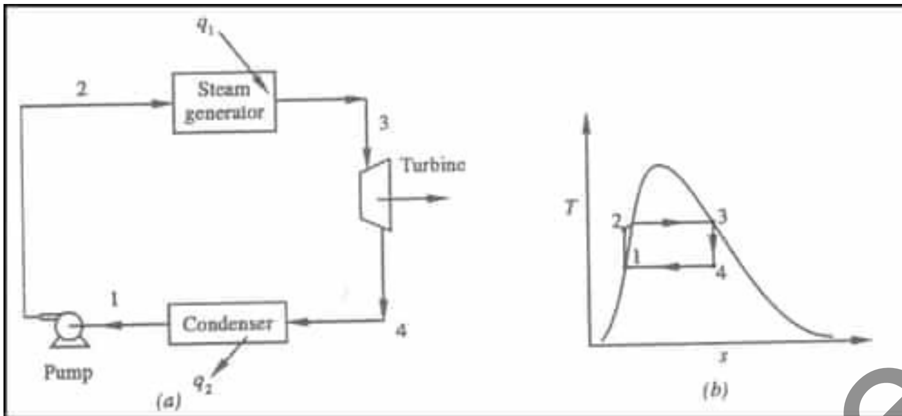
Power plant

Index

Rankine Cycle

The Rankine cycle is the fundamental operating cycle of all power plants where an operating fluid is continuously evaporated and condensed.



- **2-3 Isobaric Heat Transfer:**
  High-pressure liquid enters the boiler from the feed pump (1-2) and is heated to the saturation temperature (2). Further addition of energy causes evaporation of the liquid until it is fully converted to saturated steam (3).

- **3-4 Isentropic Expansion:**
  The vapor is expanded in the turbine, thus producing work that may be converted to electricity. In practice, the expansion is limited by the temperature of the cooling medium and by the erosion of the turbine blades by liquid entrainment in the vapor stream as the process moves further into the two-phase region. Exit vapor qualities should be greater than 90%.

- **4-1 Isobaric Heat Rejection:**
  The vapor-liquid mixture leaving the turbine (3-4) is condensed at low pressure, usually in a surface condenser using cooling water. In well-designed and maintained condensers, the pressure of the vapor is well below atmospheric pressure, approaching the saturation pressure of the operating fluid at the cooling water temperature.

- **1-2 Isentropic Compression:**
  The pressure of the condensate is raised in the feed pump. Because of

the low specific volume of liquids, the pump work is relatively small and often neglected in thermodynamic calculations.

- Work was done on the pump, per kg of water: $W_P = h_2 - h_1$

  Energy added in steam generator: $q_1 = h_3 - h_2$

- Work delivered by turbine: $W_T = h_3 - h_4$

  Energy rejected in the condenser, $q_2 = h_4 - h_1$

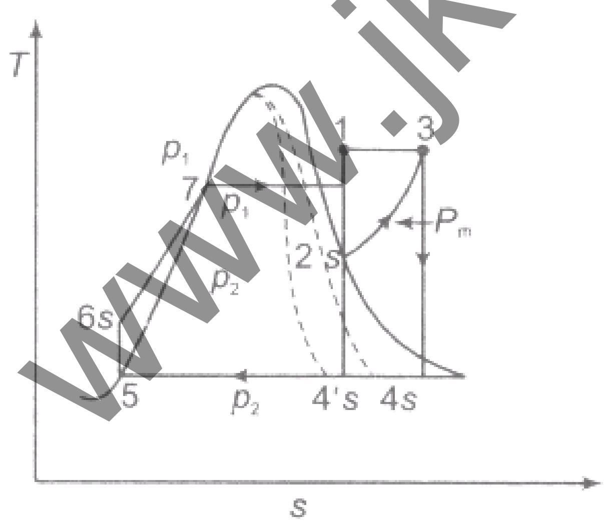
- **The thermal efficiency of the Rankine cycle is given by:**

$$\eta = \frac{q_1 - q_2}{q_1} = \frac{(h_3 - h_2) - (h_4 - h_1)}{h_3 - h_2} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

Reheating of Steam:

In the reheat cycle, the expansion of steam from the initial state 1 to the condenser pressure is carried out in two or more steps depending upon the number of reheats used.

Cycle efficiency: improves with reheat, however, the cycle efficiency in a single reheat plant is influenced by pressure at which steam is reheated. The efficiency increases as the reheat pressure are lowered and reaches a peak at a **pressure ratio** between 0.20 and 0.25.



Reheating cycle

$$\eta = \frac{W_T - W_p}{Q_1} = \frac{(h_1 - h_{2s} + h_3 - h_{4s}) - (h_{6s} - h_5)}{(h_1 - h_{6s}) + (h_3 - h_{2s})}$$

Reheating steam also increases the net output of the turbine.

Key Points:

- Internal irreversibility of Rankine cycle (Real cycle) is caused by fluid frictions throttling and mixing.
- Externally, irreversibility of the Rankine cycle is caused due to the temperature difference between the combustion gases and the working fluid on the same side and the temperature difference between the condensing working fluid and the condenser cooling water on the sink side.

Advantages of Re-heating:

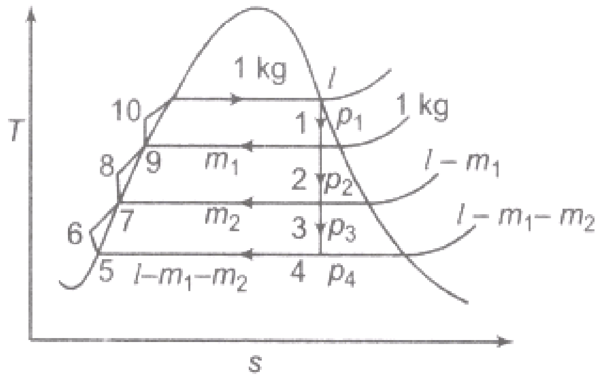
- Due to reheating, the network did increase.
- Heat supply increases.
- The thermal efficiency mat increases or decreases depending upon the mean temperature of heat addition.
- Due to reheating, the turbine exit dryness fraction increases so moisture decreases - so blade erosion becomes minimum - so the life of the turbine will be increased.

Regeneration:

(i). The mean temperature of heat addition (and so efficiency) can also be increased by reducing the amount of heat added at low temperatures in the economizer section of the steam generator.

(ii). In the regeneration process energy is exchanged internally between the expanding fluid in the turbine and the compressed fluid before heat addition.

(iii). Ideal regenerative cycle does not affect work output from the turbine, it is more efficient with a high steam rate.



Regeneration cycle with two direct contact feed water heaters

The efficiency of Steam Power Plant: Overall efficiency of the steam per plant is given by

$$\eta_{overall} = \eta_{Boiler} \times \eta_{cycle} \times \eta_{turbine} \times \eta_{generator} \times \eta_{aux}$$

$$\eta_{overall} = \frac{\text{Power available at the generator terminals}}{\text{Rate of energy released by the the combustion of fuel}}$$

$$\eta_{Boiler} = \frac{\text{Rate of energy absorption by water from steam}}{\text{Rate of energy released by the the combustion of fuel}}$$

$$\eta_{turbine} = \frac{\text{Brake output of turbine}}{\text{Internal output of the turbine}}$$

$$\eta_{auxiliary} = \frac{\text{Net power transmitted by the generator}}{\text{Gross power produced by plant}}$$

$$\eta_{cycle} = \frac{\text{Net work output}}{\text{Heat supplied}}$$

$$\eta_{generator} = \frac{\text{Electrical output at generator terminal}}{\text{Brake output of turbine}}$$

- Reheating of steam improved the thermal efficiency of the plant, the net-work output of the turbine, reduction in blade erosion (or quality of steam improve).

- By regeneration thermal efficiency of the plant can be increased but it does not affect work output from the turbine.

Combined Cycle Power Generation:

It is an assembly of heat engines that works with the same source of heat. The principle of combined cycle power generation is that the exhaust of one heat engine is used as the source of heat for another heat engine. This process increases the overall efficiency of a heat engine.

$$\eta = \eta_1 + \eta_2 - \eta_1\eta_2$$

Advantages of Regeneration cycle:

- Heat supplied to boiler becomes reduced
- Thermal efficiency is increased since the average temperature of heat added to the cycle is increased.
- Due to bleeding in the turbine, erosion of the turbine due to moisture is reduced.

Characteristics of Ideal Working Fluid

- The fluid should have a high critical temperature and the saturation pressure at the temperature of heat rejection should be above the atmospheric pressure.
- Specific heat of liquid should be small.
- The saturated vapor line of the *T-s* diagram, very close to the turbine expansion process.
- The freezing point of the fluid should be below room temperature.
- The fluid should be chemically stable, non-toxic, non-corrosive, not excessively viscous, and low in cost.

Gas turbine Cycle

GAS TURBINE CYCLE:

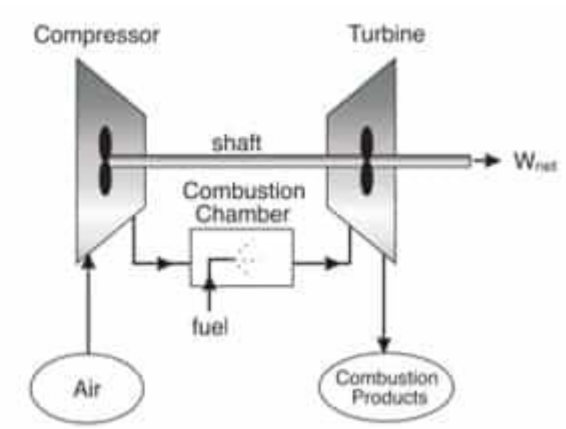
A gas turbine cycle works on Brayton cycle. Sometimes, these words are used interchangeably. A gas turbine cycle could be of the open gas turbine cycle and closed gas turbine cycle.

OPEN GAS TURBINE CYCLE

Fresh air enters the compressor at ambient temperature where its pressure and temperature are increased.

The high-pressure air enters the combustion chamber where the fuel is burned at constant pressure.

The high temperature and high-pressure gas enters the turbine where it expands to ambient pressure and produces work.



Schematic for an open gas-turbine cycle.

Features:

- Gas-turbine is used in aircraft propulsion and electric power
- High thermal efficiencies up to 44%.
- Suitable for combined cycles (with steam power plant)
- High power to weight ratio, high reliability, long
- High back work ratio (ratio of compressor work to the turbine work) up to 50%, compared to few percent in steam power

BRAYTON CYCLE

The ideal Brayton cycle is made up of four internally reversible processes:

1-2	isentropic compression (in compressor)
2-3	constant pressure heat-addition (in combustion chamber)

3-4	isentropic expansion (in turbine)
4-1	constant pressure heat rejection (exhaust)

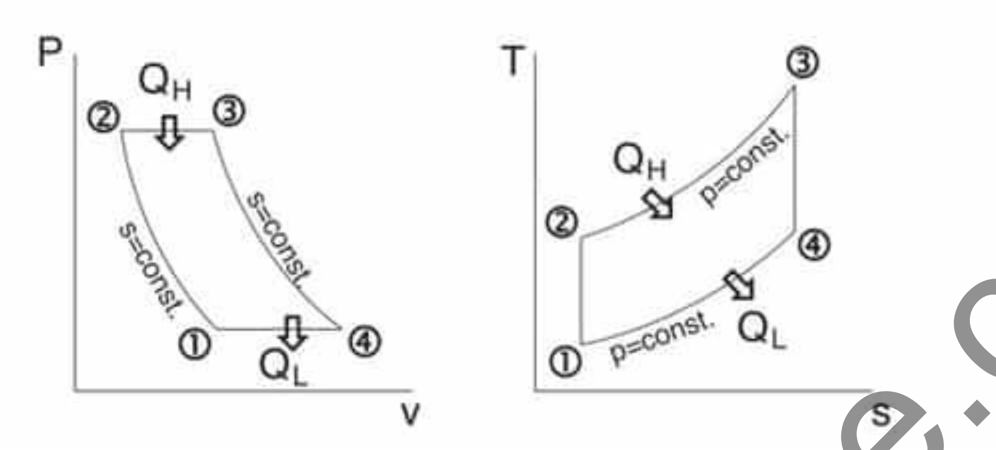


Fig.10: Brayton cycle on P-V and T-S diagram.

Heat added = $h_3 - h_2$

Heat rejected = $h_4 - h_1$

Turbine work (W_T) = $h_3 - h_4$

Compressor work (W_C) = $h_2 - h_1$

Net-work = $W_T - W_C = (h_3 - h_4) - (h_2 - h_1)$

Thermal efficiency

$$\eta = \frac{\text{Net work}}{\text{Heat added}}$$

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

The efficiency of the Brayton cycle is a function of the pressure ratio

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

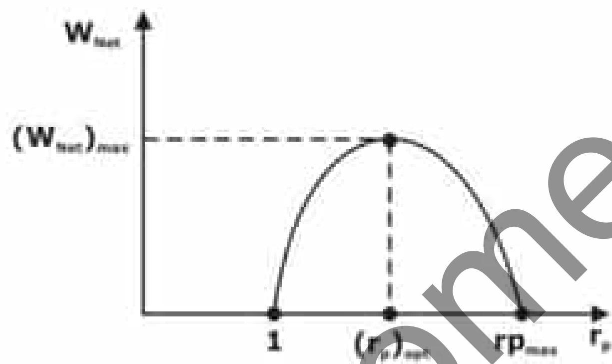
OPTIMUM PRESSURE RATIO FOR MAXIMUM WORK OUTPUT

Between 1 and $(r_p)_{max}$, there exist optimum value of pressure ratio $(r_p)_{optimum}$ for which work output is maximum.

$$(r_p)_{optimum} = \sqrt{(r_p)_{max}}$$

The maximum net-work is given by

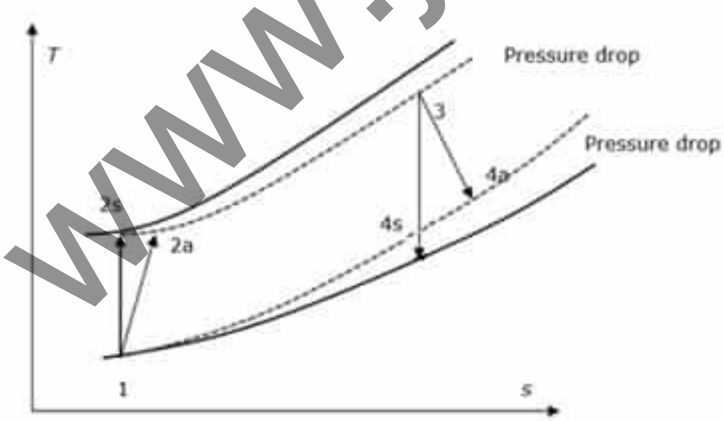
$$(W_{net})_{max} = C_p\left(\sqrt{T_{max}} - \sqrt{T_{min}}\right)^2$$



Variation of Network with pressure ratio

ACTUAL BRAYTON CYCLE

Irreversibility's exist in actual cycle. Most important differences are deviations of actual compressor and turbine from idealized isentropic compression/expansion, and pressure drop in combustion chamber.



Isentropic efficiency of compressor=$\eta = \frac{h_{2s} - h_1}{h_{2s} - h_1}$

Isentropic efficiency of turbine=$\eta = \frac{h_3 - h_{4s}}{h_3 - h_{4s}}$

WORK RATIO

It is defined as the ratio of net work output to the work output of turbine.

Work ratio (r_w)= $\frac{\text{Net Work Output}}{\text{Turbine Work}} = \frac{W_T - W_C}{W_T}$

BACK WORK RATIO

It is defined as the ratio of work consumed by the compressor to the work output of the turbine.

Back work ratio, r_{bw}= $\frac{\text{Compressor Work}}{\text{Turbine Work}} = \frac{W_C}{W_T}$

(I) Back Work Ratio for gas power cycles: 40% - 60%

(ii) Back Work Ratio for vapor power cycles: 1% - 2%

AIR RATE:

Air rate = $\frac{\text{Mass of air in kg/s}}{\text{Net work ouput in KW}} = \frac{3600}{W_{Net}}$ kg/KWh

Air Rate is the criterion of size of the plant, i.e., lower the air rate, smaller will be the plant size.

SPECIFIC POWER

Specific power = $\frac{W_{Net}}{3600}$

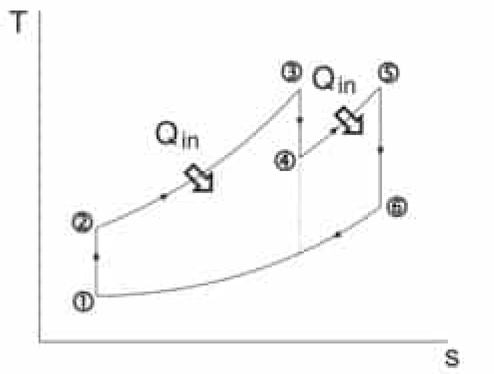
BRAYTON CYCLE WITH REHEAT

(i) In this cycle, high pressure and high temperature air (state 3) expands in the high- pressure turbine (turbine 1).

(ii)The air coming out of the high-pressure turbine (at state 4) is then reheated at constant pressure in a reheater to increase its temperature (state 5)

(iii) Then this reheated air is allowed to pass through the low-pressure turbine (turbine 2).

(iv)The thermal efficiency with reheating always decreases. This is because by reheating the mean temperature of heat rejection increases.



T-S diagram with reheat

OPTIMUM REHEAT PRESSURE

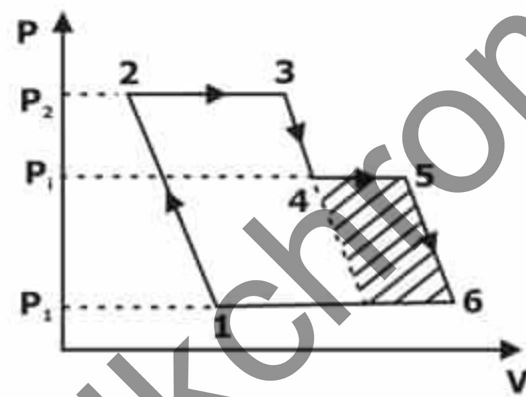


Fig.16: P-V diagram with reheat

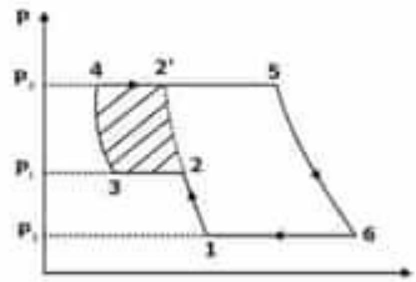
$P_i = \sqrt{P_3 . P_6}$

BRAYTON CYCLE WITH INTERCOOLING

(i) In intercooling, working fluid is compressed in more than one stage and in between the stages, intercooler is used to draw out the heat form the working fluid.

(ii)The work required to compress a fluid in a steady flow device can be reduced by compressing in no. of stages.

OPTIMUM INTERMEDIATE PRESSURE FOR INTERCOOLING:



P-V diagram with Intercooling

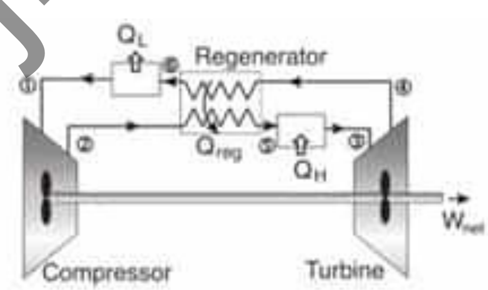
$P_i = \sqrt{P_1 P_4}$

In general, for n stages,

Pressure ratio (r_p) per stage $= \left(\frac{P_F}{P_I}\right)^{1/n}$

THE BRAYTON CYCLE WITH REGENERATION

The high-pressure air leaving the compressor can be heated by transferring heat from exhaust gases in a counter-flow heat exchanger which is called a regenerator. Hence the amount of heat to be supplied by the combustion chamber reduces and hence efficiency of the cycle increases.



Brayton Cycle with Regeneration

Thermal efficiency of an ideal Brayton cycle with regenerator can be found from:

$$\eta_{regeneration} = 1 - \frac{T_1}{T_3} r_p^{\frac{\gamma-1}{\gamma}}$$

where, T_1= Minimum temperature in Brayton cycle

T_3= Maximum temperature in Brayton cycle,

Thermal power plant & its accessories

INTRODUCTION

- A steam generator generates steam at the desired rate at the desired pressure and temperature by burning fuel in its furnace.
- Steam generators are used in both fossil-fuel and nuclear-fuel electric generating power stations.
- A steam generator is a complex integration of furnace, superheater, reheater, boiler or evaporator, economiser, and air preheater along with various auxiliaries such as pulverizers, burners, fans, stokers, dust collectors and precipitators, ash-handling equipment, and chimney or stack.
- The boiler is part of the steam generator where phase change occurs from liquid (water) to vapour (steam), at constant pressure and temperature. However, the term “boiler” is traditionally used to mean the whole steam generator.

1. BASIC TYPES OF STEAM GENERATORS

Based on application:

Classification of boilers can be made in different ways. From the point of view of applications, they can be

(a). utility steam generators

(b). industrial steam generators

(c). marine steam generators

Fire-tube boilers

- Fire-tube boilers have been used in various forms to produce steam for industrial purposes and for hauling railway locomotives and river launches.
- They are ***no longer used in utility power plants*** and steam locomotives have also mostly disappeared. However, they are ***still often used in industrial plants to produce saturated steam*** at the upper limits of about 18 bar pressure and 6.2 kg/s steaming capacity.

- For small steam requirements, fire-tube boilers are suitable. They have certain inherent advantages like:

(1). low first cost

(2). reliability in operation

(3). need of only unskilled labour

(4). less draught required

(5). quick response to load changes.

- A fire-tube boiler is so named because the products of combustion pass through its tubes or flues, which are surrounded by water. They may be either:

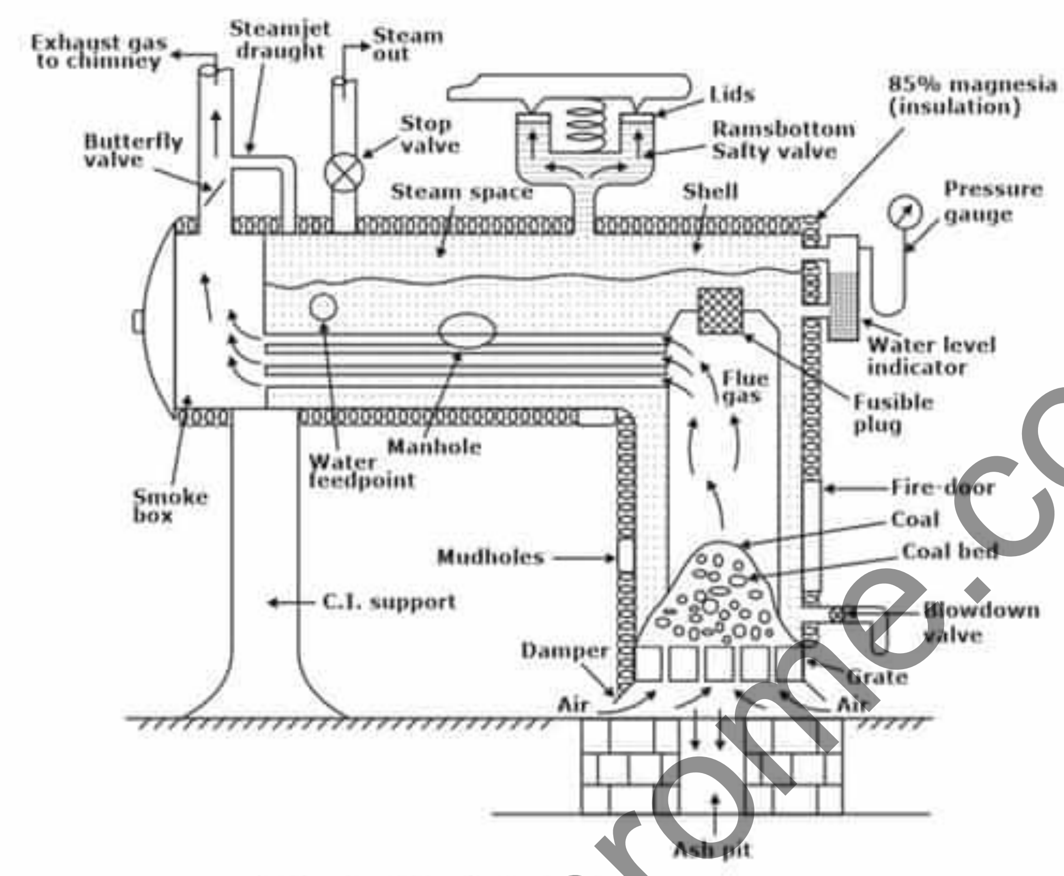
Examples: Cornish boilers, Cochran boiler, Lancashire boiler, Locomotive boiler etc.

(a). Externally fired: locomotive type boilers, Lancashire boilers, horizontal return tubular (HRT) boiler etc.

(b). Internally fired: Scotch-marine boilers, Cochran boiler, Babcock Wilcox boiler package boilers etc.

Externally fired boilers:

- Fig.1 shows a typical externally fired fire-tube boiler in which the furnace is outside the boiler shell.
- Coal is entered manually by shovels on to the grate by opening the fire-door. The products of combustion flow through the tubes which are immersed in the shell containing water.
- **A fusible plug** made up of a low melting point alloy (lead-based) is installed on the roof of the crown m the furnace. If the water-level in the shell falls below a certain level the fusible plug melts due to overheating and water pours down through the hole formed and puts out the fire.
- There is a spring-loaded safety-valve provided to the boiler pressure within the safety limit.



A typical fire tube boiler

Water-tube boilers

- Water-tube boilers were developed to resolve the shortcomings of fire tube boiler and permit increases in boiler pressure and capacity with reasonable metal stresses.

Examples: Babcock-Wilcox boiler, Stirling boiler, La-Mont boiler, Benson boiler etc.

- The water-tube boiler, where water flows through the tubes and flue gases flow outside them, puts the pressure in the tubes and the relatively small- diameter drums, which are capable of withstanding ***extreme pressures of the modern steam generator.***

REQUIREMENTS OF A GOOD BOILER

Different requirements of a good boiler are given below. In general boiler is supposed to generate large quantity of steam at desired pressure and temperature quickly and efficiently.

(a). It should be capable of generating steam at desired rate at desired pressure and temperature with minimum fuel consumption and cost.

(b). It should have sufficient steam and water storage capacity to meet fluctuation in demand and to prevent fluctuation in steam pressure or water level.

(c). Boiler should have a constant and thorough circulation of water.

(d). It should be equipped with all necessary mountings.

(e). Boiler should have capability to get started quickly from cold.

(f). Its construction should be simple and have good workmanship for the ease of inspection and repairs i.e. easily accessible parts.

(g). Boiler should have its heating surface nearly at right angle to the current of hot gases for good heat transfer.

(h). There should be minimum frictional power loss during low of hot gases and water/steam i.e. pressure drop throughout the system should be minimum.

(i). Tubes should be so designed so as to have minimum soot deposition and good strength against wear. Boiler should have a mud drum to receive all impurities.

(j). Boiler should have strength to withstand excessive thermal stresses.

(k). Boiler should occupy less floor area and space.

For deciding the boiler for any application, generally following criterion are made:

(i). Steam pressure requirement

(ii). Steam temperature requirement

(iii). Steam generation rate

(iv). Initial cost and constraints

(v). Running and maintenance costs

(vi). Availability of fuel and water

(vii). inspection and maintenance requirements

Characteristics	**Fire tube boiler**	**Water tube boiler**
Steam Pressure	It is limited to 20-30 bar. In case of waste heat boilers, it can be more.	It is virtually unlimited within metallurgical and design limits.
Unit output	Limited to about 20 MW. Within design limits.	It is virtually unlimited.
Fuel	All commercial fuels and treated waste can be used.	Any fuel can be used. Also, the furnace size is large.
Erection	It is package ready for work site.	It is to be shop assembled or erected at site.
Efficiency	Normally 80-85% gross calorific value but can be further increased using accessories.	Normally 8-90%. Gross calorific but can be further increased using accessories.
Application	Generally, for heat supply.	Generally, for power and heat supply together.
Inspection requirement	Frequent inspection requirement. It is more than in water tube.	Inspection requirement is less than in fire tube boiler, boilers.

Electrostatic precipitator

- In 1905, Dr. F.G. Cottrell, Professor of Physical Chemistry at the University of California, conducted a series of laboratory experiments that resulted in the development of the first commercial electrostatic precipitator.

- It was an immediate success and the precipitator soon came to be widely used in power plants, smelters, steel plants, paper mills and many other industries.

The principal components of an electrostatic precipitator (ESP) are two sets of electrodes insulated from each other. The first set is composed of rows of electrically grounded vertical parallel plates, called the collection electrodes, between which the dust-laden gas flows. The second set of electrodes consists of wire, called the discharge or emitting electrodes that are centrally located between each pair of parallel plates.

Ash handling system:

- Boilers burning pulverized coal (PC) have dry bottom furnaces. The large ash particles are collected under the furnace in a water-filled ash hopper.
- Fly ash is collected in dust collectors with either an electrostatic precipitator or a baghouse.

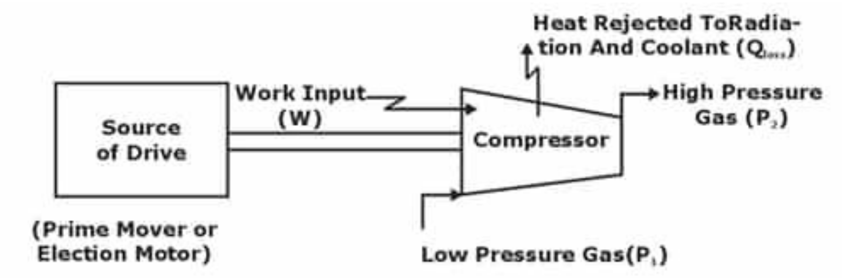
BOILER DRAUGHT

- Draught refers to the pressure difference created for the flow of gases inside the boiler.
- Boiler unit has a requirement of the expulsion of combustion products and supply of fresh air inside furnace for continuous combustion. The obnoxious gases formed during combustion should be discharged at such a height as will render the gases unobjectionable.
- A chimney of stack is generally used for carrying these combustion products from inside of boiler to outside, i.e. draught is created by use of chimney.

Compressor

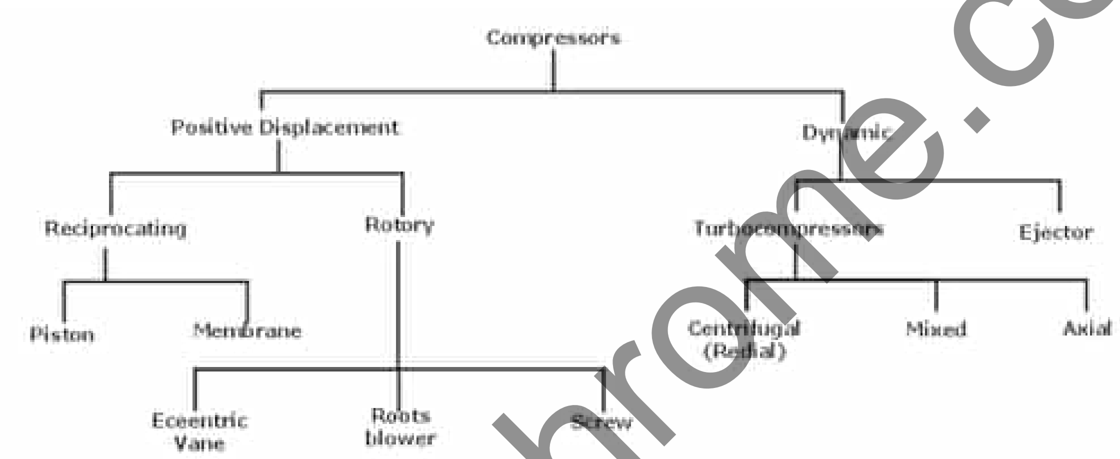
Compressor: Compressors are power-consuming thermodynamic devices that convert mechanical energy into head or pressure energy. The function of a compressor is to compress the gases and vapors from low pressure to high pressure.

According to the Second Law of Thermodynamics, this is only possible when the work is done on the gas by an external agency, such as prime movers, electric motors, etc.



Classification of Compressors

On the basis of design and principles of operation



On the basis of final pressure

1. Low-pressure compressors - final pressure does not exceed 10 bar.
2. Medium pressure compressors – final pressure with a 'range 10 bar to 80 bar.
3. High-pressure compressor - final pressure with a range 80 to 1000 bar.

On the basis of pressure rise limit

1. Fan, Pressure ratio <1.1.
2. Blower, Pressure ratio >1.1<2.3.
3. Compressor, Pressure ratio >2.3

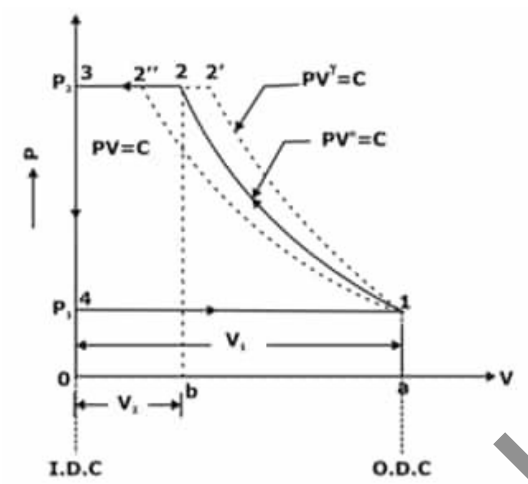
Reciprocating compressors:

- In this compressor, the gas volume decreases, and pressure increases due to the action of one or more reciprocating piston moving axially in one or more cylinders.

- It may he single acting or double acting, single cylinder or multi cylinder, single stage, or multi-stage.
- It is widely used. in the refrigeration system such as freeze, air conditioner and cold storage, mining works, chemical factories, fertilizers factories, garages etc.

Single Stage Reciprocating Compressor Without Clearance:

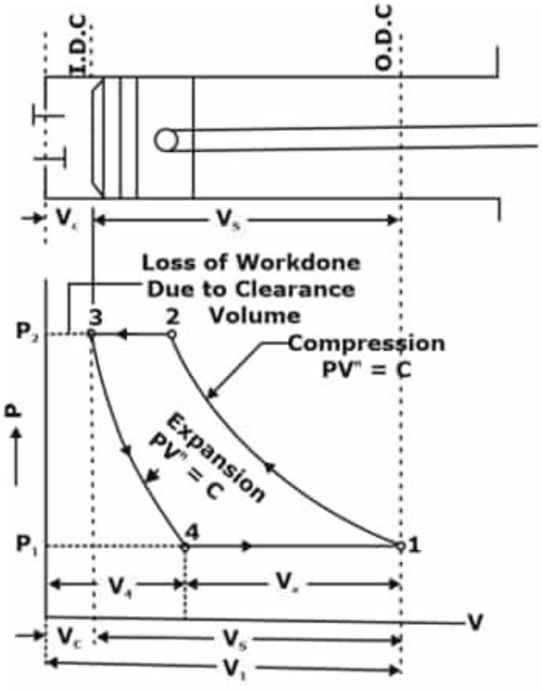
Consider a single-stage, single acting, ideal reciprocating compressor having no flow resistance at suction or delivery valve, no clearance.



$$-W = \frac{n}{n-1}P_1V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] = \frac{n}{n-1}mRT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] = \frac{n}{n-1}(P_2V_2 - P_1V_1)$$

Single Stage Compressor with Clearance:

In actual compressor there is a small clearance between the cylinder head and piston for thermal expansion, machine tolerance and for preventing the piston striking the cylinder head.



$$-W = \frac{n}{n-1} m_a R T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

Clearance volume: It is the volume occupied by the cylinder head and piston when the piston is at the top (i.e. at the inner dead center).

Swept or displacement volume: The displacement volume or swept volume V_s is defined as the volume swept by the piston in one stroke.

The clearance ratio, C is defined as the ratio of clearance volume, V_c to the swept volume V_s.

Volumetric Efficiency: The ratio of the actual volume sucked to the volume swept by the piston is known as the volumetric efficiency.

$$\eta_v = \frac{\text{Actual volume sucked per cycle}}{\text{Swept volume per cycle}} = \frac{V_a}{V_s}$$

$$\eta_v = 1 + C - C\left(\frac{P_2}{P_1} \right)^{1/n}$$

Free air delivery (FAD): Delivery volume reduces to 1 bar pressure & 15°C temperature. The Corresponding volume is known as free air delivered. With the use of free air delivered we can compare the handling capacity of different compressors working under different conditions.

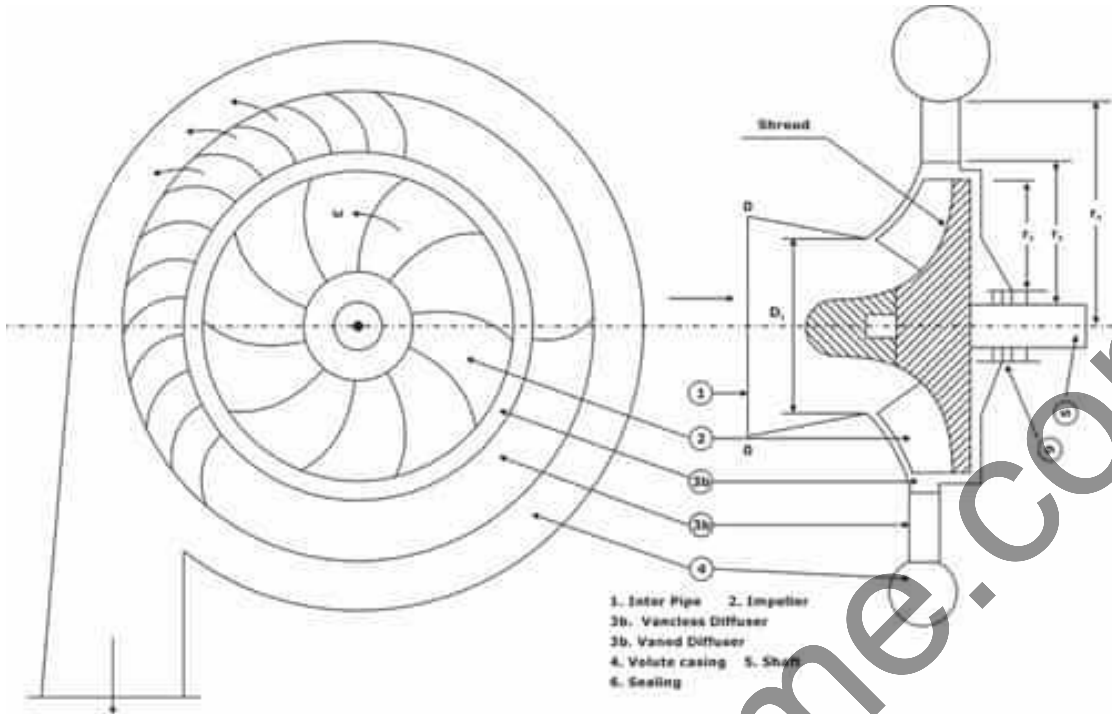
$$\frac{P_1(V_1 - V_4)}{T_1} = \frac{P_2(V_2 - V_3)}{T_2} = \frac{P_F V_F}{RT_F}$$

Rotary Compressors

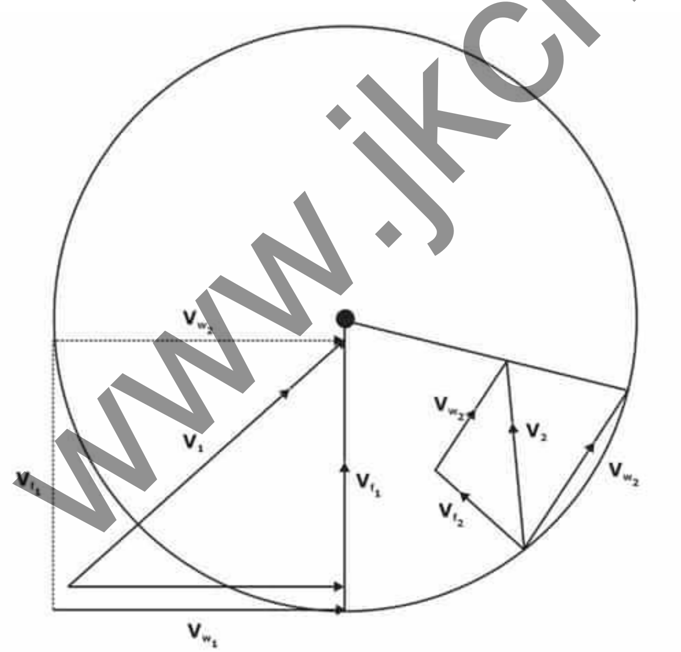
Rotary compressors are compressors gas to high pressure due to a decrease in volume of gas (more specifically due to push and pull of gas or squeezing action of the gas) by the rotary movement of a single rotor or multiple rotors. Rotary compressors are suitable for low compression ratio up to 11 bar and for small and medium amounts of free gas delivered.

Centrifugal compressors: The centrifugal compressor consists of an impeller with a series of curved radial vanes housed in a stationary casing. The impeller imparts a high velocity to the air which firms through fixed divergent passages, in which air is decelerated with a consequent increase in static pressure. The main components of the compressor are:

- inlet pipe
- impeller
- diffuser (vaneless or with vanes)
- volute casing, and
- outlet pipe.



Principle: Let us assume the fluid enters at section (1) & leaving at section (2) at a radius r_1 & r_2. Under equilibrium condition it is running at a constant angular velocity of ω then the absolute velocity component can be resolved into two components i.e.



$V_1 co\alpha$ = whirl component/tangential/component
& $V_1 \sin\alpha$ = Flow component/radial component
Rotor speed at inlet (u_1) = $r_1\omega$
Rotor speed at exit (u_2) = $r_2\ \omega$
Angular momentum at section (1) = mVw_1r_1
Angular momentum at section (2) = $mV_{w2}\ r_2$
Torque = Rate of change of Angular momentum:

$$T = \dot{m}V_{w_2 r_2} - \dot{m}V_{w1}r_1 = \dot{m}\left[V_{w2}r_2 - V_{w1}r_1\right]$$

For Compressor or pump because outlet fluid is having more energy as compare to inlet

$$\text{power}, P = T \times \omega$$

$$P = \left(\dot{m}V_{w_2}r_2 - \dot{m}V_{w1}r_1\right)\omega$$

$$P = \dot{m}\left[V_{w2}r_2\omega - V_{w1}r_1\omega\right]$$

$$\text{Euler power} = P = \dot{m}\left[V_{w2}u_2 - V_{w1}u_1\right]\text{watt}$$

Velocity triangles at inlet and outlet: Let us assume α is a nozzle angle or the absolute velocity angle at the inlet.
β: Absolute velocity angle at outlet/diffuser inlet angle.
θ & ϕ are the moving blade angle at inlet & outlet.
V_r: Relative Velocity: It is the velocity of water along the surface of the vane.

$$V_{w_2}u_2 - V_{w_1}u_1 = \frac{V_2^2 - V_1^2}{2} + \frac{u_2^2 - u_1^2}{2} + \frac{V_{r_1}^2 - V_{r_2}^2}{2}$$

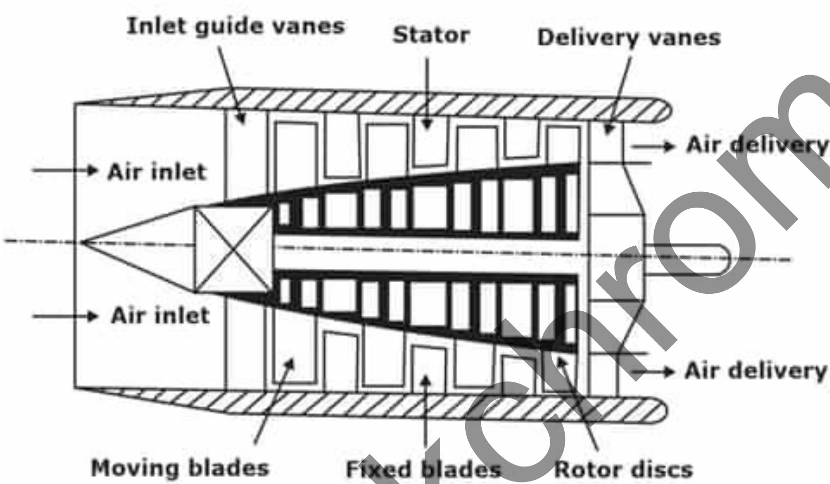
$\frac{V_2^2 - V_1^2}{2}$: is termed as impulse effect. It represents the increases in K.E. of the working fluid that needs to be converted into pressure rise in the diffuser.

$\frac{u_2^2 - u_1^2}{2}$: Centrifugal effect: It represents the rise in pressure in working fluid as fluid enters at a smaller diameter & leaving at a larger diameter.

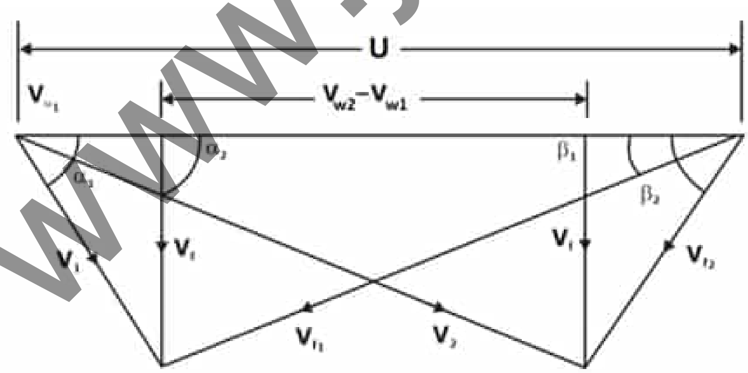
$\frac{V_{r1}^2 - V_{r2}^2}{2}$: Reaction or diffusion effect: It represents the rise in static pressure as the flow is taken place in diverging passage due to which its relative velocity decreases from inlet-outlet.

Axial flow compressors

- The axial flow compressor is more efficient and is usually preferred for bigger units with high-pressure ratios applications such as industrial and large gas turbine plants.
- Although some units may have two or more centrifugal compressors with intercooling between stages.



Velocity triangle for the rotor and stator of an axial flow compressor



Degree of Reaction: It is defined as the ratio of enthalpy rise across moving blade to the enthalpy rise across the stage.

$$R = \frac{\text{Enthalpy rise in rotor}}{\text{Enthalpy rise in the stage}} = \frac{\Delta h_r}{\Delta h_r + \Delta h_s} = \frac{\Delta T_r}{\Delta T_r + \Delta T_s}$$

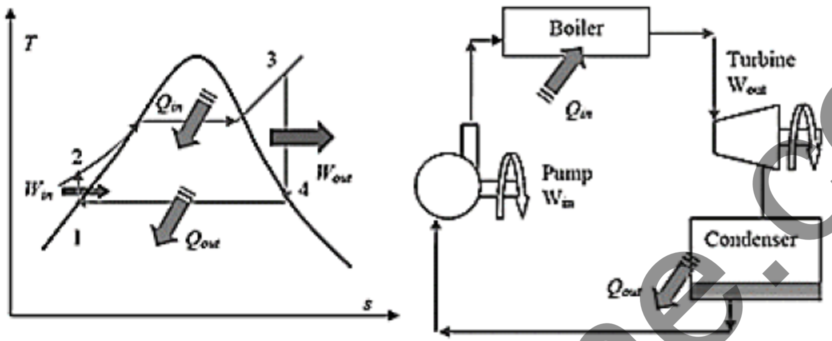
Comparison between Centrifugal and Reciprocating Compressors

Reciprocating	**Centrifugal**
(i) Presence of reciprocating masses makes the machine unbalanced and hence vibration problems are greater.	(i) Absence of reciprocating masses makes the machine better balanced.
(ii) Presence of numerous sliding or bearing members lowers its mechanical efficiency.	(ii) Absence of numerous sliding or bearing members improves its mechanical efficiency.
(iii) Higher installation cost.	(iii) Lower installation cost.
(iv) Pressure ratio per stage is high, about 5 to 8.	(iv) Pressure ratio per stage is about 3 to 4.5.
(v) Capability of delivering high pressure. By multi staging, high delivery pressure up to 5000 atm may be achieved.	(v) Capable of delivering medium pressure. By multistage, the delivery pressure up to 400 atm may be achieved.
(vi) Capable of delivering small volume. By using multi-cylinder, the volume may be increased	(vi) Capable of delivering greater volumes per unit of building space.
(vii) Greater flexibility in capacity and pressure range	(vi) No flexibility in capacity and pressure range.
(viii) Higher maintenance expense.	(viii) Lower maintenance expense.
(ix) Higher compression efficiency at compression ratio above 2.	(ix) Higher compression efficiency at compression ratio less than 2.
(x) There is always a chance of mixing working fluid with lubricating oil.	(x) No chance of mixing of working fluid with lubricating oil.
(xiv) Suitable for low, medium, and high pressure and low and medium gas volumes.	(xiv) Suitable for low and medium pressure and large gas volumes.

IMPORTANT FORMULAS TO REMEMBER

POWER PLANT ENGINEERING

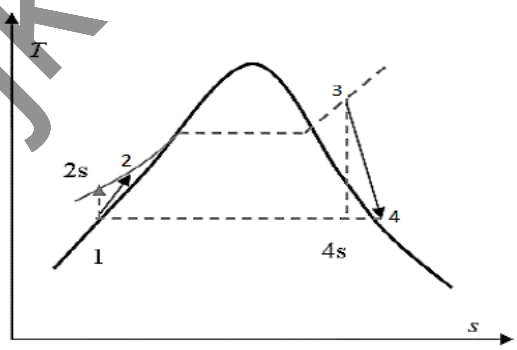
1. RANKINE CYCLE



The ideal Rankine cycle.

Pump	$q = 0$	$w_{pump,in} = h_2 - h_1$
Boiler	$w = 0$	$q_{in} = h_3 - h_2$
Turbine	$q = 0$	$w_{turbine,out} = h_3 - h_4$
Condenser	$w = 0$	$q_{out} = h_4 - h_1$

$$\eta_R = \frac{\text{net work output}}{\text{heat supplied to the boiler}} = \frac{(h3 - h4) - (h2 - h1)}{(h3 - h2)}$$



$$\text{Isentropic efficiency of pump}(\eta_{pump}) = \frac{\text{Isentropic work}}{\text{Actual work}} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

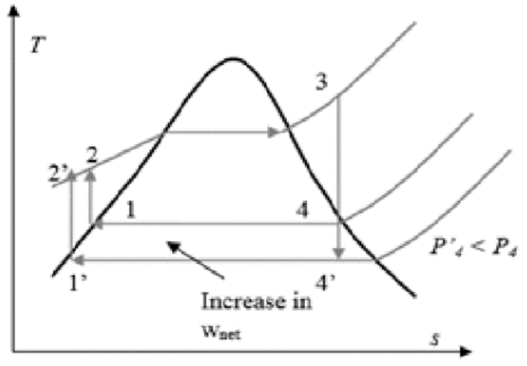
$$\text{Isentropic efficiency of turbine}(\eta_{turbine}) = \frac{\text{Actual work}}{\text{Isentropic work}} = \frac{h_3 - h_4}{h_3 - h_{4s}}$$

1.1. METHODS OF INCREASING THE EFFICIENCY OF RANKINE CYCLE

$$\eta \propto 1 - \frac{T_L}{T_H}$$

1.1.1. Decreasing the of Condenser Pressure

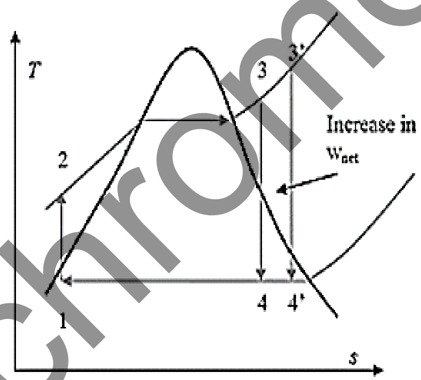
- Mean temperature of heat rejection in the condenser decreases. Thus, the thermal efficiency of the cycle will be increased.



Effect of lowering the condenser pressure on ideal Rankine cycle.

1.1.2. Superheating the Steam to High Temperature

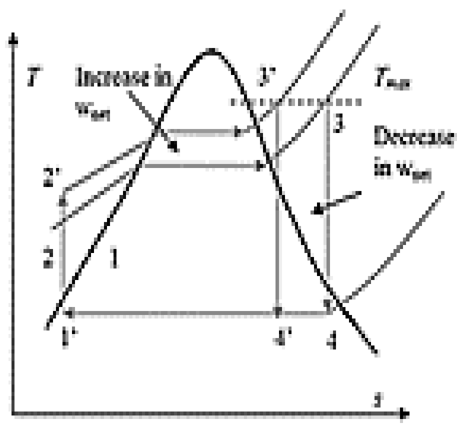
- Superheating the steam will increase the network output and the efficiency of the cycle. It also decreases the moisture contents of the steam at the turbine exit.



The effect of Superheating on the ideal Rankine cycle.

1.1.3. Increasing the Boiler Pressure

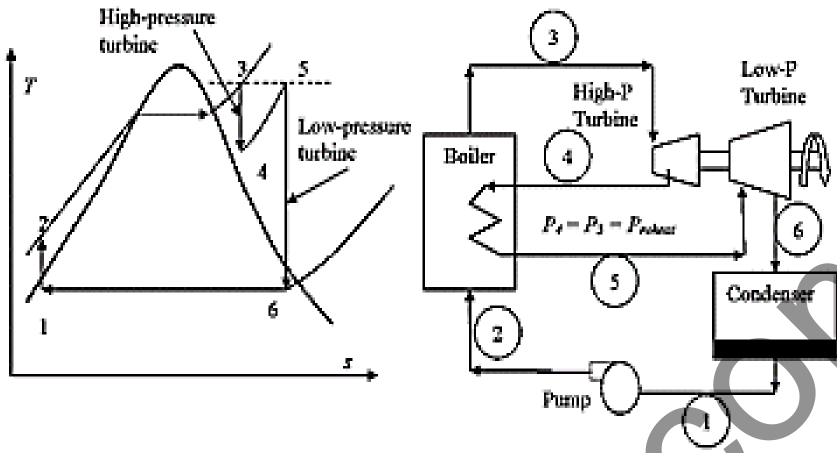
- Mean temperature of heat addition increases hence thermal efficiency increases.



The effect of increasing the boiler pressure on the ideal cycle.

1.2. IDEAL REHEAT RANKINE CYCLE

- To take advantage of the increased efficiencies at higher boiler pressure without facing the excessive moisture content at final stages of the turbine, reheating is used.



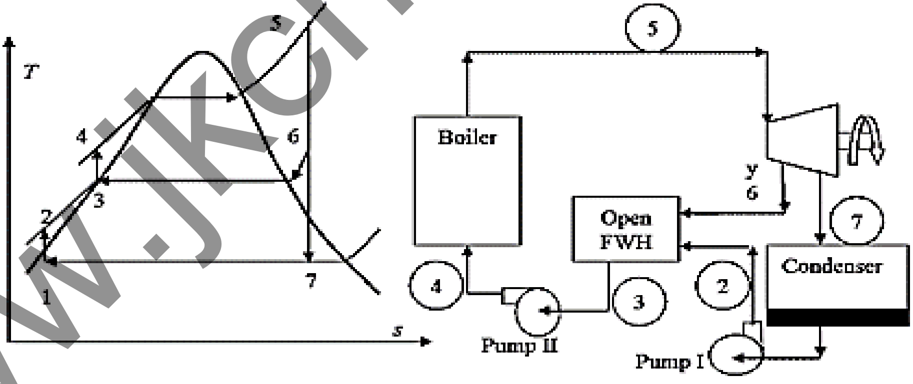
The ideal reheat Rankine cycle.

Heat input= Primary heat+Reheat= $(h_3\text{-}h_2)$+ $(h_5\text{-}h_4)$

$W_{turbine}$= $W_{H\text{-}P\ turbine}$+ $W_{L\text{-}P\ turbine}$= $(h_3\text{-}h_4)$+ $(h_5\text{-}h_6)$

1.3. IDEAL REGENERATIVE RANKINE CYCLE

- The mean temperature of heat addition can also be increased if heat addition at low temperature is avoided such that feed water enters the boiler at saturated liquid condition. The feed water can be brought to saturated condition by internal heating using extracted steam. This concept is known as regeneration.



The ideal regenerative Rankine cycle with an open FWH.

y = amount of bleed from turbine

Q_{in}= $h_5\text{-}h_4$

Q_{out}= (1-y) $(h_7\text{-}h_1)$

$W_{turbine\ out}$= $(h_5\text{-}h_6)$ +(1-y) $(h_6\text{-}h_7)$

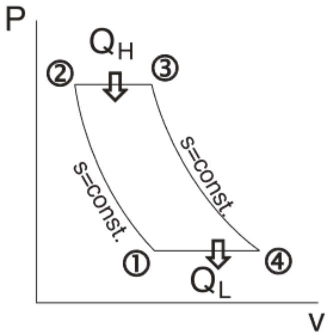
W_{pump}=(1-y) $Wpump_1$+ W_{pump2}

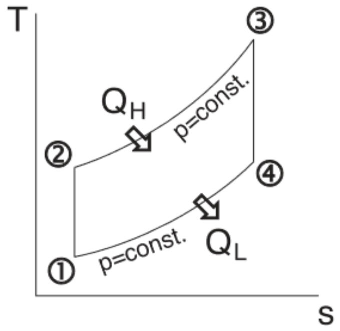
W_{pump1}= $v_1(P_2\text{-}P_1)$ and $Wpump_2$= $v_3(P_4\text{-}P_3)$

v is specific volume at pump inlets

2. GAS TURBINE ENGINE

2.1. Brayton Cycle





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

$r_p = \frac{P_2}{P_1} = \frac{P_3}{P_4}$

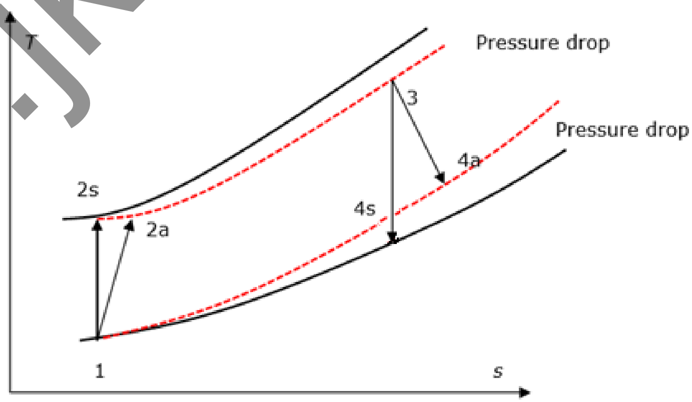
2.1.1. Maximum Pressure Ratio

- $(r_P)_{max} = \left(\frac{T_{max}}{T_{min}}\right)^{\frac{\gamma}{(\gamma-1)}}$
- At maximum pressure ratio the efficiency of brayton cycle is equal to Carnot cycle operating between same temperature limit.
- At maximum pressure ratio the net work is zero.

2.1.2. Optimum Pressure Ratio

- $(r_P)_{opt} = \left(\frac{P_2}{P_1}\right)_{opt} = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}$
- Optimum pressure ratio gives maximum network.

2.1.3. Actual Brayton Cycle



Isentropic efficiency of compressor$(\eta_{compressor}) = \frac{Isentropic\ work}{Actual\ work} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$

Isentropic efficiency of turbine$(\eta_{turbine}) = \frac{Actual\ work}{Isentropic\ work} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$

2.1.4. Work ratio

Work ratio $(r_w) = \frac{Net\ work\ output}{Turbine\ Work}$

2.1.5. Back Work ratio

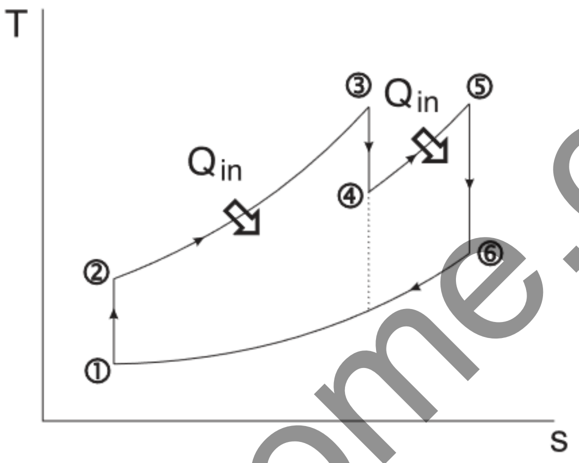
Back work ratio($r_{bw)}$= $\frac{Compressor\ Work}{Turbine\ Work}$

- Back Work Ratio for gas power cycles: 40% - 60%
- Back Work Ratio for vapor power cycles: 1% - 2%

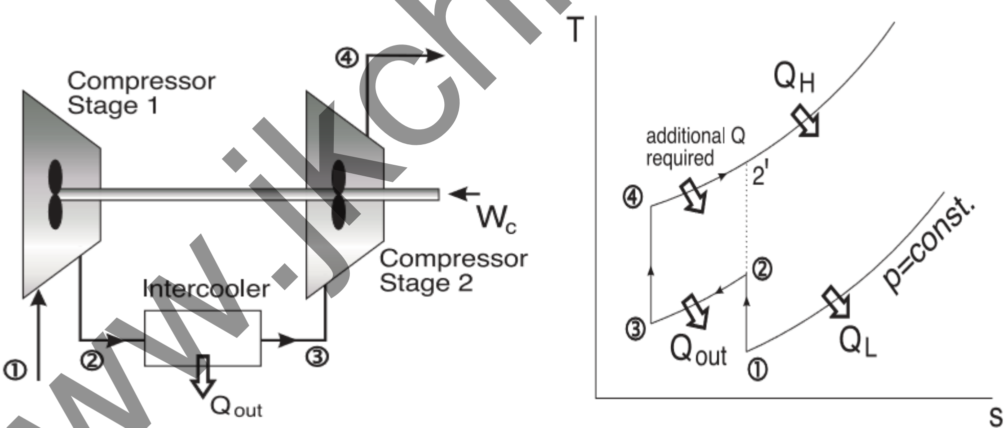
2.1.6. Specific Power

- Specific power =$\frac{Net\ Work}{3600}$ kWh/kg

2.1.7. Brayton Cycle with Reheat



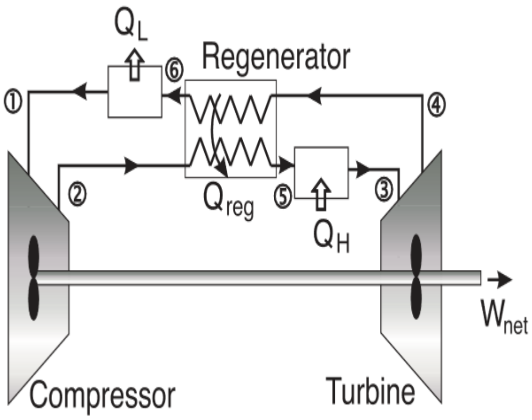
2.1.8. Brayton Cycle with Intercooling

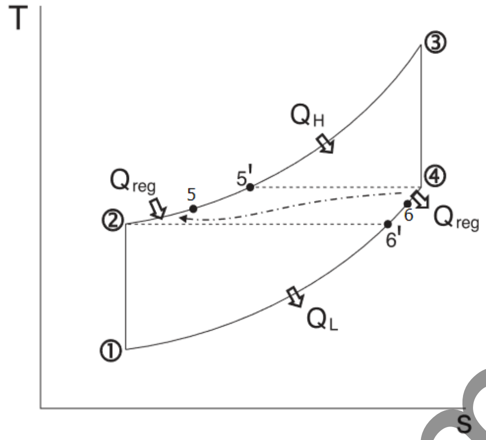


- For perfect intercooling $T_3 = T_1$
- The optimum pressure ratio per stage in case of n stage compression with intercooling

$$(r_P)_{opt} = \left[\frac{P_F}{P_i}\right]^{1/n}$$

2.1.9. Brayton Cycle with Regeneration





$Q_{regen,\text{actual}} = h_5 - h_2$

$Q_{regen,\max} = h_{5'} - h_2 = h_4 - h_2$

$$\in = \frac{Q\ regen,\text{actual}}{Q\ regen,\max} = \frac{h_5 - h_2}{h_4 - h_2} = \frac{T_5 - T_2}{T_4 - T_2}$$

3. POWER PLANT COMPONENTS

3.1 Characteristics of fire tube and water tube boilers:

Characteristics	Fire tube boiler	Water tube boiler
Steam Pressure	It is limited to 20-30 bar. In case of waste heat boilers, it can be more.	It is virtually unlimited within metallurgical and design limits.
Unit output	Limited to about 20 MW. Within design limits.	It is virtually unlimited.
Fuel	All commercial fuels and treated waste can be used.	Any fuel can be used. Also, the furnace size is large.
Erection	It is package ready for work site.	It is to be shop assembled or erected at site.
Efficiency	Normally 80-85% gross calorific value but can be further increased using accessories.	Normally 8-90%. Gross calorific but can be further increased using accessories.
Application	Generally, for heat supply.	Generally, for power and heat supply together.
Inspection requirement	Frequent inspection requirement. It is more than in water tube.	Inspection requirement is less than in fire tube boiler, boilers.

3.2 BOILER MOUNTINGS AND ACCESSORIES

- A boiler other than heat supplying unit, shell and tubes, several other devices are used for its control, safe and efficient operation.

- Devices which are mounted on boiler for ***its control and safe operation are called "mountings"*** while ***devices which are mounted on boiler for improving its performance are called "accessories".*** Thus, boiler mountings are necessary while boiler accessories are optional.

3.3 CIRCULATION

- The flow of water and steam within the boiler circuit is called circulation.
- Adequate circulation must be provided to carry away the heat from the furnace.
- If circulation is caused ***by density difference, the boiler is said to have natural circulation.***
- If it is caused ***by a pump, it has forced*** or controlled circulation.
- There is a term called "circulation ratio" (CR) used in this connection. It is defined as:

$$\text{Circulation ratio} = \frac{\text{Flow rate of saturated water in downcomers}}{\text{Flow rate of steam released from the drum}}$$

A boiler drum is said to be ***"priming" if there is too much moisture carry-over because of a high-water level or a high steaming rate***. Erratic feedwater control and rapid changes in steaming rate can induce priming.

Another phenomenon encountered in the delivery of impure steam is foaming. ***Foaming is a condition resulting from the formation of bubbles on the water surface.*** It is caused by the presence of saponification agents in the boiler water, like oil, certain dissolved salts and high alkalinity.

3.4 BOILER DRAUGHT

- Draught refers to the pressure difference created for the flow of gases inside the boiler.
- Boiler unit has a requirement of the expulsion of combustion products and supply of fresh air inside furnace for continuous combustion. The obnoxious gases formed during combustion should be discharged at such a height as will render the gases unobjectionable. Draught may be created naturally or artificially by using some external device. Draught can be classified as below:

  (a). In this the pressure difference is created naturally without using any positive displacement device.

  (b). Artificial draught is created using some external assistance causing forced displacement of gases. It can be created either by using mechanical devices or steam. Artificial draught can be of induced type, forced type or combination of two types.

Draught

- **(a) Natural draught:** **In this pressure difference is created naturally without using any positive displacement device.**
- **(b) Artificial draught:** **Artificial draught is created using some external assistance causing forced displacement of gases. It can be created either by using mechanical devices or steam. Artificial draught can be further of induced, forced or combination of two types.**
  - **Mechanical draught**
    - **Induced draught**
    - **Forced draught**
    - **Balanced draught**
  - **Steam draught**
    - **Induced draught**
    - **Forced draught**

3.5 EQUIVALENT EVAPORATION

- For comparing one boiler with other any of the above parameters cannot be considered as they are interdependent. Therefore, for comparing the capacity of boilers working at different pressures, temperatures, different final steam conditions etc. a parameter called "equivalent evaporation" can be used.

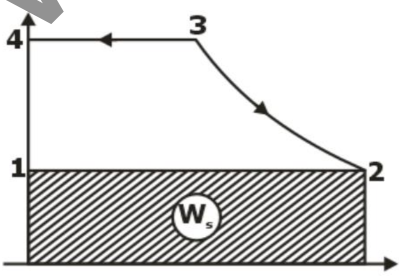
$$\text{Equivalent evaporation} = \frac{\text{Mass of steam generated per hour} \times (\text{Heat supplied to generate steam in boiler})}{\text{Heat supplied for steam generation at } 100^\circ\text{C from water at } 100^\circ\text{C (i.e. Latent heat)}}$$

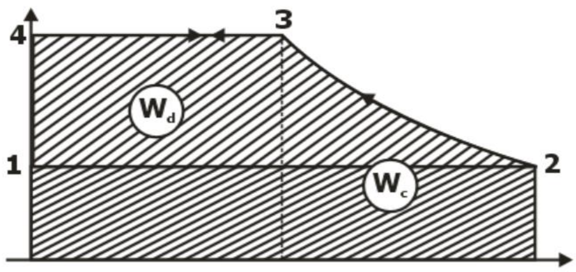
4. AIR COMPRESSOR

- Compressor is a device which is used to compress the gas or vapour from lower to higher pressure and for that work input is required from outside.

4.1. Reciprocating compressor

4.1.1. Work input required (without clearance volume)

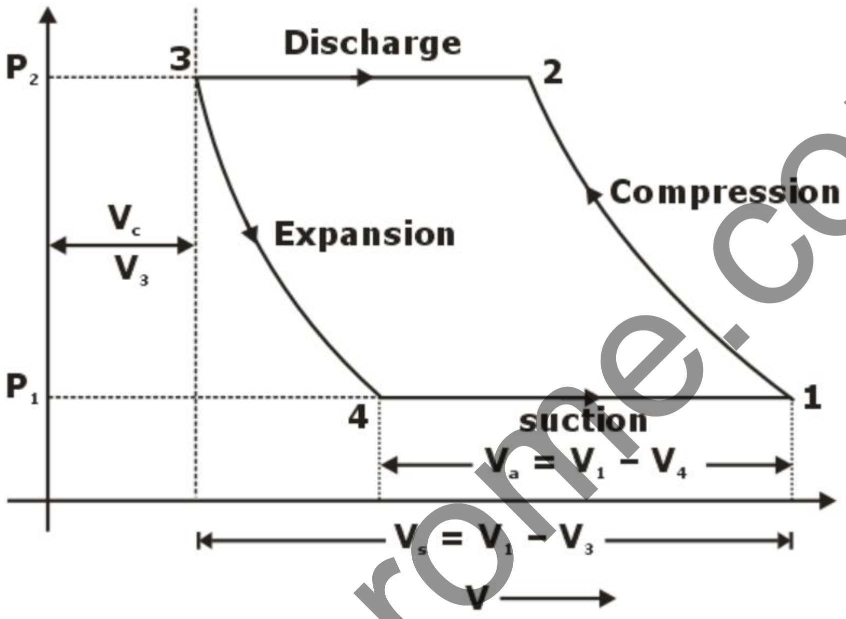




$$W / cycle = \left(\frac{n}{n-1}\right)\left[p_2 v_2 - p_1 v_1\right]$$

$$W / cycle = \left(\frac{n}{n-1}\right) p_1 v_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] \rightarrow kJ / cycle$$

4.1.2. Compressor work input (with clearance volume)



$$W / cycle = \frac{n}{n-1} p_1 \left[v_1 - v_4\right]\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

4.1.3. Volumetric efficiency

$$\eta_{\text{vol}} = \frac{\text{Actual volume}}{\text{Swept volume}}$$

$$\eta_v = 1 + C - C\left(\frac{p_2}{p_1}\right)^{1/n}$$

4.1.4. Multi-stage compression

- The compression is done with multi-stage with intercooling between stages which results in less total compressor work.
- The optimum pressure ratio per stage in case of n stage compression with intercooling

$$(r_P)_{opt} = \left[\frac{P_F}{P_i}\right]^{1/n}$$

- The work done in each stage is same.

5. CENTRIFUGAL COMPRESSOR

- The principal components of centrifugal compressor are impeller and diffuser.
- Forward curved blade consumes maximum power
- Backward curved blade gives best efficiency and are stable for wide operating range.
- Surging is the complete breakdown of steady flow through compressor, due to periodic flow reversal. This reversal of flow occurs during closing of outlet valve, in operating range having flow rate less than corresponding to maximum pressure ratio. This reversal of flow causes abnormal sound, vibration, decrease in efficiency, increase in temp and if the intensity is more it will lead to mechanical damage.
- The maximum mass flow rate possible through compressor is termed as choking. It occurs when the Mach no. corresponding to relative velocity at inlet become sonic. Choking means fixed mass flow rate irrespective of pressure ratio.

  Stalling is an aerodynamic flow separation form the blade surface due to improper design of blade. It is a local phenomenon and chances of flow separation are more at low mass flow rate, non-uniform surface, improper design of blades and higher no. of diffuser blades.

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