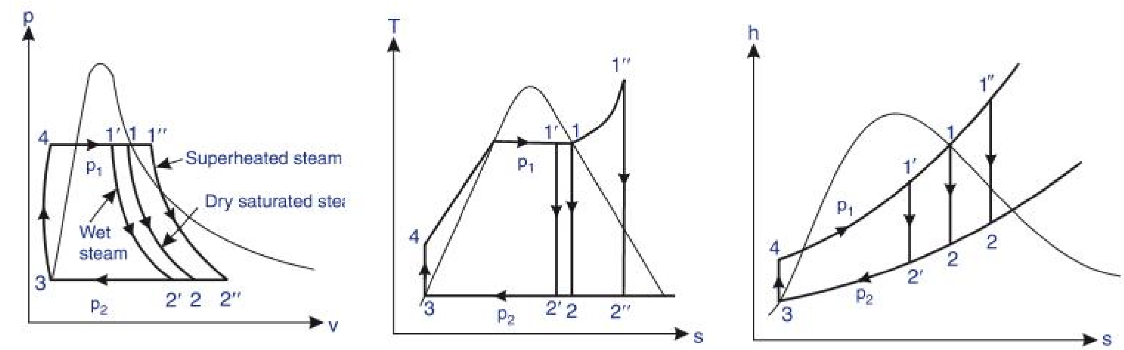
Process 1-2: Reversible adiabatic expansion of steam in the steam turbine.

Process 2-3: Constant pressure heat rejection in the condenser to convert condensate into water.

Process 3-4: Water from the condenser at low pressure is pumped into the boiler at high pressure. This process is reversible adiabatic compression



Rankine cycle.



The steam leaving the boiler may be dry and saturated, wet or superheated. The corresponding T-s diagrams are 1-2-3-4-1; 1-2-3’-4’-1 or 1-2-3”-4”-1

Considering 1 kg of fluid :

Applying *steady flow energy equation* (S.F.E.E.) to boiler, turbine, condenser and pump :

(*i*) **For boiler** (as control volume), we get

$h_{f4} + Q_1 = h_1$

$Q_1 = h_1 - h_{f4}$

(*ii*) **For turbine** (as control volume), we get

$h_1 = W_T + h_2$, where W_T = turbine work

$W_T = h_1 - h_2$

(*iii*) **For condenser**, we get

$h_2 = Q_2 + h_{f3}$

$Q_2 = h_2 - h_{f3}$

(*iv*) **For the feed pump**, we get

$h_{f3} + W_P = h_{f4}$, where, W_P = Pump work

$W_P = h_{f4} - h_{f3}$

Now, efficiency of Rankine cycle is given by

$$\eta_{\text{Rankine}} = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_P}{Q_1}$$
$$= \frac{(h_1 - h_2) - (h_{f_4} - h_{f_3})}{(h_1 - h_{f_4})}$$

For the whole cycle, the energy balance can be obtained by summarizing the four energy equations above. It yields,

$(q_{in} - q_{out}) - (w_{turbine, out} - w_{pump, in}) = 0$

The thermal efficiency of the Rankine cycle is determined from

$\eta_{th} = w_{net,out}/q_{in} = 1 - q_{out}/q_{in}$

where the net work output from the cycle is

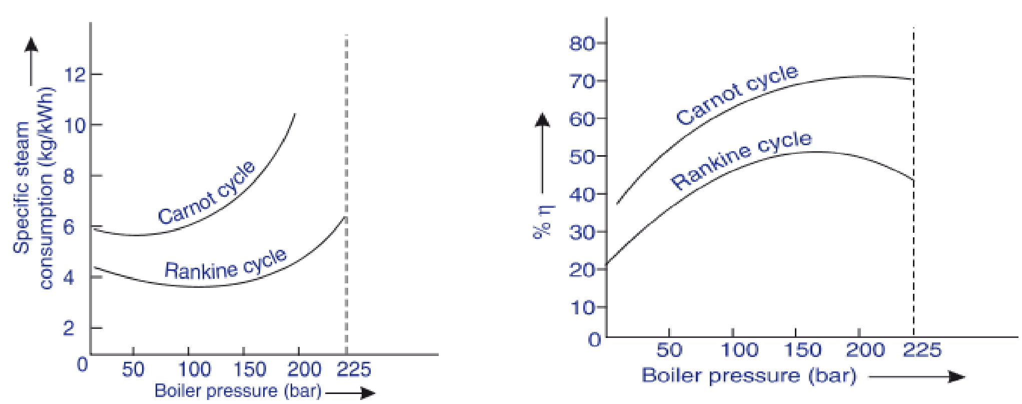
$w_{net,out} = w_{turbine, out} - w_{pump, in}$

.***Comparison between Rankine Cycle and Carnot Cycle***

(i) Between the same temperature limits Rankine cycle provides a higher specific work output than a Carnot cycle, consequently Rankine cycle requires a smaller steam flow rate resulting in smaller size plant for a given power output. However, Rankine cycle calls for higher rates of heat transfer in boiler and condenser.

(ii) Since in Rankine cycle only part of the heat is supplied isothermally at constant higher temperature T_1, therefore, its efficiency is lower than that of Carnot cycle. The efficiency of the Rankine cycle will approach that of the Carnot cycle more nearly if the superheat temperature rise is reduced.

(iii) The advantage of using pump to feed liquid to the boiler instead to compressing a wet vapour is obvious that the work for compression is very large compared to the pump



Effect of Operating Conditions on Rankine Cycle Efficiency

The Rankine cycle efficiency can be *improved* by :

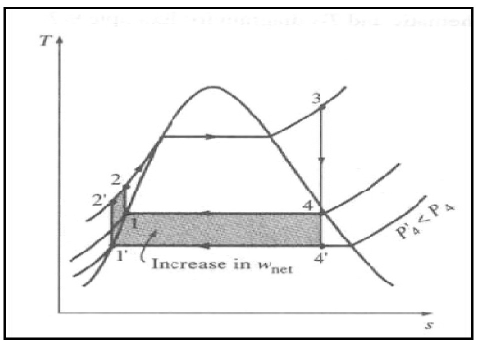
(i) *Increasing the average temperature at which heat is supplied to the working fluid in the boiler.*

- a) Increasing boiler pressure
- *b)* Superheating.

(ii) *Decreasing/reducing the temperature at which heat is rejected from the working fluid in the condenser*

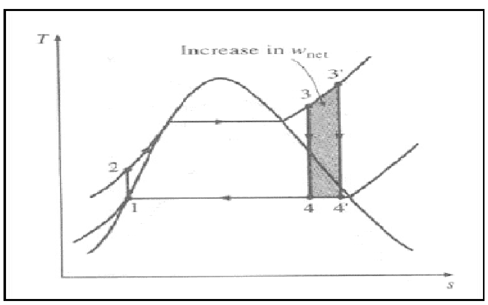
i,e *Reducing condenser pressure*

1. *Lowering the condenser Pressure*:-



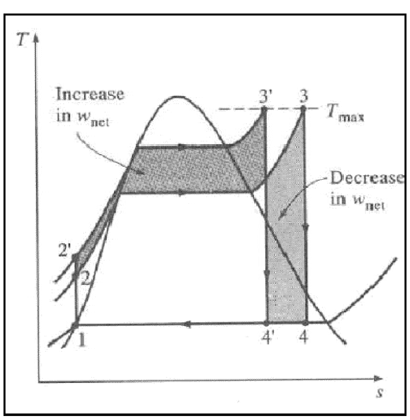
Lowering the operating pressure of the condenser lowers the temperature at which heat is rejected. The overall effect of lowering the condenser pressure is an increase in the thermal efficiency of the cycle.

2. *Superheating the steam to high temperatures*:-



The average temperature at which heat is added to the steam can be increased without increasing the boiler pressure by superheating the steam to high temperatures.

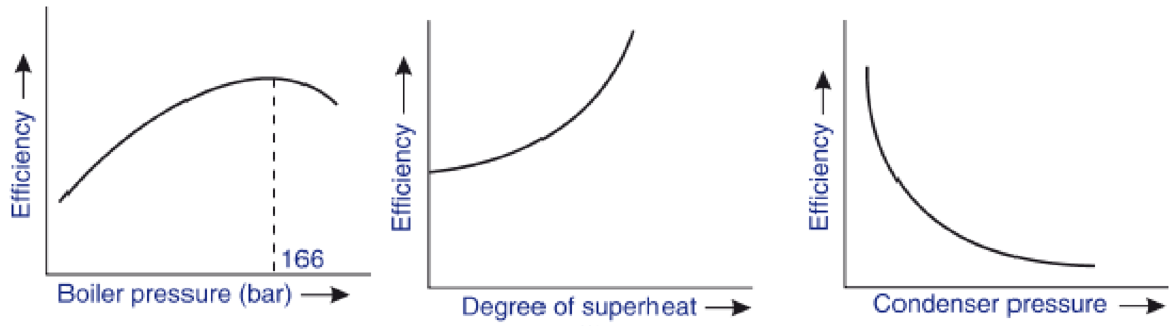
Superheating the steam to higher temperatures has another very desirable effect: It decreases the moisture content of the steam at the turbine exit.



3. *Increasing the Boiler pressure*:-

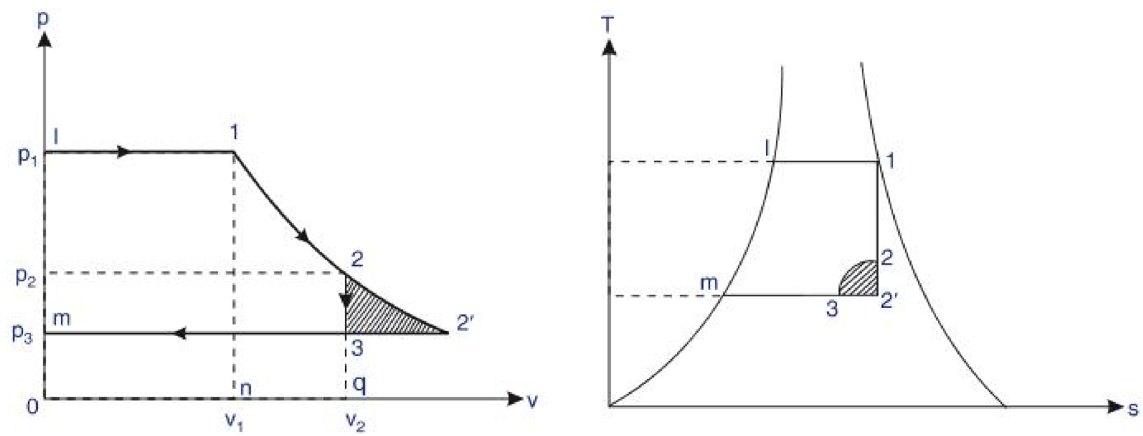
Increasing the operating pressure of the boiler, automatically raises the temperature at which boiling takes place.

This raises the average temperature at which heat is added to the steam and thus raises the thermal efficiency of the cycle.



The thermal efficiency of the Rankine cycle is also *improved* by the following methods :
(i) By regenerative feed heating.
(ii) By reheating of steam

MODIFIED RANKINE CYCLE :



The above fig show the modified Rankine cycle on p-V and T-s diagrams (neglecting pump work) respectively. It will be noted that p-V diagram is very narrow at the toe i.e., point '2′' and the work obtained near toe is very small. In fact this work is too inadequate to overcome friction (due to reciprocating parts) even. Therefore, the adiabatic is terminated at '2'; the pressure drop decreases suddenly whilst the volume remains constant. This operation is represented by the line 2-3. By this doing the stroke length is reduced ; in other words the cylinder dimensions reduce but at the expense of small loss of work (area 2-3-2′) which, however, is negligibly small.

The work done during the modified Rankine cycle can be calculated in the following way :

Let p_1, v_1, u_1 and h_1 correspond to initial condition of steam at '1'.

p_2, v_2, u_2 and h_2 correspond to condition of steam at '2'.

p_3, h_3 correspond to condition of steam at '3′'.

Work done during the cycle/kg of steam= area l-1-2-3-m

= area ‘o-l-1-n’ + area ‘1-2-q-n’ – area ‘o-m-3-q’

= $p_1v_1 + (u_1 - u_2) - p_3v_2$

Heat supplied = $h_1 - h_{f3}$

∴ The modified Rankine efficiency = Work done/ Heat supplied

$$= \frac{(h_1 - h_2) + (p_2 - p_3)\,v_2}{h_1 - h_{f_3}}$$

Regenerative Rankine cycle:

In the Rankine steam power cycle it is observed that the condensate which is at low temperature has an irreversible mixing with hot boiler water and this result in decrease of cycle efficiency. To increase the efficiency methods are adopted to heat the feed water entering in boiler by interchanging the heat with in the system. This heating of feed water and in steps is called regenerative feed heat method and the cycle is called regenerative cycle.

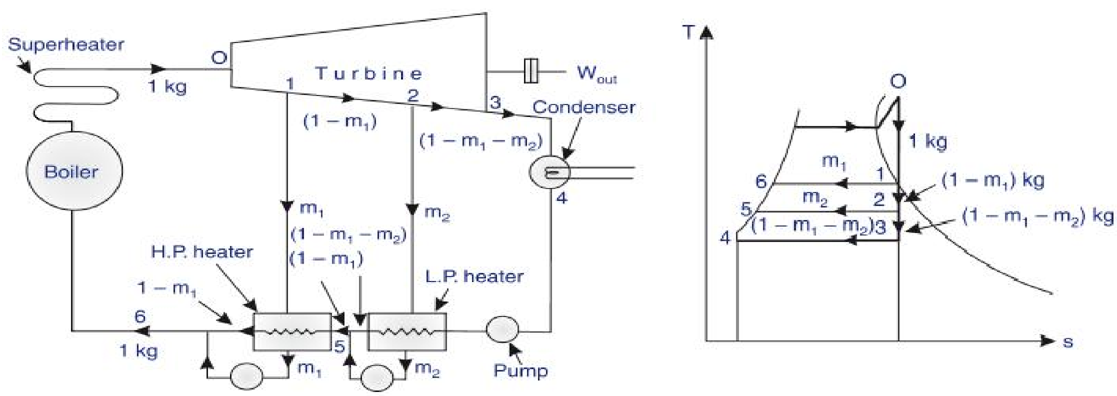
Principle of Regenerative power cycle:

The principle is to extract the steam from the turbine at several locations and supplying the steam to the regenerative feed water heaters. This cycle is also called as bleeding cycle. According the capacity of the turbines the heater arrangements for effective efficiency is derived as follows:

Medium capacity turbines – not more than 3 feed heater

High pressure high capacity – not more than 5 to 7 feed heaters

Super-critical turbines – 8 to 9 heaters



Regenerative power cycle operation:

The figure shows the layout of steam power plant with regenerative power cycle operation. The surface condenser is used to condensate all the steam extracted from the turbine. The condensed water is allows to flow through the LP and HP heater in stages. The steam extracted from the turbine at different stages is supplied to LP and HP stages to heat the feed water. The conditions of steam bled for each heater are selected so that the temperature of saturated steam will be at 4 to 10^0 higher than final condensate temperature.

Fig shows a diagrammatic layout of a condensing steam power plant in which a surface condenser is used to condense all the steam that is not extracted for feed water heating. The turbine is double extracting and the boiler is equipped with a superheater. This arrangement constitutes a regenerative cycle

Let, m_1 = kg of high pressure (H.P.) steam per kg of steam flow,

m_2 = kg of low pressure (L.P.) steam extracted per kg of steam flow, and

$(1 - m_1 - m_2)$ = kg of steam entering condenser per kg of steam flow.

Energy/Heat balance equation for H.P. heater :

$$m_1 (h_1 - h_{f6}) = (1 - m_1) (h_{f6} - h_{f5})$$

$$m_1[(h_1 - h_{f6}) + (h_{f6} - h_{f5})] = (h_{f6} - h_{f5})$$

Energy/Heat balance equation for L.P. heater :

$$m_2 (h_2 - h_{f5}) = (1 - m_1 - m_2) (h_{f5} - h_{f3})$$

$$m_2[(h_2 - h_{f5}) + (h_{f5} - h_{f3})] = (1 - m_1) (h_{f5} - h_{f3})$$

The heat supplied externally in the cycle = $(h_0 - h_{f6})$

Work done = $(h_0 - h_1) + (1 - m_1) (h_1 - h_2) + (1 - m_1 - m_2) (h_2 - h_3)$

The thermal efficiency of regenerative cycle is

$$\eta_{thermal} = \text{Work done/ Heat supplied} = \frac{(h0 - h1) + (1 - m1)(h1 - h2) + (1 - m1 - m2)(h2 - h3)}{(h0 - hf6)}$$

Advantages of regenerative power cycle:

- The heating process in the boiler tends to become reversible.
- The thermal stresses in the boiler are minimized. This is due to the inlet temperature is increased so that the temperature difference is less in the boiler.
- The thermal efficiency is improved because average temperature of heat addition to the cycle is increased.
- The Heating rate is reduced.

- The LP turbine blade height can be reduced because steam flow at lower stage is reduced.
- The steam condenser size can be reduced.
- The turbine efficiency increases and damage to the turbine is less.

***Disadvantages of regenerative power cycle*:**

- The plant becomes more complicated and cost.
- The added heater in the circuit increases the maintenance is required.
- For a given power a large capacity of boiler is required.

Reheat Cycle:

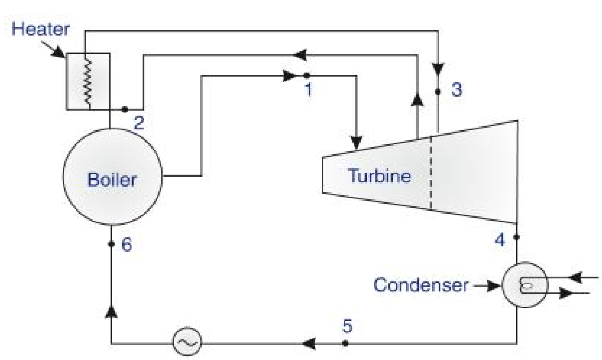
For attaining greater thermal efficiencies when the initial pressure of steam was raised beyond 42 bar it was found that resulting condition of steam after, expansion was increasingly wetter and exceeded in the safe limit of 12 per cent condensation.

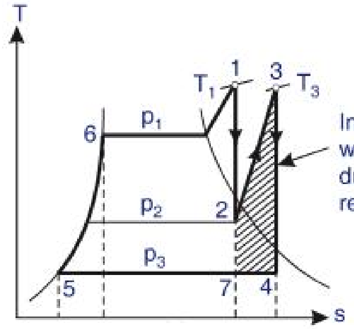
The purpose of a reheating cycle is to remove the moisture carried by the steam at the final stages of the expansion process

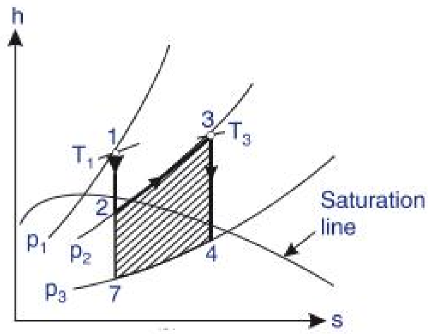
It, therefore, became necessary to reheat the steam after part of expansion was over so that the resulting condition after complete expansion fell within the region of permissible wetness. The reheating or resuperheating of steam is now universally used when high pressure and temperature steam conditions such as 100 to 250 bar and 500°C to 600°C are employed for throttle. For plants of still higher pressures and temperatures, a double reheating may be used. In actual practice reheat improves the cycle efficiency by about 5% for a 85/15 bar cycle.

Usually a plant with a base load capacity of 50000 kW and initial steam pressure of 42 bar would economically justify the extra cost of reheating.

The improvement in thermal efficiency due to reheat is greatly dependent upon the *reheat pressure* with respect to the original pressure of steam.







The steam as at state point 1 (i.e., pressure p_1 and temperature T_1) enters the turbine and expands isentropically to a certain pressure p_2 and temperature T_2. From this state point 2 the whole of steam is drawn out of the turbine and is reheated in a reheater to a temperature T_3. This reheated steam is then readmitted to the turbine where it is expanded to condenser pressure isentropically

Thermal efficiency with 'Reheating' (neglecting pump work) :

Heat supplied = $(h_1 - h_{f4}) + (h_3 - h_2)$

Heat rejected = $h_4 - h_{f4}$

Work done by the turbine = Heat supplied – heat rejected
= $(h_1 - h_{f4}) + (h_3 - h_2) - (h_4 - h_{f4})$
= $(h_1 - h_2) + (h_3 - h_4)$
Thus, theoretical thermal efficiency of reheat cycle is

$$\eta_{\text{thermal}} = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f_4}) + (h_3 - h_2)}$$

Pump work $W_p = \dfrac{v_f\,(p_1 - p_b)}{1000}$

<u>Advantages of 'Reheating' :</u>

1. There is an increased output of the turbine.
2. Erosion and corrosion problems in the steam turbine are eliminated/avoided.
3. There is an improvement in the thermal efficiency of the turbines.
4. Final dryness fraction of steam is improved.
5. There is an increase in the nozzle and blade efficiencies.

<u>Disadvantages :</u>

1. Reheating requires more maintenance.
2. The increase in thermal efficiency is not appreciable in comparison to the expenditure incurred in reheating

Objective Questions

1. Rankine cycle efficiency of a good steam power plant may be in the range of
(a) 15 to 20%
(b) 35 to 45%
(c) 70 to 80%
(d) 90 to 95% .

2. Rankine cycle operating on low pressure limit of p1 and high pressure limit of p_2
(a) has higher thermal efficiency than the Carnot cycle operating between same pressure limits
(b) has lower thermal efficiency than Carnot cycle operating between same pressure limits
(c) has same thermal efficiency as Carnot cycle operating between same pressure limits
(d) may be more or less depending upon the magnitudes of p_1 and p_2.

3. Rankine efficiency of a steam power plant
(a) improves in summer as compared to that in winter
(b) improves in winter as compared to that in summer
(c) is unaffected by climatic conditions
(d) none of the above.

4. Rankine cycle comprises of
(a) two isentropic processes and two constant volume processes
(b) two isentropic processes and two constant pressure processes
(c) two isothermal processes and two constant pressure processes
(d) none of the above.

5. In Rankine cycle the work output from the turbine is given by
(a) change of internal energy between inlet and outlet
(b) change of enthalpy between inlet and outlet
(c) change of entropy between inlet and outlet
(d) change of temperature between inlet and outlet.

6. Regenerative heating i.e., bleeding steam to reheat feed water to boiler
(a) decreases thermal efficiency of the cycle
(b) increases thermal efficiency of the cycle
(c) does not affect thermal efficiency of the cycle
(d) may increase or decrease thermal efficiency of the cycle depending upon the point of extraction of steam.

7. Regenerative cycle thermal efficiency
(a) is always greater than simple Rankine thermal efficiency
(b) is greater than simple Rankine cycle thermal efficiency only when steam is bled at particular pressure
(c) is same as simple Rankine cycle thermal efficiency
(d) is always less than simple Rankine cycle thermal efficiency.

8. In a regenerative feed heating cycle, the optimum value of the fraction of steam extracted for feed heating
(a) decreases with increase in Rankine cycle efficiency
(b) increases with increase in Rankine cycle efficiency
(c) is unaffected by increase in Rankine cycle efficiency
(d) none of the above.

9. In a regenerative feed heating cycle, the greatest economy is affected
(a) when steam is extracted from only one suitable point of steam turbine
(b) when steam is extracted from several places in different stages of steam turbine
(c) when steam is extracted only from the last stage of steam turbine
(d) when steam is extracted only from the first stage of steam turbine.

10. The maximum percentage gain in Regenerative feed heating cycle thermal efficiency
(a) increases with number of feed heaters increasing
(b) decreases with number of feed heaters increasing
(c) remains same unaffected by number of feed heaters
(d) none of the above.

11 . How can we differentiate Rankine cycle from Carnot cycle?
(a). Heat addition process of Rankine cycle is reversible isothermal whereas heat addition process of Carnot cycle is reversible isobaric
(b). Heat addition process of Rankine cycle is reversible isobaric whereas heat addition process of Carnot cycle is reversible isothermal
(c). Heat addition process of Rankine cycle is reversible isentropic whereas heat addition process of Carnot cycle is reversible isothermal
(d). both cycles are identical except the working fluid used

12. What is the relation between efficiencies of Rankine cycle () and Carnot cycle for the same pressure ratio?
(a) $(\eta_{Rankine}) = (\eta_{Carnot})$
b) $(\eta_{Rankine}) > (\eta_{Carnot})$
(c)$(\eta_{Rankine}) < (\eta_{Carnot})$
(d)none of the above

13. The maximum efficiency of Rankine cycle ($\eta_{Rankine}$) is the function of
(a) the mean temperature of heat addition (T_m) only
(b) the mean temperature of heat addition (T_m) and temperature of steam at the exit of the turbine
(c)the mean temperature of heat addition (T_m) and temperature of steam at the entry of the turbine
(d) the mean temperature of heat addition (T_m) and temperature of steam at exit of the condenser

14. What is the effect of superheated steam on efficiency of Rankine cycle?
(a) efficiency of Rankine cycle decreases with increase in superheat of the steam
(b) efficiency of Rankine cycle increases with increase in superheat of the steam
(c) efficiency of Rankine cycle is not affected by change in superheat of the steam
(d) none of the above

15. What is the effect of increase in pressure at which heat is added on the pump work in the Rankine cycle?
a. the pump work increases with increase in pressure of heat addition
b. the pump work decreases with increase in pressure of heat addition
c. the pump work does not change with increase in pressure of heat addition
d. the pump work either increases or decreases with increase in pressure of heat addition

Answers :

1.(b) 2. (a) 3. (b) 4. (b) 5. (b) 6. (b) 7. (a) 8. (b) 9. (b) 10. (a). 11.(b) 12 .(c) 13 .(a) 14 .(b) 15 .(a)

University Questions:

1. Describe the different processes of Rankine cycle. Derive the expression for its efficiency and indicate the processes on P-v and T-s diagrams
2. Explain the factors that effect the efficiency and output of a Rankine cycle.
3. Explain the working of Rankine cycle with reheating system.
4. Explain with the help of neat diagram a `Regeneration cycle`. Derive an expression for its thermal efficiency
5. What do you mean by compounding of steam turbines? Discuss various methods of compounding steam turbines
6. Explain the difference between an impulse turbine and a reaction turbine.
7. Derive an expression for optimum stage efficiency of a reaction turbine
8. Draw the velocity diagrams of a simple impulse turbine and reaction turbine and explain their significance.

Problems:

1. In a Rankine cycle, the steam at inlet to turbine is saturated at a pressure of 30 bar and the exhaust pressure is 0.25 bar. Determine: i) The pump work ii) Turbine work iii) Rankine efficiency iv) Condenser heat flow v) Dryness at the end of expansion. Assume flow rate of 10 kg/s.
2. A simple Rankine cycle works between pressure of 30 bar and 0.04 bar, the initial condition of steam being dry saturated, calculate the cycle efficiency, work ratio and specific steam consumption
3. Steam initially at 1.5 MPa, 300^0C expands reversibly and adiabatically in a steam turbine to 40^0C. Determine the ideal work output of the turbine per kg of steam. indicate the process on T-s and h-s plots.
4. In a 50% reaction turbine stage running at 3000rpm, the exit angles are 30^0 and the inlet angles are 50^0 . The mean diameter is 1m.The steam flow rate is 10000 kg/minute and the stage efficiency is 85%. Determine: i) Power output of the stage. ii) The specific enthalpy drop in the stage.
5. In a single-stage impulse turbine, the steam jet leaves the nozzles at 20º to the plane of the wheel at a speed of 670 m/s and it enters the moving blades at an angle of 35º to the drum axis. The moving blades are symmetrical in shape. Determine the blade velocity and diagram efficiency.
6. In a single stage reaction turbine, both the fixed and moving blades have the same tip angles of 35º and 20º for inlet and outlet respectively. Determine the power required if the isentropic heat drop in both fixed and moving rows is 24.5 kJ/kg. The mean blade speed is 70 m/s and the steam consumption is 22,000 kg/h

Short Answer Questions

1. Explain various operation of a Carnot cycle. Also represent it on T-s and P-V diagrams
2. Give the differences of Rankine cycle and Carnot cycle
3. State the methods of increasing the thermal efficiency of a Rankine cycle.
4. Explain about reheating and regeneration
5. Define a steam turbine, classify steam turbine and state its fields of application.
6. Discuss the advantages of a steam turbine over the steam engines
7. Find the saturation temperature, change in specific volume and entropy during evaporation, and the latent heat of vaporization of steam at 2.5 MPa

UNIT:3 Gas Turbines

A gas turbine is a combustion engine that can convert natural gas or other liquid fuels to mechanical energy. This energy then drives a generator that produces electrical energy. Gas turbine is rotary internal combustion engine. They are used for producing very large quantities of power in a self-contained and compact unit. The thermal efficiency of the gas turbine alone is still quite modest 20 to 30% compared with that of a modern steam turbine plant 38 to 40%. It is possible to construct combined plants whose efficiencies are of order of 45% or more.

Application of gas turbines:

1. Aviation
2. Power generation
3. Oil and gas industry
4. Marine propulsion.

Uses of gas turbines:

The efficiency of a gas turbine is not the criteria for the choice of this plant. A gas turbine is used in aviation and marine fields because it is *self-contained, light weight, not requiring cooling water and generally fits into the overall shape of the structure.* It is selected for power generation because of its *simplicity, lack of cooling water, needs quick installation and quick starting*. It is used in oil and gas industry because of *cheaper supply of fuel and low installation cost*.

Limitations of gas turbines :

(i) They are not self-starting
(ii) Low efficiencies at part loads
(iii) Non-reversibility
(iv) Higher rotor speeds and
(v) Overall efficiency of the plant is low.

Classification of Gas Turbines:

The gas turbines are mainly *divided* into two groups

1. Constant pressure combustion gas turbine :

(*a*) Closed cycle constant pressure gas turbine
(*b*). Open cycle constant pressure gas turbine

2. Constant volume combustion gas turbine:

In almost all the fields open cycle gas turbine plants are used. Closed cycle plants were introduced at one stage because of their ability to burn cheap fuel. In between their progress remained slow because of availability of cheap oil and natural gas. Because of rising oil prices, now again, the attention is being paid to closed cycle plants.

Merits And Demerits Of Gas Turbines:

Merits over I.C. engines :

1. The mechanical efficiency of a gas turbine (95%) is quite high as compared with I.C. engine (85%) since the I.C. engine has a large many sliding parts.
2. A gas turbine does not require a flywheel as the torque on the shaft is continuous and uniform. Whereas a flywheel is a must in case of an I.C. engine.
3. The weight of gas turbine per H.P. developed is less than that of an I.C. engine.
4. The gas turbine can be driven at a very high speeds (40,000 r.p.m.) whereas this is not possible with I.C. engines.
5. The work developed by a gas turbine per kg of air is more as compared to an I.C. engine. This is due to the fact that gases can be expanded upto atmospheric pressure in case of a gas turbine whereas in an I.C. engine expansion upto atmospheric pressure is not possible.
6. The components of the gas turbine can be made lighter since the pressures used in it are very low, say 5 bar compared with I.C. engine, say 60 bar.
7. In the gas turbine the ignition and lubrication systems are much simpler as compared with I.C. engines.
8. Cheaper fuels such as paraffine type, residue oils or powdered coal can be used whereas special grade fuels are employed in petrol engine to check knocking or pinking.
9. The exhaust from gas turbine is less polluting comparatively since excess air is used for combustion.
10. Because of low specific weight the gas turbines are particularly suitable for use in aircrafts.

Demerits of gas turbines:

1. The thermal efficiency of a simple turbine cycle is low (15 to 20%) as compared with I.C. engines (25 to 30%)
2. With wide operating speeds the fuel control is comparatively difficult
3. Due to higher operating speeds of the turbine, it is imperative to have a speed reduction device.
4. It is difficult to start a gas turbine as compared to an I.C. engine
5. The gas turbine blades need a special cooling system
6. One of the main demerits of gas turbine is its poor thermal efficiency at part loads as the quantity of air remains same irrespective of load and out put is reduced by reducing the quantity of fuel supplied

Merits of gas turbines over steam turbine:

1. For the same output the space required is less
2. Weight per H.P is far less
3. Staring is more easy and quick
4. Boiler along with accessories not required
5. Control of gas turbine is much easier
6. Capital and running cost is less

Constant pressure combustion gas turbine :

Closed cycle constant pressure gas turbine or Brayton cycle Or joules cycle:

An ideal gas turbine plant would perform the processes that make up a Brayton cycle.

The various operations are as follows:

Operation 1-2. The air is compressed isentropically from the lower pressure p_1 to the upper pressure p_2, the temperature rising from T_1 to T_2. No heat flow occurs.

Operation 2-3. Heat flows into the system increasing the volume from V_2 to V_3 and temperature from T_2 to T_3 whilst the pressure remains constant at p_2. Heat received = $mcp\ (T_3 - T_2)$.

Operation 3-4. The air is expanded isentropically from p_2 to p_1, the temperature falling from T_3 to T_4. No heat flow occurs.

Operation 4-1. Heat is rejected from the system as the volume decreases from V_4 to V_1 and the temperature from T_4 to T_1 whilst the pressure remains constant at p_1.

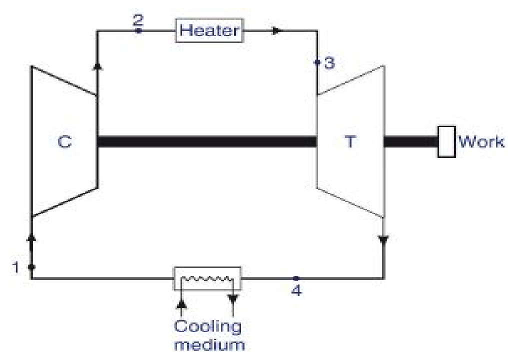
Heat rejected = $mc_p(T_4 - T_1)$

Now, from isentropic expansion

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = T_1\ (r_p)^{\frac{\gamma-1}{\gamma}}\text{, where } r_p = \text{Pressure ratio}$$

Similarly, $$\frac{T_3}{T_4} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \text{ or } T_3 = T_4\ (r_p)^{\frac{\gamma-1}{\gamma}}$$

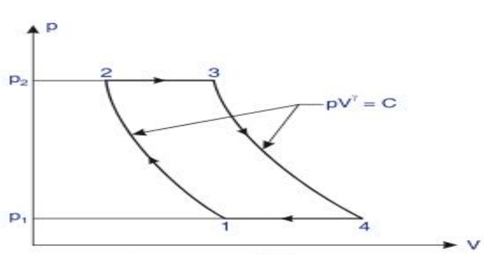


$$\eta_{\text{air-standard}} = \frac{\text{Work done}}{\text{Heat received}} = \frac{\text{Heatreceived/cycle} - \text{Heat rejected/cycle}}{\text{Heat received/cycle}}$$

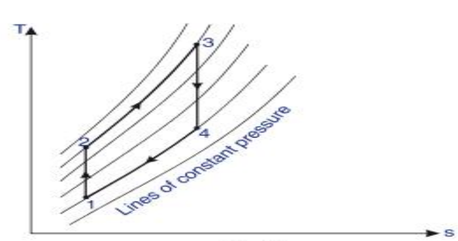
$$= \frac{mc_p(T_3 - T_2) - mc_p(T_4 - T_1)}{mc_p(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$\therefore \quad \eta_{air\text{-}standard} = 1 - \frac{T_4 - T_1}{T_4(r_p)^{\frac{\gamma-1}{\gamma}} - T_1(r_p)^{\frac{\gamma-1}{\gamma}}}$$

$$= 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}}$$



p-V diagram.



T-s diagram.

Open Cycle Gas Turbine—Actual Brayton Cycle

The fundamental gas turbine unit is one operating on the open cycle in which a rotary compressor and a turbine are mounted on a common shaft. Air is drawn into the compressor and after compression passes to a combustion chamber. Energy is supplied in the combustion chamber by spraying fuel into the air stream, and the resulting hot gases expand through the turbine to the atmosphere. In order to achieve net work output from the unit, the turbine must develop more gross work output than is required to drive the compressor and to overcome mechanical losses in the drive. The products of combustion coming out from the turbine are exhausted to the atmosphere as they cannot be used any more. The working fluids (air and fuel) must be replaced continuously as they are exhausted into the atmosphere.

The various operations are as follows

1-2′ represents : irreversible adiabatic compression.
2′-3 represents : constant pressure heat supply in the combustion chamber.
3-4′ represents : irreversible adiabatic expansion.
1-2 represents : ideal isentropic compression.
3-4 represents : ideal isentropic expansion.

Work input (compressor) = $c_p\,(T_2' - T_1)$
Heat supplied (combustion chamber) = $c_p\,(T_3 - T_2')$
Work output (turbine) = $c_p\,(T_3 - T_4')$
∴ Net work output = Work output – Work input
= $c_p\,(T_3 - T_4') - c_p(T_2' - T_1)$

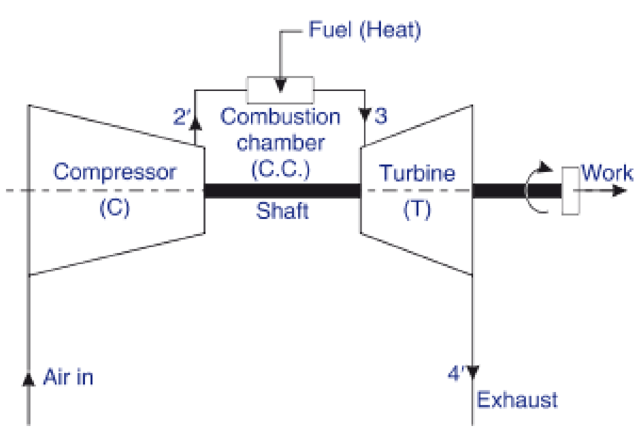
$$\eta_{thermal} = \frac{\text{Network output}}{\text{Heat supplied}} = \frac{c_p\,(T_3 - T_4') - c_p\,(T_2' - T_1)}{c_p(T_3 - T_2')}$$

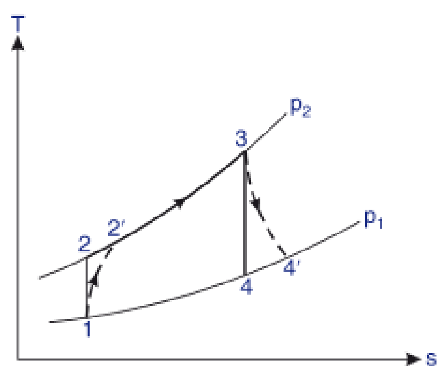
Compressor isentropic efficiency,

$$\eta_{comp} = \frac{\text{Work input required in isentropic compression}}{\text{Actual work required}} = \frac{c_p(T_2 - T_1)}{c_p(T_2' - T_1)} = \frac{T_2 - T_1}{T_2' - T_1}$$

Turbine isentropic efficiency,

$$\eta_{turbine} = \frac{\text{Actual work output}}{\text{Isentropic work output}} = \frac{c_p\,(T_3 - T_4')}{c_p(T_3 - T_4)} = \frac{T_3 - T_4'}{T_3 - T_4}$$





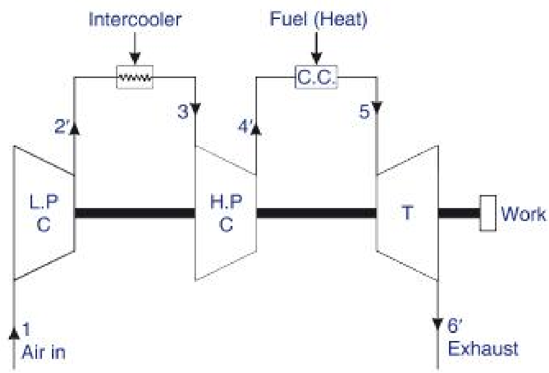
Methods for Improvement of Thermal Efficiency of Open Cycle Gas Turbine Plant:

The following methods are employed *to increase the specific output and thermal efficiency of the plant:*

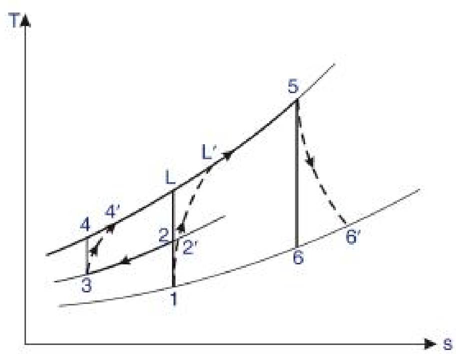
1. Intercooling
2. Reheating
3. Regeneration.

1. ***Intercooling.***

A compressor in a gas turbine cycle utilises the major percentage of power developed by the gas turbine. The work required by the compressor can be reduced by compressing the air in two stages and incorporating an intercooler between the two compressors.



Turbine plant with intercooler.



T-s diagram for the unit.

The actual processes take place as follows :

1-2′ ... L.P. (Low pressure) compression
2′-3 ... Intercooling
3-4′ ... H.P. (High pressure) compression
4′-5 ... C.C. (Combustion chamber)-heating
5-6′ ... T (Turbine)-expansion

The ideal cycle for this arrangement is 1-2-3-4-5-6 ; the compression process without intercooling is shown as 1-L′ in the actual case, and 1-L in the ideal isentropic case.

Now,
Work input (with intercooling)

$$= c_p(T_{2'} - T_1) + c_p(T_{4'} - T_3)$$

Work input (without intercooling)

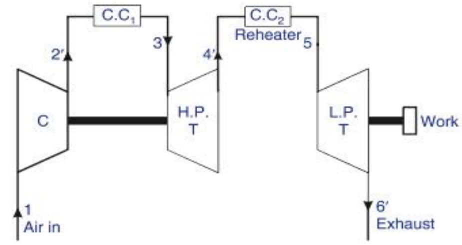
$$= c_p(T_{L'} - T_1) = c_p(T_{2'} - T_1) + c_p(T_{L'} - T_{2'})$$

By comparing above equations it can be observed that the work input with intercooling is less than the work input with no intercooling, when $c_p(T_{4'} - T_3)$ is less than $c_p(T_{L'} - T_{2'})$. This is so if it is assumed that isentropic efficiencies of the two compressors, operating separately, are each equal to the isentropic efficiency of the single compressor which would be required if no intercooling were used. Then $(T_{4'} - T_3) < (T_{L'} - T_{2'})$ since the pressure lines diverge on the T-s diagram from left to the right

From this we may conclude that *when the compressor work input is reduced then the work ratio is increased*.
However the heat supplied in the combustion chamber when intercooling is used in the cycle, is given by,
Heat supplied *with intercooling* $= c_p(T_5 - T_{4'})$
Also the heat supplied when intercooling is not used, with the same maximum cycle temperature T_5, is given by
Heat supplied *without intercooling* $= c_p(T_5 - T_{L'})$
Thus, the *heat supplied when intercooling is used is greater than with no intercooling. Although the net work output is increased by intercooling it is found in general that the increase in heat to be supplied causes the thermal efficiency to decrease.* When intercooling is used a supply of cooling water must be readily available. The additional bulk of the unit may offset the advantage to be gained by increasing the work ratio.

Reheating.

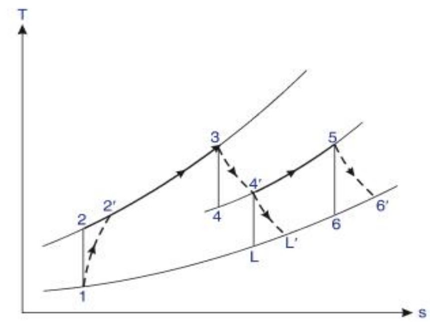
The output of a gas turbine can be amply improved by expanding the gases in two stages with a *reheater* between the two. The H.P. turbine drives the compressor and the L.P. turbine provides the useful power output. The line $4'$-L' represents the expansion in the L.P. turbine if reheating is *not* employed.



Gas turbine with reheater.

the work output of the H.P. turbine must be exactly equal to the work input required for the compressor i.e.,

$$c_{pa}\,(T_2' - T_1) = c_{pg}\,(T_3 - T_4')$$



T-s diagram for the unit.

The work output (net output) of L.P. turbine is given by,

Net work output (with reheating) $= c_{pg}\,(T_5 - T_6')$

and Net work output (without reheating) $= c_{pg}\,(T_4' - T_L')$

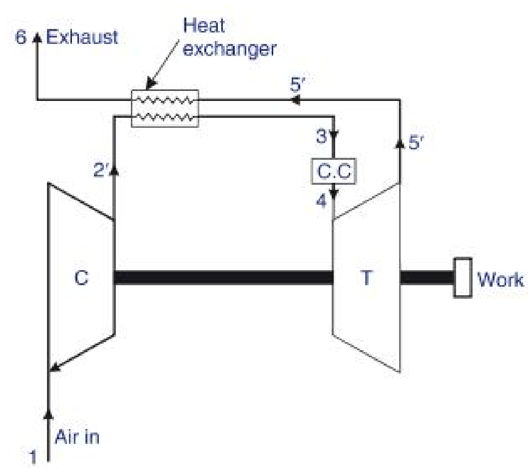
Since the pressure lines diverge to the right on T-s diagram it can be seen that the temperature difference $(T_5 - T_6')$ is always *greater* than $(T_4' - T_L')$, so that *reheating increases the net work output.*

Although net work is increased by reheating the heat to be supplied is also increased, and the net effect *can be to reduce the thermal efficiency*

Heat supplied $= c_{pg}\,(T_3 - T_2') + c_{pg}\,(T_5 - T_4')$.

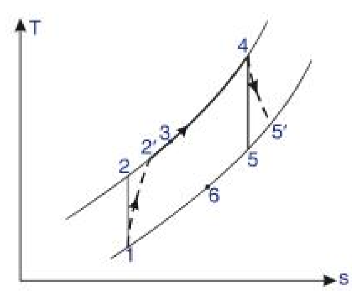
Regeneration.

The exhaust gases from a gas turbine carry a large quantity of heat with them since their temperature is far above the ambient temperature. They can be used to heat the air coming from the compressor thereby reducing the mass of fuel supplied in the combustion chamber.



Gas turbine with regenerator.

$2'$-3 represents the heat flow into the compressed air during its passage through the heat exchanger and 3-4 represents the heat taken in from the combustion of fuel. Point 6 represents the temperature of exhaust gases at discharge from the heat exchanger. The maximum temperature to which the air could be heated in the heat exchanger is ideally that of exhaust gases, but less than this is obtained in practice because a temperature gradient must exist for an unassisted transfer of energy. A heat exchanger is usually used in large gas turbine units for marine propulsion or industrial power.



T-s diagram for the unit.

The *effectiveness* of the heat exchanger is given by :

$$\varepsilon = \frac{\text{Increase in enthalpy per kg of air}}{\text{Available increase in enthalpy per kg of air}} = \frac{(T_3 - T_2')}{(T_5' - T_2')}$$

Effect of Operating Variables on Thermal Efficiency:

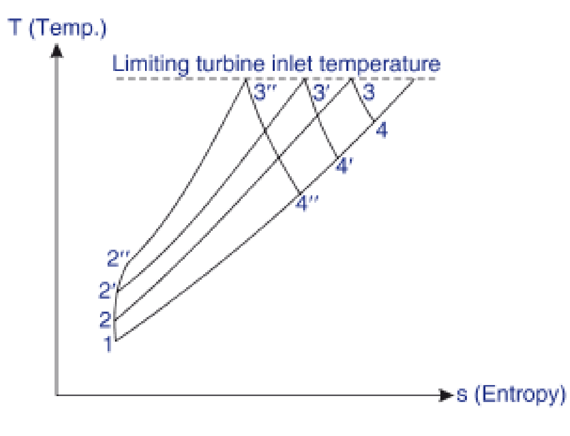
The thermal efficiency of actual open cycle depends on the following thermodynamic variables :

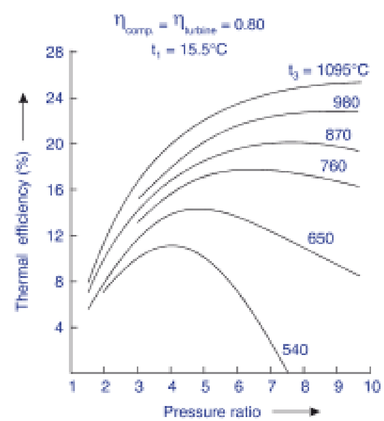
(i) Pressure ratio
(ii) Turbine inlet temperature (T3)
(iii) Compressor inlet temperature (T1)
(iv) Efficiency of the turbine (ηturbine)
(v) Efficiency of the compressor (ηcomp)

Effect of turbine inlet temperature and pressure ratio :

If the permissible turbine inlet-temperature (with the other variables being constant) of an *open cycle gas turbine power plant* is increased its *thermal efficiency* is *amply improved*. A practical limitation to increasing the turbine inlet temperature, however, is the ability of the material available for the turbine blading to *withstand the high rotative and thermal stresses.*

. For *a given turbine inlet temperature, as the pressure ratio increases, the heat supplied as well as the heat rejected are reduced. But the ratio of change of heat supplied is not the same as the ratio of change heat rejected.* As a consequence, there *exists an optimum pressure ratio producing maximum thermal efficiency for a given turbine inlet temperature.*





As the pressure ratio increases, the thermal efficiency also increases until it becomes maximum and then it drops off with a further increase in pressure ratio Further, as the turbine inlet temperature increases, the peaks of the curves flatten out giving a greater range of ratios of pressure optimum efficiency

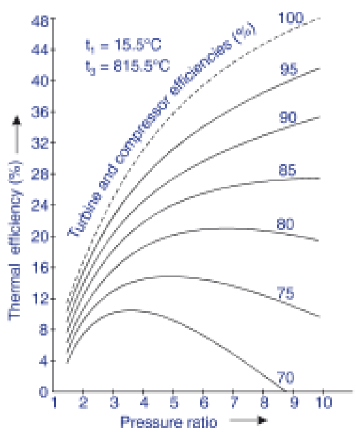
Gas temperatures	*Efficiency (gas turbine)*
550 to 600°C	20 to 22%
900 to 1000°C	32 to 35%
Above 1300°C	more than 50%

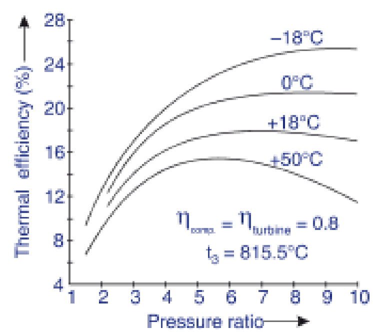
Effect of turbine and compressor efficiencies :

The thermal efficiency of the actual gas turbine cycle is very sensitive to variations in the efficiencies of the compressor and turbine. There is a particular pressure ratio at which maximum efficiencies occur. For lower efficiencies, the peak of the thermal efficiency occurs at lower pressure ratios and vice versa.

Effect of compressor inlet temperature :

With the decrease in the compressor inlet temperature *there is increase in thermal efficiency of the plant.* Also the peaks of thermal efficiency occur at high pressure ratios and the curves become flatter giving thermal efficiency over a wider pressure ratio range.





Gas Turbine Fuels

The various fuels used in gas turbines are enumerated and discussed below:
1. Gaseous fuels
2. Liquid fuels
3. Solid fuels

1. Gaseous fuels.

Natural gas is the ideal fuel for gas turbines, but this is not available everywhere. *Blast furnace* and *producer gases* may also be used for gas turbine power plants.

2. Liquid fuels.

Liquid fuels of petroleum origin such as distillate oils or residual oils are most commonly used for gas turbine plant. The essential qualities of these fuels include *proper volatility, viscosity and calorific value*. At the same time it *should be* free *from any contents of moisture* and *suspended impurities that would log the small passages of the nozzles and damage valves and plungers of the fuel pumps.*

Minerals like *sodium, vanadium* and *calcium* prove *very harmful* for the *turbine blading* as these build deposits or corrode the blades. The sodium in ash should be less than 30% of the vanadium content as otherwise the ratio tends to be critical. The actual sodium content may be between 5 ppm to 10 ppm (part per million). If the vanadium is over 2 ppm, the magnesium in ash tends to become critical. *It is necessary that the magnesium in ash is at least three times the quantity of vanadium.* The content of calcium and lead should not be over 10 ppm and 5 ppm respectively.

Sodium is removed from residual oils by mixing with 5% of water and then double centrifuging when sodium leaves with water. Magnesium is added to the washed oil in the form of Epsom salts, before the oil is sent into the combustor. This checks the corrosive action of vanadium. Residual oils burn with less ease than distillate oils and the latter are often used to start the unit from cold, after which the residual oils are fed in the combustor. In cold conditions residual oils need to be preheated.

3. Solid fuels.

The use of solid fuels such as coal in pulverised form in gas turbines presents several difficulties most of which have been only partially overcome yet. The pulverising plant for coal in gas turbines applications is much lighter and small than its counterpart in steam generators. *Introduction of fuel in the combustion chamber of a gas turbine is required to be done against a high pressure whereas the pressure in the furnace of a steam plant is atmospheric.* Furthermore, the *degree of completeness of combustion in gas turbine applications has to be very high as otherwise soot and dust in gas would deposit on the turbine blading.* Some practical applications of solid fuel burning in turbine combustors have been commercially, made available in recent years. In one such design finely crushed coal is used instead of pulverised fuel. This fuel is carried in stream of air tangentially into one end of a cylindrical furnace while gas comes out at the centre of opposite end. As the fuel particles roll around the circumference of the furnace they are burnt and a high temperature of about 1650°C is maintained which causes the mineral matter of fuel to be converted into a liquid slag. The slag covers the walls of the furnace and runs out through a top hole in the bottom. The result is that fly-ash is reduced to a very small content in the gases. In *another design* a regenerator is used to transfer the heat to air, the combustion chamber being located on the outlet of the turbine, and the combustion is carried out in the turbine exhaust stream. The advantage is that only clean air is handled by the turbine.

Objective Questions

1. The major field(s) of application of gas turbine is (are)
   a. Aviation
   b. Oil and gas industry
   c. Marine propulsion
   d. All of the above

2. The ratio of heat actually released by 1kg of fuel to heat that would be released by complete perfect combustion, is called
   a. Thermal efficiency
   b. Combustion efficiency
   c. Engine efficiency
   d. Compression efficiency

3. The percentage of total energy input appearing as net work output of the cycle
   a. Thermal efficiency
   b. Combustion efficiency
   c. Engine efficiency
   d. Compression efficiency

4. The following is (are) the limitation(s) of gas turbines.
   a. They are not self starting
   b. Higher rotor speeds
   c. Low efficiencies at part loads
   d. All of the above

5. Gas turbine is shut down by
   a. Turning off starter
   b. Stopping the compressor
   c. Fuel is cut off from the combustor
   d. Any of the above

6. The following method(s) can be used to improve the thermal efficiency of open cycle gas turbine plant
   a. inter-cooling
   b. Reheating
   c. Regeneration
   d. All of the above

7. In gas turbine, intercooler is placed
   a. before low pressure compressor
   b. in between low pressure compressor and high pressure compressor
   c. in between high pressure compressor and turbine
   d. None of the above

8. In gas turbine, the function of Re-heater is to
   a. Heat inlet air
   b. Heat exhaust gases
   c. Heat air coming out of compressor
   d. Heat gases coming out of high pressure turbine

9. The ‘work ratio’ increases with
   a. increase in turbine inlet pressure
   b. decrease in compressor inlet temperature
   c. decrease in pressure ratio of the cycle
   d. all of the above

10. In the _____ heat transfer takes place between the exhaust gases and cool air.
   a. Intercooler
   b. Re-heater
   c. Regenerator
   d. Compressor

11. Which of the following is (are) used as starter for a gas turbine
   a. An Internal combustion engine
   b. A steam turbine
   c. An auxiliary electric motor
   d. All of the above

12. _______ can be used as fuels in gas turbines.
   a) Natural gases
   b) petroleum
   c) Diesel
   d) All of the mentioned

13. Fuels used in gas turbines should have _____ ash content.
   a) low
   b) high
   c) zero
   d) none of the mentioned

14. Regenerator is also called as ___________
   a) Intercooler
   b) Reheater
   c) Recuperator
   d) None of the mentioned

15. By two stage compression work output from turbine is _______
   a) decreased
   b) increased
   c) remains constant
   d) none

Answers : 1.(d) 2. (b) 3. (a) 4. (d) 5. (c) 6. (d) 7. (b) 8. (c) 9. (d) 10. (c). 11.(d) 12.(d) 13(a) 14(c) 15(b)

University Questions:

1. Derive an expression of air standard efficiency for the open cycle gas turbine with the neat Sketch and indicate the operations on P-V and T-s diagram
2. Describe with neat diagram a closed cycle gas turbine and also derive the expression of thermal efficiency of the closed cycle. State also its merits and demerits over open cycle gas turbine
3. List out the differences between the open cycle gas turbine and closed cycle gas Turbine
4. Explain the Inter cooling method applied to the gas turbine plant for improvement of the performance of plant with the help of P-V diagram and H-S diagram
5. Explain the Regenerative method applied to the gas turbine plant for improvement of the performance of plant with the help of P-V diagram and H-s diagram
6. Explain the Re-heat method applied to the gas turbine plant for improvement of the performance of plant with the help of P-V diagram and H-S diagram
7. What are different operating variables that affect the thermal efficiency of gas turbine power plant? Explain
8. Explain the working of closed cycle gas turbine plant with intercooler and reheater
9. Explain with a neat sketch the working of a constant volume combustion turbine

Problems:

1. In an open cycle constant pressure gas turbine air enters the compressor at 1 bar and 300K.The pressure of air after the compression is 4 bar. The isentropic efficiencies of compressor and turbine are 78% and 85% respectively. The air fuel ratio is 80:1.Calculate the power developed and thermal efficiency of the cycle if the flow rate of air is 2.5 kg/s. Take Cp=1.005KJ/ KgK and γ =1.4 and Cpg=1.147 KJ/KgK and γ =1.33 for gases. R=0.287KJ/KgK Calorific value of fuel=42000KJ/Kg
2. A simple gas turbine cycle works with a pressure ratio of 8. The compressor and turbine inlet temperatures are 300 K and 800 K respectively. If the volume flow rate of air is 250 m3 /s, compute the power output and thermal efficiency
3. A Gas turbine plant works between the temperature limits of 11520K and 2880 K Isentropic efficiency for compressor and turbines are 0.85 and 0.8 respectively. Determine the optimum pressure ratio for maximum work output and also for maximum Cycle thermal efficiency.
4. A gas turbine plant is supplied with air at a pressure of 2 bar and 300 K. The air is then compressed to a pressure of 6 bar and then heated to 800^0C in the combustion chamber. Calculate the thermal efficiency of the cycle
5. In a gas turbine the compressor is driven by the high pressure turbine. The exhaust from the high pressure turbine goes to a free low pressure turbine which runs the load. The air flow rate is 20 kg/s and the minimum and maximum temperatures are respectively 300K and 1000K. The compressor pressure ratio is 4. Calculate the pressure ratio of the low pressure turbine and the temperature of exhaust gases from the unit. The compressor and turbine are isentropic. Cp of air and exhaust gases = 1 kJ/kgk and γ = 1.4.
6. The gas turbine has an overall pressure ratio of 5:1 and a maximum cycle temperature of 550^0C. the turbine drives the compressor and an electric generator, the mechanical efficiency of the drive being 97%. The ambient temperature is 20^0C and the isentropic efficiencies for the compressor and turbine are 0.8 and 0.83 respectively. Calculate the power output in kilowatts for an air flow of 15 kg/s. calculate also the thermal efficiency and the work ratio. Neglect changes in kinetic energy and the loss of pressure in combustion chamber

Short Answer Questions

1. State the merits of gas turbines over I.C. engines and steam turbines. Discuss also the demerits of gas turbines
2. List out the applications of the gas turbines
3. Differentiate open and closed cycle gas turbine plants
4. Write a short note on fuels used for gas turbines
5. What do you mean by the term `gas turbine`? how are gas turbines classified
6. Define work ratio and efficiency of a gas turbine
7. Write the advantages and limitations of gas turbines