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New Scheme Based On AICTE Flexible Curricula

Mechanical Engineering, VI-Semester

ME- 601 Thermal Engineering and Gas Dynamics

Unit 1: Steam generators and boilers

Steam generators: classification, conventional boilers, high-pressure boilers-Lamont, Benson, Loeffler and Velox steam generators, performance and rating of boilers, equivalent evaporation, boiler efficiency, heat balance sheet, combustion in boilers, super critical boilers, fuel and ash handling, boiler draught, overview of boiler codes.

Unit 2 : Vapour Cycles

Phase Change Cycles: Vapor Carnot cycle and its limitation, Rankin cycle, effect of boiler and Condenser pressure and superheat on end moisture and efficiency of ranking cycle, modified Rankin cycle, reheat cycle, perfect regenerative cycle, Ideal and actual regenerative cycle with single and multiple heaters, open and closed type of feed water heaters, regenerative-reheat cycle, supercritical pressure and binary-vapor cycle, work done and efficiency calculations.

Unit 3: Gas Dynamics

Gas dynamics: speed of sound, in a fluid mach number, mach cone, stagnation properties, one dimensional isentropic flow of ideal gases through variable area duct-mach number variation, area ratio as a function of mach number, mass flow rate and critical pressure ratio, effect of friction, velocity coefficient, coefficient of discharge, diffusers, normal shock.

Unit 4: Air Compressors

Air compressors: working of reciprocating compressor, work input for single stage compression different, compression processes, effect of clearance, volumetric efficiency real indicator diagram, isentropic & isothermal and mechanical efficiency, multi stage compression, inter - cooling, condition for minimum work done, classification and working of rotary compressors.

Unit 5: Nozzles and Condensers

Steam nozzles: isentropic flow of vapors, flow of steam through nozzles, condition for maximum discharge, effect of friction, super-saturated flow. Steam condensers, cooling towers: introduction, types of condensers, back pressure and its effect on plant performance air leakage and its effect on performance of condensers, various types of cooling towers.

References:

1. Arasu Valan A; Thermal Engineering; TMH
2. Nag PK; Basic and applied Thermo-dynamics; TMH
3. Nag PK; Power plant Engineering; TMH
4. Rathakrishnan E; Gas Dynamics; PHI Learning
5. Balachandran P; Gas Dynamics for Engineers; PHI Learning
6. Yahya SM; Fundamentals of Compressible flow; New Age
7. Gordon J. Van Wylen; Thermodynamics
8. R.Yadav Thermal Engg.
9. Kadambi & Manohar; An Introduction to Energy Conversion – Vol II. Energy conversion cycles

List of Experiments (Please Expand it) (Thermal Engg and gas dynamics):

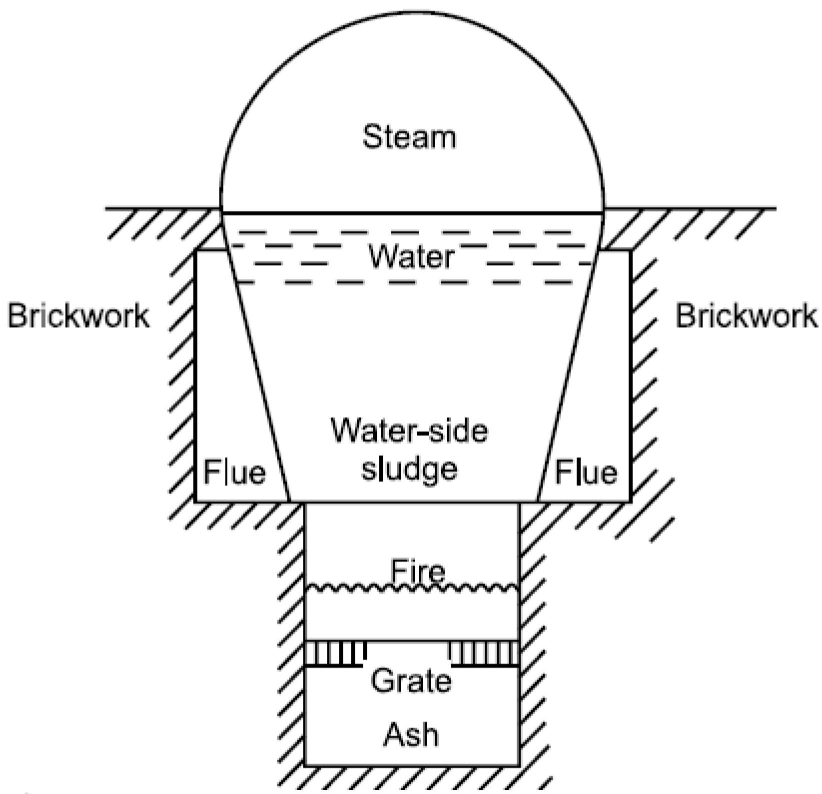
1. Study of working of some of the high pressure boilers like Lamont or Benson
2. Study of Induced draft/forced and balanced draft by chimney
3. Determination of Calorific value of a fuel
4. Study of different types of steam turbines

5. Determination of efficiencies of condenser
6. Boiler trail to chalk out heat balance sheet
7. Determination of thermal efficiency of steam power plant
8. Determination of Airflow in ducts and pipes.
9. To find out efficiencies of a reciprocating air compressor and study of multistage Compressors
10. Find Out heat transfer area of a parallel flow/counter flow heat exchanger

Unit -1
Steam Generators

INTRODUCTION

Steam is extensively used for various applications such as power production, industrial processes, work interaction, heating etc. With the increasing use of steam in different engineering systems the steam generation technology has also undergone various developments starting from 100 B.C. when Hero of Alexandria invented a combined reaction turbine and boiler. Boiler, also called steam generator is the engineering device which generates steam at constant pressure. It is a closed vessel, generally made of steel in which vaporization of water takes place. Heat required for vaporization may be provided by the combustion of fuel in furnace, electricity, nuclear reactor, hot exhaust gases, solar radiations etc. Earlier boilers were closed vessels made from sheets of wrought iron which were lapped, riveted and formed into shapes of simple sphere type or complex sections such as the one shown in Fig. It is the 'Wagon boiler' of Watt developed in 1788.



***Wagon boiler of Watt*, (1788)**

According to A.S.M.E. (American Society of Mechanical Engineers, U.S.A.) code a boiler is defined as a combination of apparatus for producing, furnishing or recovering heat together with the apparatus for transferring the heat so made available to water which could be heated and vaporized to steam form.

TYPES OF BOILERS

Boilers are of many types. Depending upon their features they can be classified as given under:

(a) Based upon the orientation/axis of the shell: According to the axis of shell boiler can be classified as vertical boiler and horizontal boiler.

(i) *Vertical boiler* has its shell vertical.

(ii) *Horizontal boiler* has its shell horizontal.

(iii) *Inclined boiler* has its shell inclined.

(b) Based upon utility of boiler: Boilers can be classified as

(i) *Stationery boiler*, such boilers are stationery and are extensively used in power plants, industrial processes, heating etc.

(ii) *Portable boiler*, such boilers are portable and are of small size. These can be of the following types,

Locomotive boiler, Marine boiler.

(c) Based on type of firing employed: According to the nature of heat addition process boilers can be classified as,

(i) Externally fired boilers, in which heat addition is done externally i.e. furnace is outside the boiler unit, such as Lanchashire boiler, Locomotive boiler etc.

(ii) Internally fired boilers, in which heat addition is done internally i.e. furnace is within the boiler unit, such as Cochran boiler, Bobcock Wilcox boiler etc.

(d) Based upon the tube content: Based on the fluid inside the tubes, boilers can be,

(i) *Fire tube boilers*, such boilers have the hot gases inside the tube and water is outside surrounding them. Examples for these boilers are, Cornish boiler, Cochran boiler, Lancashire boiler, Locomotive boiler etc.

(ii) *Water tube boilers*, such boilers have water flowing inside the tubes and hot gases surround them. Examples for such boilers are Babcock-Wilcox boiler, Stirling boiler, La-Mont boiler, Benson boiler etc.

(e) Based on type of fuel used: According to the type of fuel used the boilers can be,

(i) *Solid fuel fired boilers*, such as coal fired boilers etc.

(ii) *Liquid fuel fired boilers*, such as oil fired boilers etc.

(iii) *Gas fired boilers*, such as natural gas fired boilers etc.

(f) Based on circulation: According to the flow of water and steam within the boiler circuit the boilers may be of following types,

(i) *Natural circulation boilers*, in which the circulation of water/steam is caused by the density difference which is due to the temperature variation.

(ii) *Forced circulation boilers*, in which the circulation of water/steam is caused by a pump i.e. externally, assisted circulation

(g) Based on extent of firing: According to the extent of firing the boilers may be,

(i) *Fired boilers*, in which heat is provided by fuel firing.

(ii) *Unfired boilers*, in which heat is provided by some other source except fuel firing such as hot flue gases etc.

(iii) *Supplementary fired boilers*, in which a portion of heat is provided by fuel firing and remaining by some other source.

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.

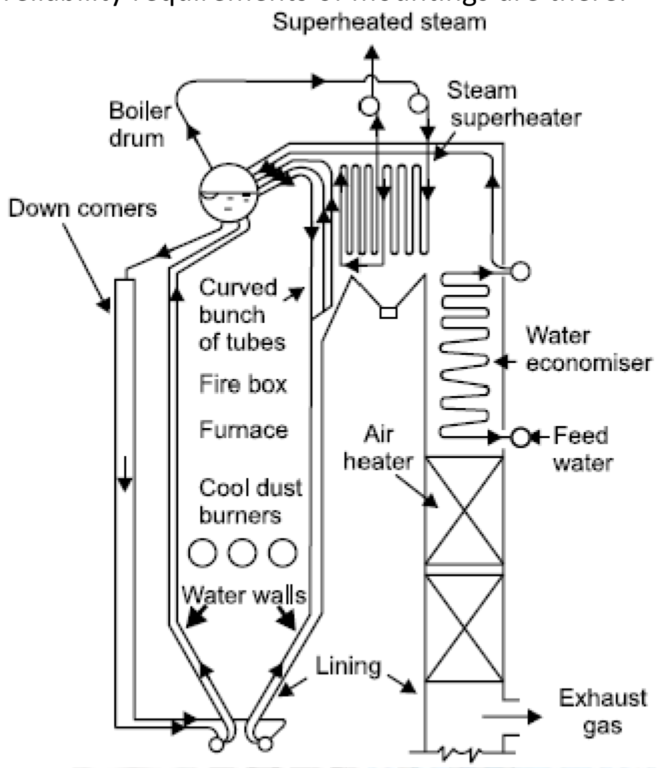
(a) It should be capable of generating steam at desired rate at desired pressure and temperature with minimum fuel consumption and cost.
(b) It should have sufficient steam and water storage capacity to meet fluctuation in demand and to prevent fluctuation in steam pressure or water level.
(c) Boiler 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 flow 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.

Boilers may be selected for a particular applications considering above general requirements and constraints, if any. 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

HIGH PRESSURE BOILER

High pressure boilers generally operate in supercritical range. Need of such boilers is felt because high pressure and temperature of steam generated in boiler improves plant efficiency. These boilers have forced circulation of water/steam in the boiler. This forced circulation is maintained by employing suitable pump. The steam drum is of very small size and in some cases it may be even absent too. This
is because of using forced circulation. In case of natural circulation drum size has to be large. Schematic of high pressure boiler is shown in figure. In fact the high pressure boilers have been possible because of availability of high temperature resistant materials. Here direct heating of water tubes is done by the excessively hot gases present in fire box. The fire box has large volume as otherwise exposed water tubes shall melt. Heat is picked by number of parallel tubes containing water. These parallel tubes appear as if it is a wall due to close spacing of tubes. Water circulation circuit is shown in line diagram. High pressure boilers may have natural circulation in case the steam pressure desired lies between 100 and 170 bar and size is not

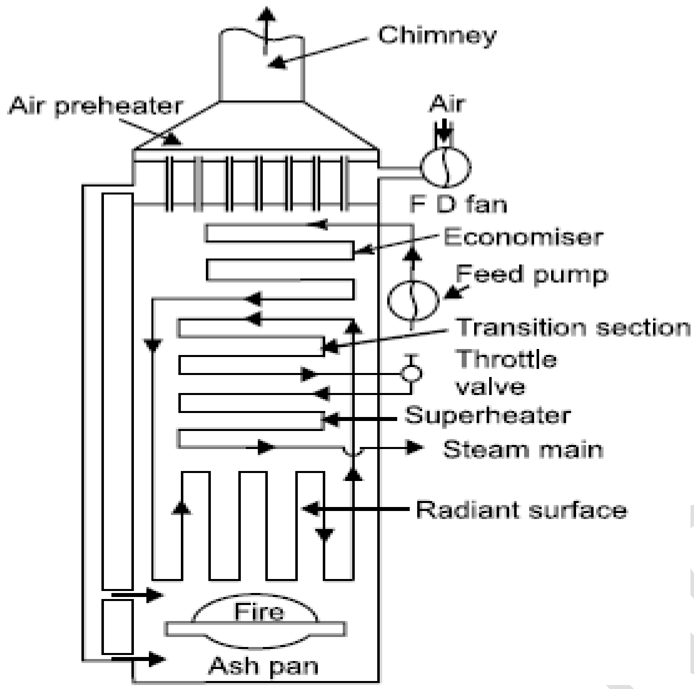
constraint. High pressure boilers have capability of generating larger quantity of steam per unit of furnace volume. High pressure boilers are disadvantageous from safety point of view and therefore, stringent reliability requirements of mountings are there.



High pressure boiler with natural circulation

BENSON BOILER

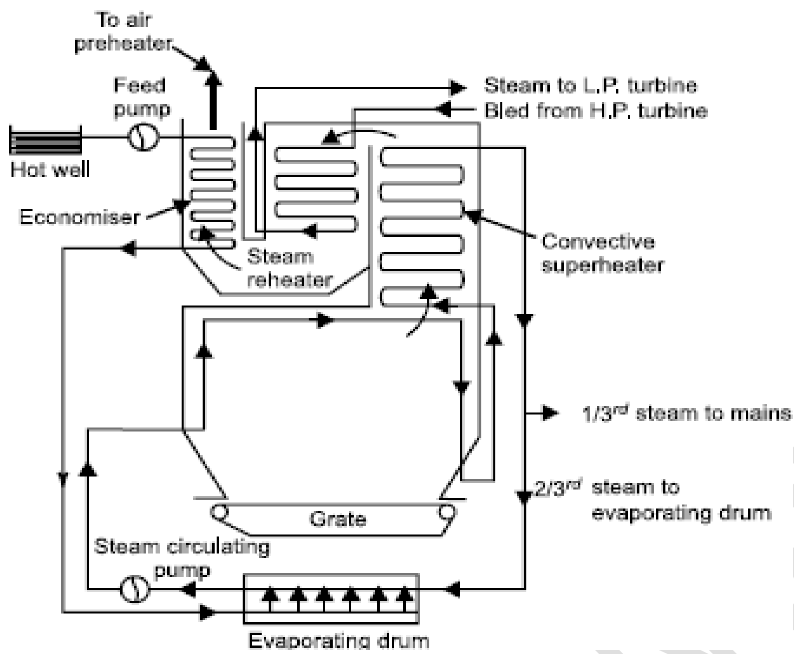
It is a water tube boiler capable of generating steam at supercritical pressure. Figure. show the schematic of Benson boiler. Mark benson, 1992 conceived the idea of generating steam at supercritical pressure in which water flashes into vapour without any latent heat requirement. Above critical point the water transforms into steam in the absence of boiling and without any change in volume i.e. same density. Contrary to the bubble formation on tube surface impairing heat transfer in the normal pressure boilers, the supercritical steam generation does not have bubble formation and pulsations etc. due to it. Steam generation also occurs very quickly in these boilers. As the pressure and temperatures have to be more than critical point, so material of construction should be strong enough to withstand thermal stresses. Feed pump has to be of large capacity as pressure inside is quite high, which also lowers the plant efficiency due to large negative work requirement. Benson boilers generally have steam generation pressure more than critical pressure and steaming rate of about 130–135 tons/hr. Thermal efficiency of these boilers is of the order of 90%.



Benson boiler

LOEFFLER BOILER

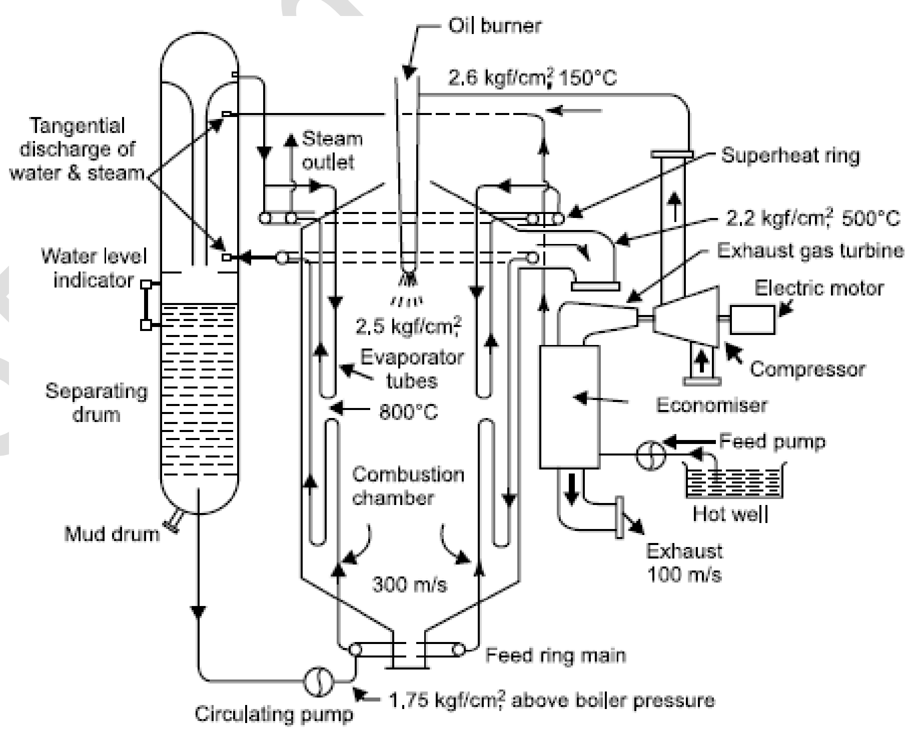
This a forced circulation type boiler having both direct and indirect type of heat exchange between superheated steam/water and hot gases/steam respectively. Schematic arrangement of a Loeffler boiler is shown in Fig. Here the hot combustion gases emerging out of furnace are firstly used for superheating of steam and secondly for reheating/economiser sections. Steam generation is realized through the superheated steam being injected into evaporator drum. Saturated steam thus generated in evaporator drum as a result of mixing of superheated steam and water is picked up by steam circulation pump. This pump forces saturated steam at high pressure through superheater tubes where the hottest flue gases from furnace superheat steam coming from evaporator. Flue gases subsequently pass through reheated/economizer sections as shown. Superheated steam coming out of superheater section is partly taken out through steam main and remaining is injected into evaporator rum. Generally superheated steam is divided in proportion of 1 : 2 for steam main and evaporator drum respectively. Feed water to the boiler is pumped by feed pump through the economiser section to evaporator drum. Generally steam generated is at pressure of about 120 bar and temperature of 500 C.



Schematic arrangement in Loeffler Boiler

VELOX BOILER

Velox boiler is a fire tube boiler having forced circulation. Boiler has gas turbine, compressor, generator, feed pump, circulation pump etc. as its integral components. Thus Velox boiler unit is a compact steam generating plant. Figure shows the line diagram of Velox boiler unit. Boiler unit has a compressor supplying high pressure air at about 3 bar into the oil burner so as to produce combustion products at high pressure and thus have hot flue gases flowing through fire tubes at very high velocity of the order of supersonic velocity. Flue gases flowing at supersonic velocity

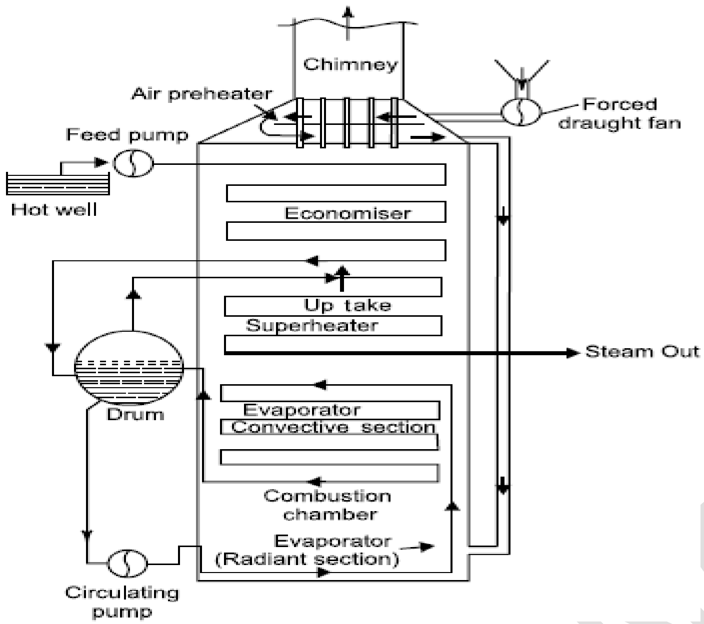


Velox boiler unit

facilitate very high rate of heat interaction between two fluids, generally of the order of 2 - 107 kcal/m3 of combustion volume. Combustion space is lined with concentric vertical tubes having hot flue gases passing through the inner tube and water surrounding it in outer tube. Hot flue gases pass through superheater section and subsequently enter into gas turbine for its expansion. Gas turbine drives the compressor used for producing compressed air. Expanded gases coming out of gas turbine at about 100–125 m/sec enter into economiser where feed water picks up heat from gas turbine exhaust. Hot feed water coming out of economiser is sent into steam/water drum from where water is circulated through vertical concentric tubes using a circulating pump. During the water flow in combustion volume space it partially gets transformed into steam and the mixture is injected tangentially into drum. Tangential discharge of mixture forms a circulatory flow (vortex) causing steam release due to centrifugal action, thus separation of water/steam. Steam is subsequently passed through superheater section while water is again circulated using circulation pump. Steam passes through steam headers after superheating. Surplus energy, if any in gas turbine is used by alternator attached to it which supplements the electricity requirement in various auxiliary devices. Velox boilers are very flexible and capable of quick starting. Overall efficiency of the boiler unit is about 55–60%. Boiler is capable of handling maximum of 100 tons/hr water which is limited by the limitation of maximum power requirement in compressor

LA MONT BOILER

This is a water tube boiler having forced circulation. Schematic showing the arrangement inside boiler is given in Fig. Boiler has vertical shell having three distinct zones having water tubes in them, namely evaporator section, superheater section and economiser section Feed water is fed from feed pump to pass through economiser tubes. Hot water from economizer goes into drum from where hot feed water is picked up by a circulating pump. Centrifugal pump may be steam driven or of electric driven type. Pump increases pressure and water circulates through evaporation section so as to get converted into steam and enters back to drum. Steam available in drum enters into superheater tubes and after getting superheated steam leaves through steam main.



BOILER MOUNTINGS AND ACCESSORIES

Boiler mountings and accessories have been defined earlier and shown on the different boilers. Different mountings are

(i) Water level indicator
(ii) Safety valves
(iii) High steam and low water safety valves
(iv) Fusible plug
(v) Pressure gauge
(vi) Stop valve
(vii) Feed check valve
(viii) Blow off cock
(ix) Manhole and mud box

Various boiler accessories are:

(i) Superheater
(ii) Economiser
(iii) Air preheater
(iv) Feed pump

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 an height as will render the gases unobjectionable. A chimney or stack is generally used for carrying these combustion products from inside of boiler to outside, i.e. draught is created by use of chimney. Draught may be created naturally or artificially by using some external device. Draught can be classified as below:

- In this the pressure difference is created naturally without using any positive displacement device.

- 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.

Thus the draught in boiler may be said to be required for, providing and maintaining the supply of sufficient air for combustion expulsion of combustion products from furnace region' and 'discharge of burnt gases to atmosphere. The amount of draught required shall depend upon, 'type of boiler', 'rate of fuel burning rate at which combustion products are produced' and 'the air requirement rate. As the pressure difference is very small so draught is measured in 'mm' of water. Mathematically, pressure due to 1 mm of water column is equivalent to 1 kgf/m2.

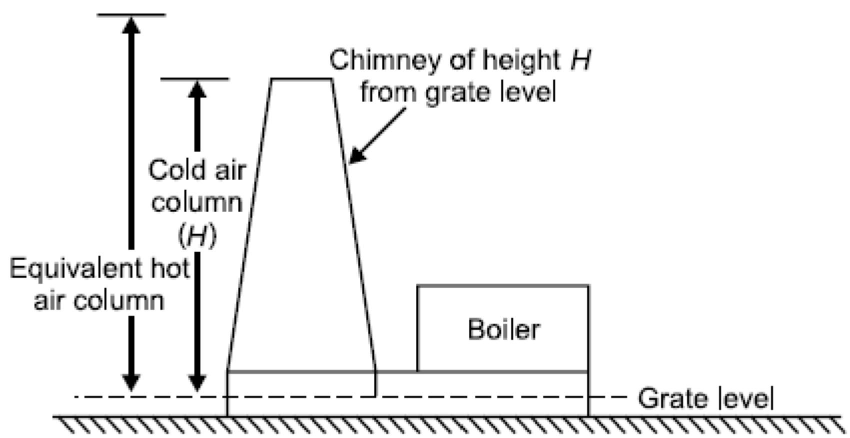
Draught
- (a) Natural draught : In this the pressure difference is created naturally without using any positive displacement device.
- (b Artificial draught: Artificial draught is created using some external assistance causing forced displacement of gases. It can be created either by using mechanical 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

NATURAL DRAUGHT

It is produced employing chimney. The natural draught is produced by a chimney due to the fact that the hot gases inside the chimney are lighter than the outside cold air i.e. density difference of hot gases inside chimney and cold atmospheric air. Thus in a boiler unit the combustion products (hot) rise from fuel bed through chimney, and are replaced by fresh air (cold) entering the grate. It means that amount of draught produced by a chimney depends upon flue-gas temperature. Intensity of draught produced by chimney also depends upon height of chimney. Draught produced by a taller chimney is large as the difference in weight between the column of air inside and that of air outside increases with height. Generally draught is less than 12 kgf/m^2 in chimneys.

In stricter terms the word 'chimney' is used for brick or concrete structure and 'stack' is used for metallic one. Chimneys are generally made of steel, brick or reinforced concrete. Steel chimneys or stacks are most desirable for smaller boiler units due to small initial cost, ease of construction and erection. On account of small space requirement as compared to other stacks, self sustaining steel stacks are used in some large power plants. Steel stacks have problem of rust and corrosion, so painting requirements are quite stringent. Brick chimneys are required where permanent chimney with longer life is required. Such chimneys have inherent disadvantages of leakages etc. across the construction, therefore careful construction is required. Leakage of air across chimney wall effects intensity of draught. Brick chimneys are constructed of round, octagonal, or square section. Generally brick chimney has two walls with air space between them and inner wall having fire brick lining. Concrete chimneys are used due to the absence of joints, light weight and space economy as compared with brick chimneys. Also the reinforced concrete chimney is less expensive compared to brick chimney along with minimum chances of leakage across walls.

Calculations: As it is obvious from earlier discussion that the vertical duct called chimney creates natural draught so estimation of height of chimney is very important. Figure shows the schematic of chimney in a boiler unit. During no working of boiler the pressure inside boiler is atmospheric pressure. Pressure at outlet of chimney will be less than atmospheric pressure due to altitude difference.



EQUIVALENT EVAPORATION

From earlier discussions it is seen that there exists a large variety of the boilers in terms of their arrangement, efficiency, steam generation rate, steam condition, type of fuel used, firing method and draught etc. 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 and different final steam conditions etc. a parameter called “equivalent evaporation” can be used. Equivalent evaporation actually indicates the amount of heat added in the boiler for steam generation. Equivalent evaporation refers to the quantity of dry saturated steam generated per unit time from feed water at 100_C to steam at 100_C at the saturation pressure corresponding to 100_C. Sometimes it is also called equivalent evaporation from and at 100_C. Thus, mathematically it could be given as

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

BOILER EFFICIENCY

HEAT BALANCE ON BOILER

Heat balance on boiler refers to the accounting for total heat released inside boiler and its distribution. Total heat available inside boiler is due to burning of fuel and can be quantified by the product of mass of fuel and heating value of fuel. Heat distribution can be given comprising of the following, based on unit mass of fuel burnt.

Numerical problem :-

1. Determine the height of chimney required to produce draught equivalent to 16.7 mm of water column for the flue gases at 300_C and ambient temperature of 20_C. Take the air requirement to be 20 kg/kg of fuel.(30m)
2. Calculate the draught produced in *mm* of water by chimney of 35 m height, flue gas temperature of 643 K, boiler house temperature of 307 K and air supplied at 18.8 kg per kg of coal (20mm).

Unit -2
Vapour Power Cycles or Phase change cycle

CARNOT CYCLE

Figure shows a Carnot cycle on T-s and p-V diagrams. It consists of (I) two constant pressure operations (4-1) and (2-3) and (ii) two frictionless adiabatic (1-2) and (3-4). These operations are discussed below:

1. Operation (4-1). 1 kg of boiling water at temperature T1 is heated to form wet steam of dryness fraction x1. Thus heat is absorbed at constant temperature T1 and pressure p1 during this operation.

2. Operation (1-2). During this operation steam is expanded isentropically to temperature T2 and pressure p2. The point '2' represents the condition of steam after expansion.

3. Operation (2-3). During this operation heat is rejected at constant pressure p2 and temperature T2. As the steam is exhausted it becomes wetter and cooled from 2 to 3.

4. Operation (3-4). In this operation the wet steam at '3' is compressed isentropically till the steam regains its original state of temperature T1 and pressure p1. Thus cycle is completed.

Refer T-s diagram:

Heat supplied at constant temperature T1 [operation (4-1)] = area 4-1-b-a = T1 (s1 – s4) or T1 (s2 – s3).

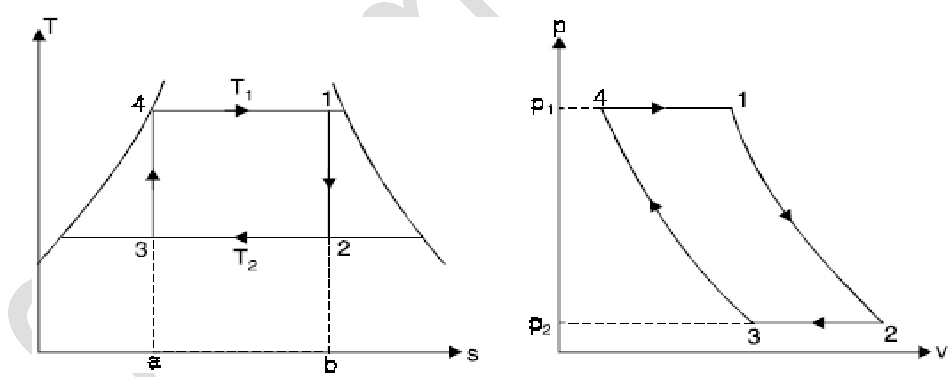


Fig. 1 Carnot cycle on T-s and p-V diagrams

Heat rejected at constant temperature T2 (operation 2-3) = area 2-3-a-b = T2 (s2 – s3).

Limitations of Carnot Cycle

Though Carnot cycle is simple (thermodynamically) and has the highest thermal efficiency for given values of T1 and T2, yet it is extremely difficult to operate in practice because of the following reasons:

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.

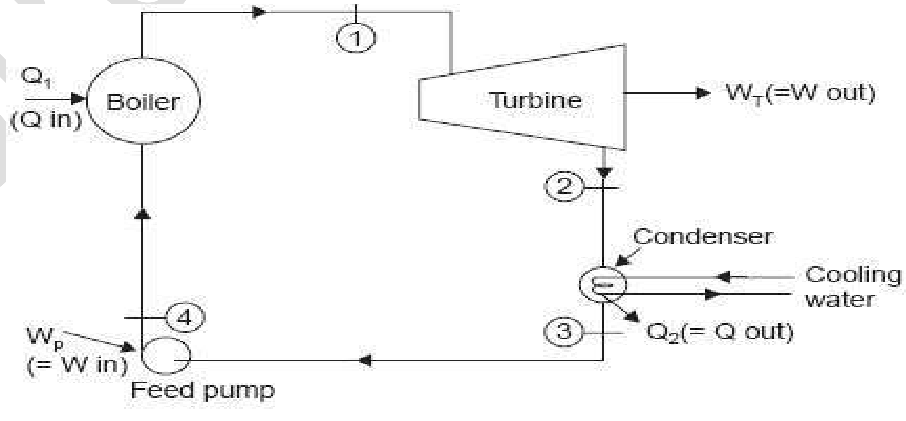
3. The efficiency of the Carnot cycle is greatly affected by the temperature T1 at which heat is transferred to the working fluid. Since the critical temperature for steam is only 374°C, therefore, if the cycle is to be operated in the wet region, the maximum possible temperature is severely limited.

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 (as it is customary).

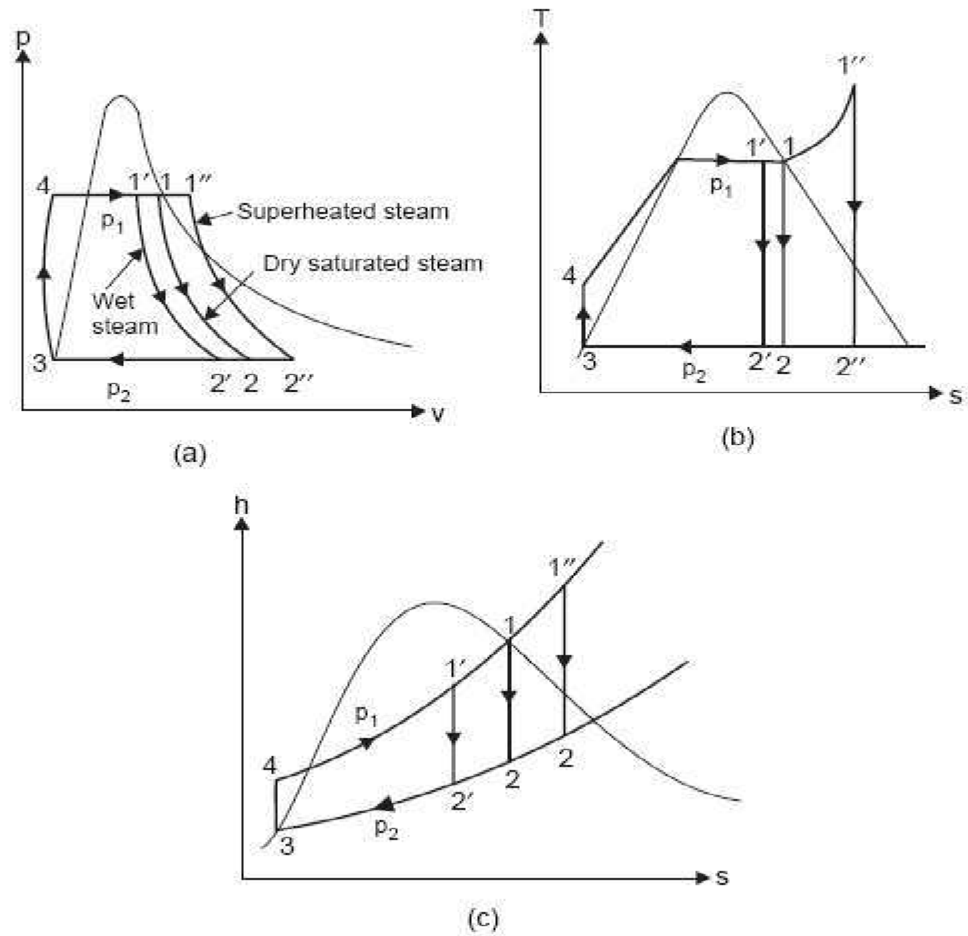
In a practical cycle, limits of pressure and volume are far more easily realised than limits of temperature so that at present no practical engine operates on the Carnot cycle, although all modern cycles aspire to achieve it.

RANKINE CYCLE

Rankine cycle is the theoretical cycle on which the steam turbine (or engine) works.



Rankine cycle.



(a) p-v diagram ; (b) T-s diagram ; (c) h-s diagram for Rankine cycle.

(b) The Rankine cycle is shown in Fig. It comprises of the following *processes* :
(c) **Process 1-2 :** Reversible adiabatic expansion in the turbine (or steam engine).
(d) **Process 2-3 :** Constant-pressure transfer of heat in the condenser.
(e) **Process 3-4 :** Reversible adiabatic pumping process in the feed pump.
(f) **Process 4-1 :** Constant-pressure transfer of heat in the boiler.
(g) Fig. 12.3 shows the Rankine cycle on *p-v*, *T-s* and *h-s* diagrams (when the saturated steam
(h) enters the turbine, the steam can be wet or superheated also).
(i) **Considering 1 kg of fluid :**
(j) Applying *steady flow energy equation* (S.F.E.E.) to boiler, turbine, condenser and pump :
(k) (*i*) **For boiler** (as control volume), we get

Comparison between Rankine Cycle and Carnot Cycle-

The following points are worth noting :

(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 T1, 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.

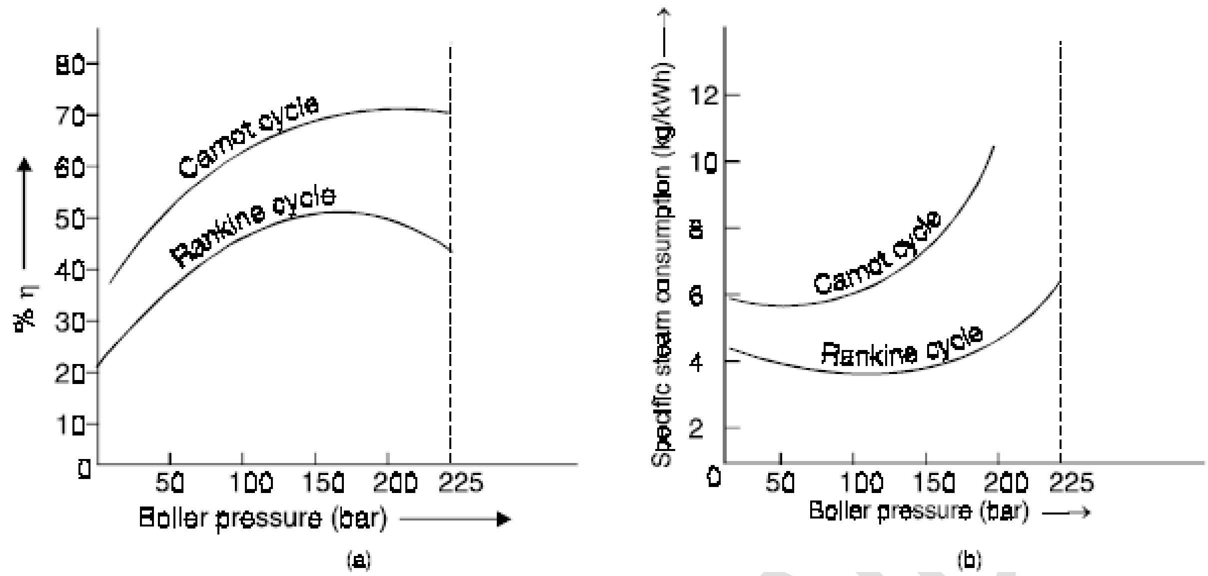
Fig. shows the plots between efficiency and specific steam consumption against boiler pressure for Carnot and ideal Rankine cycles.

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.

(ii) Decreasing/reducing the temperature at which heat is rejected



This can be achieved by making suitable changes in the conditions of steam generation or condensation, as discussed below :

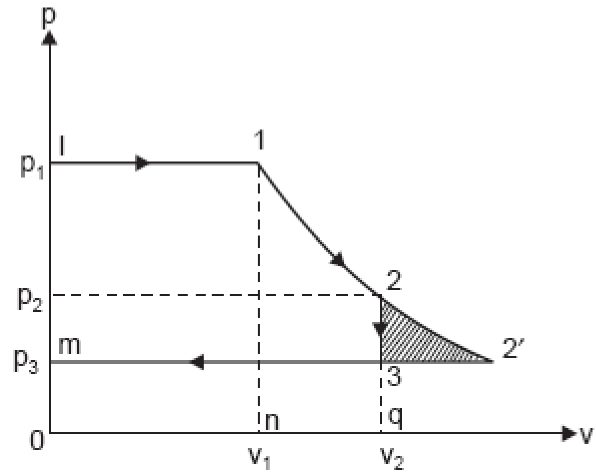
1. ***Increasing boiler pressure*.** It has been observed that by increasing the boiler pressure (other factors remaining the same) the cycle tends to rise and reaches a maximum value at a boiler pressure of about 166 bar [Fig. (*a*)].

2. ***Superheating*.** All other factors remaining the same, if the steam is superheated before allowing it to expand the Rankine cycle efficiency may be increased [Fig. (*b*)]. The use of superheated steam also ensures longer turbine blade life because of the absence of erosion from high velocity water particles that are suspended in wet vapour.

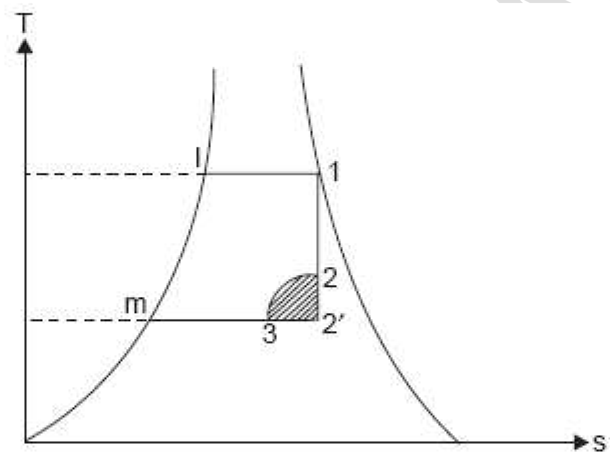
3. ***Reducing condenser pressure*.** The thermal efficiency of the cycle can be amply improved by reducing the condenser pressure [Fig. 12.5 (*c*)] (hence by reducing the temperature at which heat is rejected), especially in high vacuums. But the increase in efficiency is obtained at the increased cost of condensation apparatus

MODIFIED RANKINE CYCLE

Figures 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 to e 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.



. *p-V* diagram of Modified Rankine Cycle.

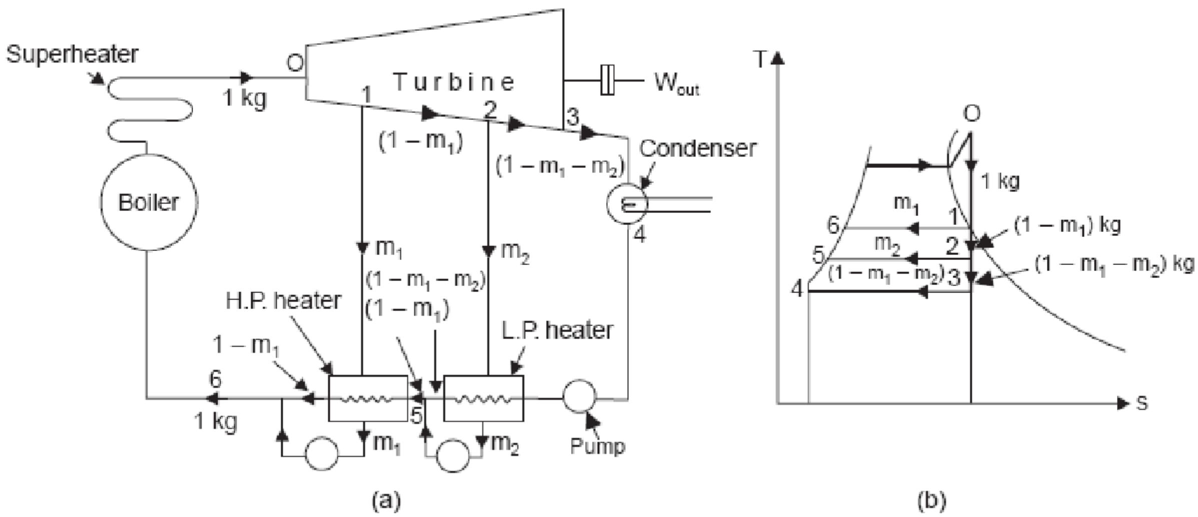


. *T-s* diagram of Modified Rankine cycle.

REGENERATIVE CYCLE

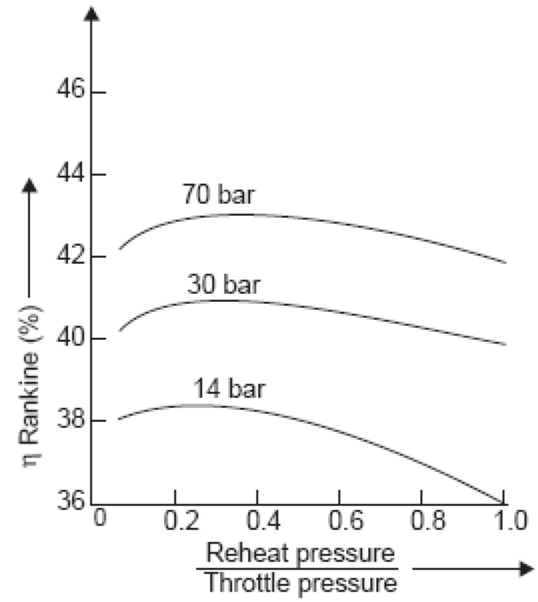
In the Rankine cycle it is observed that the condensate which is fairly at low temperature has an irreversible mixing with hot boiler water and this results in decrease of cycle efficiency. Methods are, therefore, adopted to heat the feed water from the hot well of condenser irreversibly by interchange of heat within the system and thus improving the cycle efficiency. This heating method is called regenerative feed heat and the cycle is called regenerative cycle. The principle of regeneration can be practically utilised by extracting steam from the turbine at several locations and supplying it to the regenerative heaters. The resulting cycle is known as regenerative or bleeding cycle. The heating arrangement comprises of : (i) For medium capacity turbines—not more than 3 heaters ; (ii) For high pressure high capacity turbines—not more than 5 to 7 heaters ; and (iii) For turbines of super critical parameters 8 to 9 heaters. The most advantageous condensate heating temperature is selected depending on the turbine throttle conditions and this determines the number of heaters to be used. The final condensate heating temperature is kept 50 to 60°C below the boiler saturated steam temperature so as to prevent evaporation of water in the feed mains following a drop in the boiler drum pressure. The conditions of steam bled for each heater are so selected that the temperature of saturated steam will be 4 to 10°C higher than the final condensate temperature 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. The cycle diagram (T-s) would appear as shown in Fig.

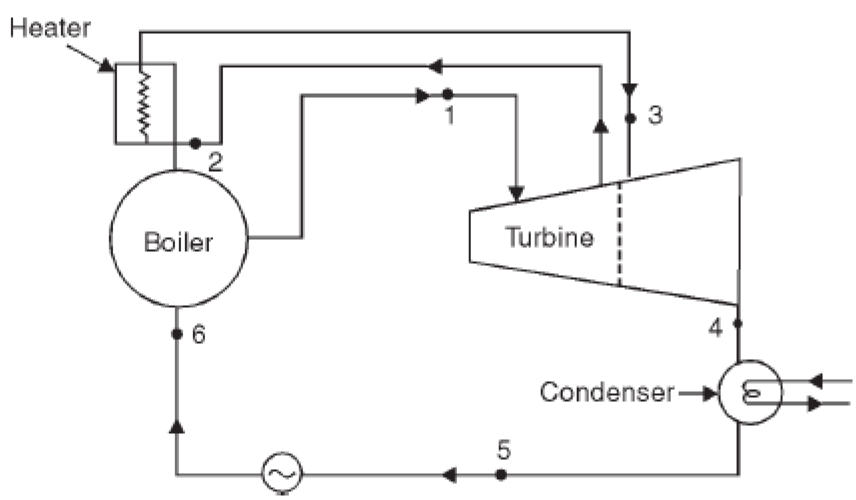


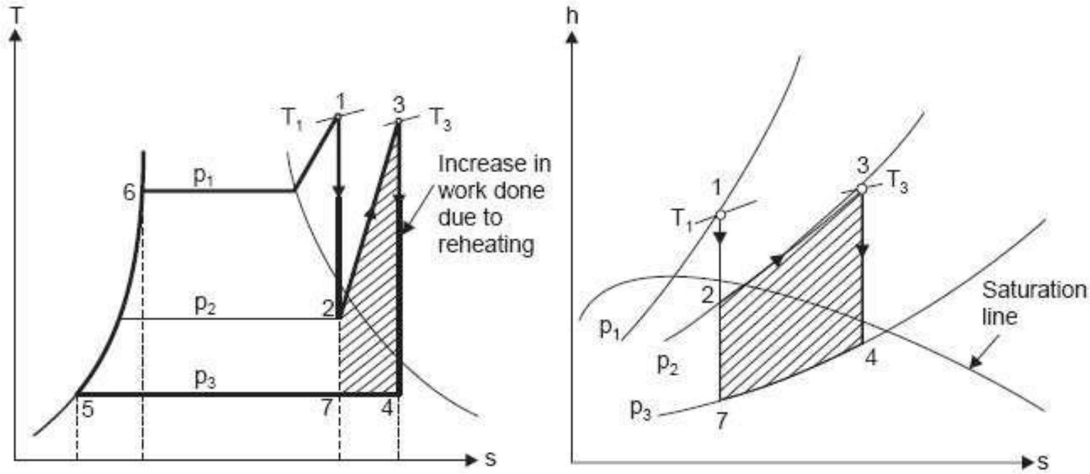
REHEAT CYCLE

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. 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. A second reheat will give a much less gain while the initial cost involved would be so high as to prohibit use of two stage reheat except in case of very high initial throttle conditions. The cost of reheat equipment consisting of boiler, piping and controls may be 5% to 10% more than that of the conventional boilers and this additional expenditure is justified only if gain in thermal efficiency is sufficient to promise a return of this investment. 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.



Condenser pressure : 12.7 mm Hg
Temperature of throttle and heat : 427°C

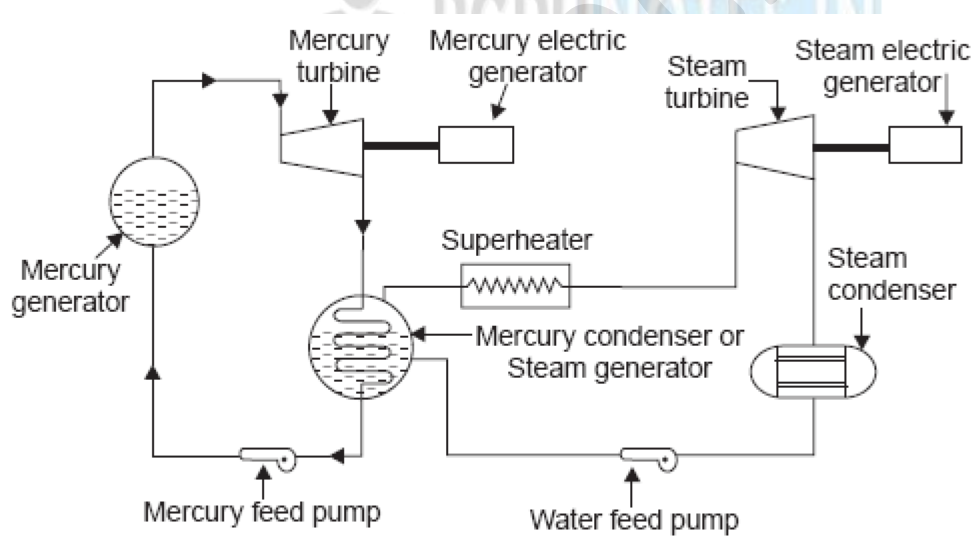




Thermal efficiency *without reheating* is

$$\eta_{\text{thermal}} = \frac{h_1 - h_7}{h_1 - h_{f_4}} \quad (\because \quad h_{f_4} = h_{f_7})$$

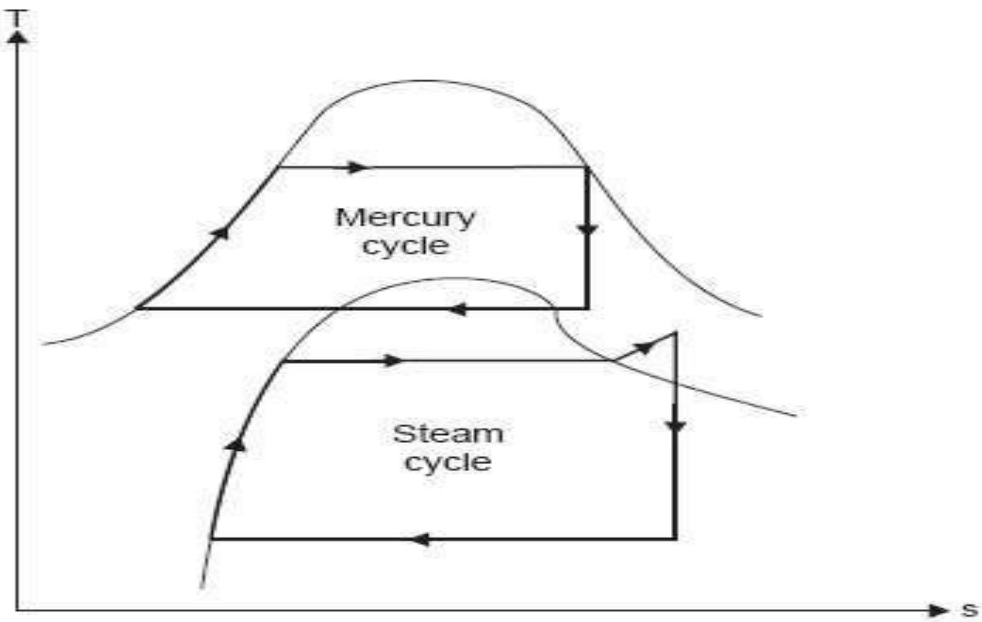
BINARY VAPOUR CYCLE



<u>BINARY VAPOUR CYCLE</u>

Overall efficiency of the binary cycle is given by

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{W_t}{h_t} = \frac{mW_{hg} + W_s}{mh_{hg_1}}$$



The thermal efficiency of the steam cycle is given by

$$\eta_s = \frac{W_s}{h_s} = \frac{h_{s_1} - h_{s_2}}{h_{s_1}} = \frac{h_{s_1} - h_{s_2}}{m h_{hg_2}}$$

THEORETICAL QUESTIONS

1. Explain the various operation of a Carnot cycle. Also represent it on a T-s and p-V diagrams.

2. Describe the different operations of Rankine cycle. Derive also the expression for its efficiency.

3. State the methods of increasing the thermal efficiency of a Rankine cycle.

4. Explain with the help of neat diagram a ‘Regenerative Cycle’. Derive also an expression for its thermal efficiency.

5. State the advantages of regenerative cycle/simple Rankine cycle.

6. Explain with a neat diagram the working of a Binary Vapour cycle.

NUMERICAL QESTION:-

1. 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. [Ans. 35%, 0.997, 3.84 kg/kWh]

2. A steam power plant works between 40 bar and 0.05 bar. If the steam supplied is dry saturated and the cycle of operation is Rankine, find: (i) Cycle efficiency (ii) Specific steam consumption. [Ans. (i) 35.5%, (ii) 3.8 kg/kWh]

3. Compare the Rankine efficiency of a high pressure plant operating from 80 bar and 400°C and a low pressure plant operating from 40 bar 400°C, if the condenser pressure in both cases is 0.07 bar. [Ans. 0.391 and 0.357]

4. A steam power plant working on Rankine cycle has the range of operation from 40 bar dry saturated to 0.05 bar. Determine:

(i) The cycle efficiency (ii) Work ratio

(iii) Specific fuel consumption. [Ans. (i) 34.64%, (ii) 0.9957, (iii) 3.8 kg/kWh]

5. 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. [Ans. (i) 30 kW, (ii) 7410 kW, (iii) 29.2%, (iv) 17900 kW, (v) 0.763]

6. In a regenerative cycle the inlet conditions are 40 bar and 400°C. Steam is bled at 10 bar in regenerative heating. The exit pressure is 0.8 bar. Neglecting pump work determine the efficiency of the cycle.

[Ans. 0.296]

7. A turbine with one bleeding for regenerative heating of feed water is admitted with steam having enthalpy of 3200 kJ/kg and the exhausted steam has an enthalpy of 2200 kJ/kg. The ideal regenerative feed water heater is fed with 11350 kg/h of bled steam at 3.5 bar (whose enthalpy is 2600 kJ/h). The feed water (condensate from the condenser) with an enthalpy of 134 kJ/kg is pumped to the heater. It leaves the heater dry saturated at 3.5 bar. Determine the power developed by the turbine. [Ans. 16015 kW]

Unit -3

Gas Dynamics

INTRODUCTION

A compressible flow is that flow in which the density of the fluid changes during flow. All real fluids are compressible to some extent and therefore their density will change with change in pressure or temperature. If the relative change in density $\Delta\rho/\rho$ is small, the fluid can be treated as incompressible. A compressible fluid, such as air, can be considered as incompressible with constant ρ if changes in elevation are small, acceleration is small, and/or temperature changes are negligible. In other words, if Mach's number U/C, where C is the sonic velocity, is small, compressible fluid can be treated as incompressible.

• The gases are treated as compressible fluids and study of this type of flow is often referred to as 'Gas dynamics'.

• Some important problems where compressibility effect has to be considered are:

(i) Flow of gases through nozzles, orifices;

(ii) Compressors;

(iii) Flight of aeroplanes and projectiles moving at higher altitudes;

(iv) Water hammer and acoustics.

• 'Compressibility' affects the drag coefficients of bodies by formation of shock waves, discharge coefficients of measuring devices such as orifice meters, venturimeters and pitot tubes, stagnation pressure and flows in converging-diverging sections.

BASIC EQUATIONS OF COMPRESSIBLE FLUID FLOW

The basic equations of compressible fluid flow are: (i) Continuity equation, (ii) Momentum equation, (iii) Energy equation, and (iv) Equation of state.

Continuity Equation

In case of one-dimensional flow, mass per second = ρAV

(Where ρ = mass density, A = area of cross-section, V = velocity)

Since the mass or mass per second is constant according to law of conservation of mass, therefore,

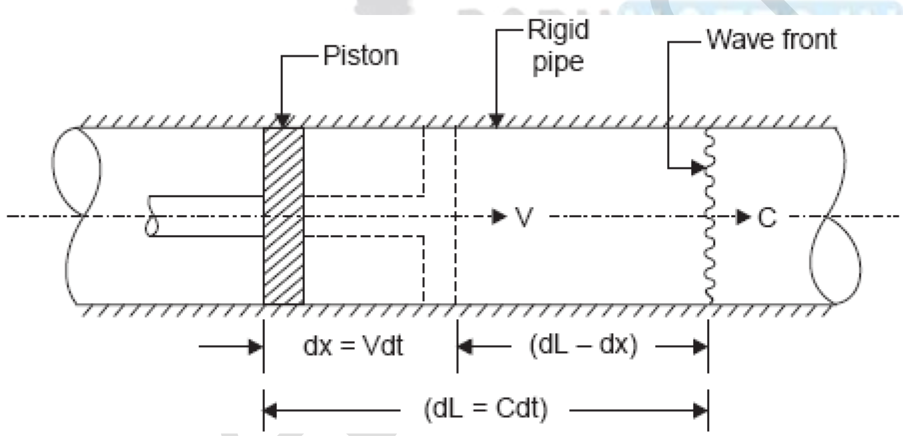
ρAV = constant

PROPAGATION OF DISTURBANCES IN FLUID AND VELOCITY OF SOUND

The solids as well as fluids consist of molecules. Whereas the molecules in solids are close together, these are relatively apart in fluids. Consequently whenever there is a minor disturbance, it travels instantaneously in case of solids; but in case of fluid the molecules change its position before the transmission or propagation of the disturbance. Thus the velocity of disturbance in case of fluids will be less than the velocity of the disturbance in solids. In case of fluid, the propagation of disturbance depends upon its elastic properties. The velocity of disturbance depends upon the changes in pressure and density of the fluid. The propagation of disturbance is similar to the propagation of sound through a media. The speed of propagation of sound in a media is known as acoustic or sonic velocity and depends upon the difference of pressure. In compressible flow, velocity of sound (sonic velocity) is of paramount importance

Derivation of Sonic Velocity (velocity of sound)

Consider a one-dimensional flow through long straight rigid pipe of uniform cross-sectional area filled with a frictionless piston at one end as shown in Fig. The tube is filled with a compressible fluid initially at rest. If the piston is moved suddenly to the right with a velocity, a *pressure wave* would be propagated through the fluid with the velocity of sound wave



One dimensional pressure wave propagation.

Let A = cross-sectional area of the pipe,

V = piston velocity,

p = fluid pressure in the pipe before the piston movement,

ρ = fluid density before the piston movement,

dt = a small interval of time during which piston moves, and

C = velocity of pressure wave or sound wave (travelling in the fluid).

Before the movement of the piston the length dL has an initial density ρ, and its total mass = $\rho \times dL \times A$.

When the piston moves through a distance dx, the fluid density within the compressed region of length $(dL - dx)$ will be increased and becomes $(\rho + d\rho)$ and subsequently the total mass of fluid in the compressed region = $(\rho + d\rho)(dL - dx) \times A$

$\therefore \rho \times dL \times A = (\rho + d\rho)(dL - dx) \times A$ ...by principle of continuity.

But $dL = C\,dt$ and $dx = Vdt$; therefore, the above equation becomes

$\rho Cdt = (\rho + d\rho)(C - V)\,dt$

or, $\rho C = (\rho + d\rho)(C - V)$ or $\rho C = \rho C - \rho V + d\rho \,.\, C - d\rho \,.\, V$

or, $0 = -\rho V + d\rho \,.\, C - d\rho \,.\, V$

Neglecting the term $d\rho.V$ (V being much smaller than C), we get

$$d\rho \,.\, C = \rho V \text{ or } C = \frac{\rho V}{d\rho}$$

$$\underset{\text{(force on the fluid)}}{dp \times A \times dt} = \underset{\text{(rate of change of momentum)}}{\rho \times dL \times A\,(V - 0)}$$

$$dp = \rho\,\frac{dL}{dt}\,V = \rho \times \frac{Cdt}{dt} \times V = \rho CV$$

$$C = \frac{dp}{\rho V}$$

$$C^2 = \frac{\rho V}{d\rho} \times \frac{dp}{\rho V} = \frac{dp}{d\rho}$$

$$C = \sqrt{\frac{dp}{d\rho}}$$

MACH NUMBER

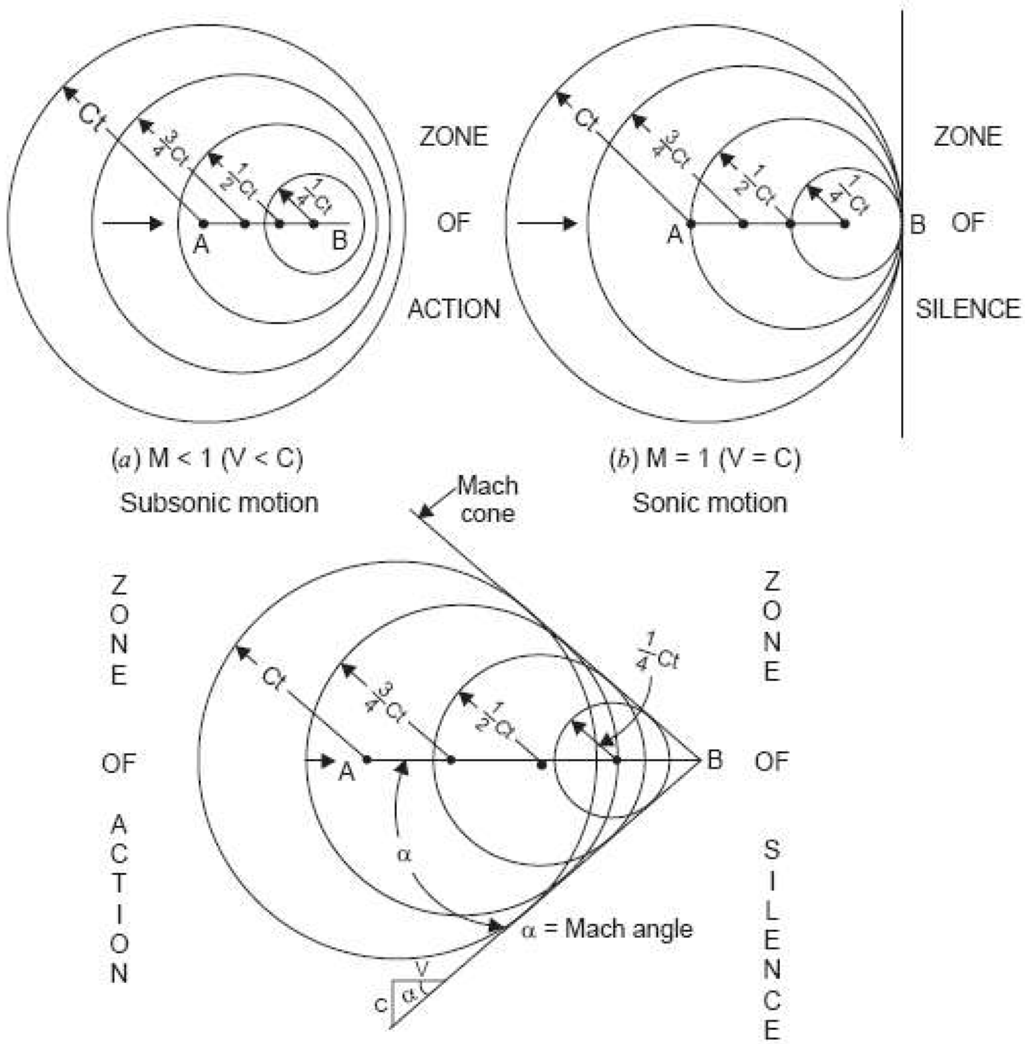
The Mach number is an important parameter in dealing with the flow of compressible fluids, when elastic forces become important and predominant. ***Mach number*** is defined as the *square root of the ratio of the inertia force of a fluid to the elastic force.*

$$\therefore \text{ Mach number,} \qquad M = \sqrt{\frac{\text{Inertia force}}{\text{Elastic force}}} = \sqrt{\frac{\rho A V^2}{KA}}$$

$$= \sqrt{\frac{V^2}{K/\rho}} = \frac{V}{\sqrt{K/\rho}} = \frac{V}{C} \qquad \left[\because \sqrt{K/\rho} = C\right.$$

$$M = \frac{V}{C}$$

$$\text{Thus,} \qquad M = \frac{\text{Velocity at a point in a fluid}}{\text{Velocity of sound at that point at a given instant of time}}$$



(*a*) M < 1 (V < C)
Subsonic motion

(*b*) M = 1 (V = C)
Sonic motion

(*c*) M > 1 (V > C)
Supersonic motion

STAGNATION PROPERTIES

The point on the immersed body where the velocity is zero is called **stagnation point.** At this point velocity head is converted into pressure head. The values of pressure (p_s), temperature (T_s) and density (ρ_s) at stagnation point are called *stagnation properties.*

FLOW OF COMPRESSIBLE FLUID THROUGH A CONVERGENT NOZZLE

Fig. Shows a large tank/vessel fitted with a short convergent nozzle and containing a compressible fluid. Consider two points 1 and 2 inside the tank and exit of the nozzle respectively.

Let p_1 = pressure of fluid at the point 1,

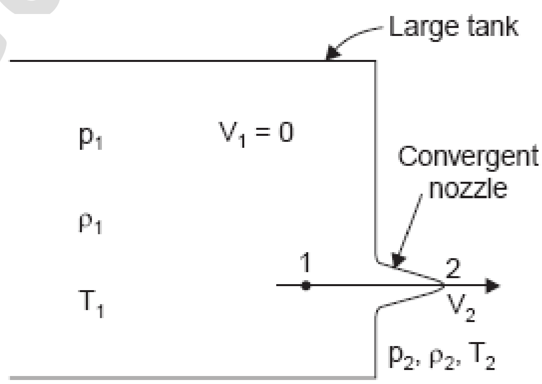
V_1 = velocity of fluid in the tank (= 0),

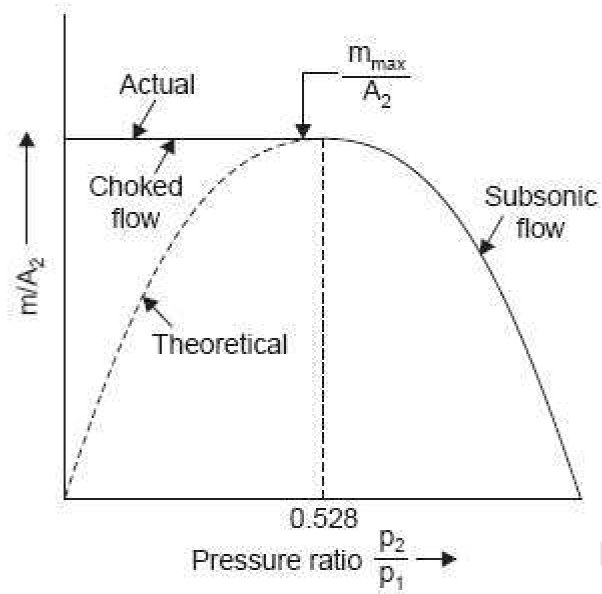
T_1 = temperature of fluid at point 1,

ρ_1 = density of fluid at point 1, and p_2, V_2, T_2 and

ρ_2 are corresponding values of pressure, velocity, temperature and density at point 2.

Assuming the flow to take place *adiabatically*, then by using Bernoulli's equation (for adiabatic flow), we have





THEORETICAL QUESTIONS

1. Differentiate between compressible and incompressible flows.

2. Give the examples when liquid is treated as a compressible fluid.

3. When is the compressibility of fluid important ?

4. What is the difference between isentropic and adiabatic flows ?

5. What is the relation between pressure and density of a compressible fluid for (*a*) isothermal process (*b*) adiabatic process ?

6. Obtain an expression in differential form for continuity equation for one-dimensional compressible flow.

7. Derive an expression for Bernoulli's equation when the process is adiabatic.

8. How are the disturbances in compressible fluid propagated ?

9. What is sonic velocity ? On what factors does it depend ?

10. What is Mach number ? Why is this parameter so important for the study of flow of compressible fluids.

Numerical problems:-

1. A 100 mm diameter pipe reduces to 50 mm diameter through a sudden contraction. When it carries air at 20.16°C under isothermal conditions, the absolute pressures observed in the two pipes just before and after the contraction are 400 kN/m2 and 320 kN/m2 respectively. Determine the densities and velocities at the two sections. Take *R* = 290 J/kg K. [Ans. 4.7 kg/m3 ; 3.76 kg/m3 ; 39.7 m/s ; 198.5 m/s]

2. A gas with a velocity of 300 m/s is flowing through a horizontal pipe at a section where pressure is 60 kN/m2 (*abs*.) and temperature 40°C. The pipe changes in diameter and at this section the pressure is 90 kN/m2. If the flow of gas is adiabatic find the velocity of gas at this section. Take : *R* = 287 J/kg K and γ = 1.4. [Ans. 113 m/s]

3. An aeroplane is flying at 21.5 m/s at a low altitude where the velocity of sound is 325 m/s. At a certain point just outside the boundary layer of the wings, the velocity of air relative to the plane is 305 m/s. If the flow is frictionless adiabatic determine the pressure drop on the wing surface near this position Assume γ = 1.4, pressure of ambient air = 102 kN/m2. [Ans. 28.46 kN/m2]

4. A jet propelled aircraft is flying at 1100 km/h. at sea level. Calculate the Mach number at a point on the aircraft where air temperature is 20°C Take : *R* = 287 J/kg K and γ = 1.4. [Ans. 0.89]

5. An aeroplane is flying at an height of 20 km where the temperature is – 40°C. The speed of the plane is corresponding to *M* = 1.8. Find the speed of the plane. Take : *R* = 287 J/kg K, γ = 1.4. [Ans. 1982.6 km/h]

6. Find the velocity of bullet fired in standard air if its Mach angle is 30°. [Ans. 680.4 m/s]

7. Air, thermodynamic state of which is given by pressure *p* = 230 kN/m2 and temperature = 300 K is moving at a velocity *V* = 250 m/s. Calculate the stagnation pressure if (*i*) compressibility is neglected and (*ii*) compressibility is accounted for.

Take γ = 1.4 and *R* = 287 J/kg K. [Ans. 313 kN/m2, 323 kN/m2]

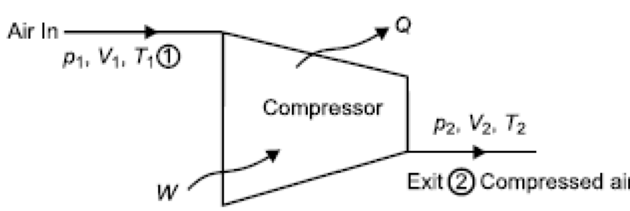
8. A large vessel, fitted with a nozzle, contains air at a pressure of 2943 kN/m2 (*abs*.) and at a temperature of 20°C. If the pressure at the outlet of the nozzle is 2060 kN/m2 (*abs*.) find the velocity of air flowing at the outlet of the nozzle. Take: *R* = 287 J/kg K and γ = 1.4 [**Ans.** 239.2 m/s]

Unit 4

AIR COMPRESSOR

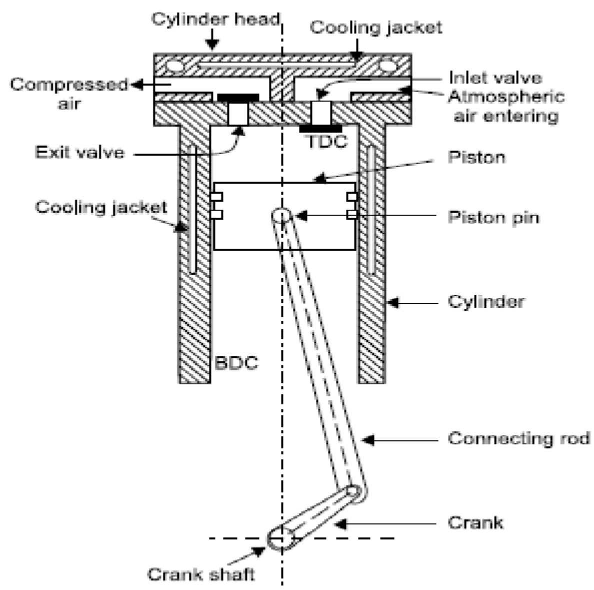
INTRODUCTION

Compressors are work absorbing devices which are used for increasing pressure of fluid at the expense of work done on fluid. The compressors used for compressing air are called air compressors. Compressors are invariably used for all applications requiring high pressure air. Some of popular applications of compressor are, for driving pneumatic tools and air operated equipment's, spray painting, compressed air engine, supercharging in internal combustion engines, material handling (for transfer of material), surface cleaning, refrigeration and air conditioning, chemical industry etc. Compressors are supplied with low pressure air (or any fluid) at inlet which comes out as high pressure air (or any fluid) at outlet, Fig. Work required for increasing pressure of air is available from the prime mover driving the compressor. Generally, electric motor, internal combustion engine or steam engine, turbine etc. are used as prime movers. Compressors are similar to fans and blowers but differ in terms of pressure ratios. Fan is said to have pressure ratio up to 1.1 and blowers have pressure ratio between 1.1 and 4 while compressors have pressure ratios more than 4.



Reciprocating compressors –

Reciprocating compressor is the workhorse of the refrigeration and air conditioning industry. It is the most widely used compressor with cooling capacities ranging from a few Watts to hundreds of kilowatts. Modern day reciprocating compressors are high speed (≈ 3000 to 3600 rpm), single acting, single or multi-cylinder (upto 16 cylinders) type. Figure shows the schematic of a reciprocating compressor. Reciprocating compressors consist of a piston moving back and forth in a cylinder, with suction and discharge valves to achieve suction and compression of the refrigerant vapor. Its construction and working are somewhat similar to a two-stroke engine, as suction and compression of the refrigerant vapor are completed in one revolution of the crank. The suction side of the compressor is connected to the exit of the evaporator, while the discharge side of the compressor is connected to the condenser inlet. The suction (inlet) and the discharge (outlet) valves open and close due to pressure differences between the cylinder and inlet or outlet manifolds respectively. The pressure in the inlet manifold is equal to or slightly less than the evaporator pressure. Similarly the pressure in the outlet manifold is equal to or slightly greater than the condenser pressure. The purpose of the manifolds is to provide stable inlet and outlet pressures for the smooth operation of the valves and also provide a space for mounting the valves.



The valves used are of reed or plate type, which are either floating or clamped. Usually, backstops are provided to limit the valve displacement and springs may be provided for smooth return after opening or closing. The piston speed is decided by valve type. Too high a speed will give excessive vapor velocities that will decrease the volumetric efficiency and the throttling loss will decrease the compression efficiency.

Performance of reciprocating compressors-

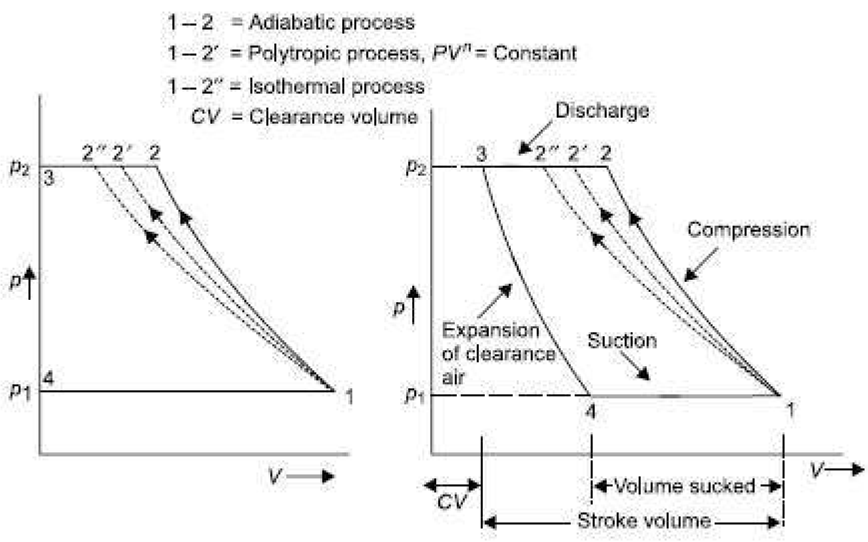
For a given evaporator and condenser pressures, the important performance parameters of a refrigerant compressor are:

a) The mass flow rate (m) of the compressor for a given displacement rate

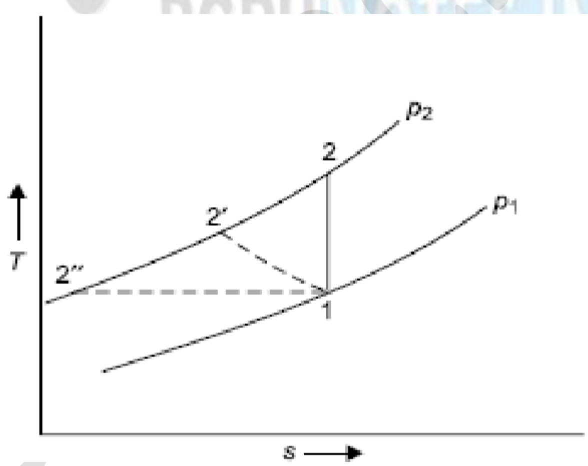
b) Power consumption of the compressor (Wc)

c) Temperature of the refrigerant at compressor exit, Td, and

d) Performance under part load conditions-



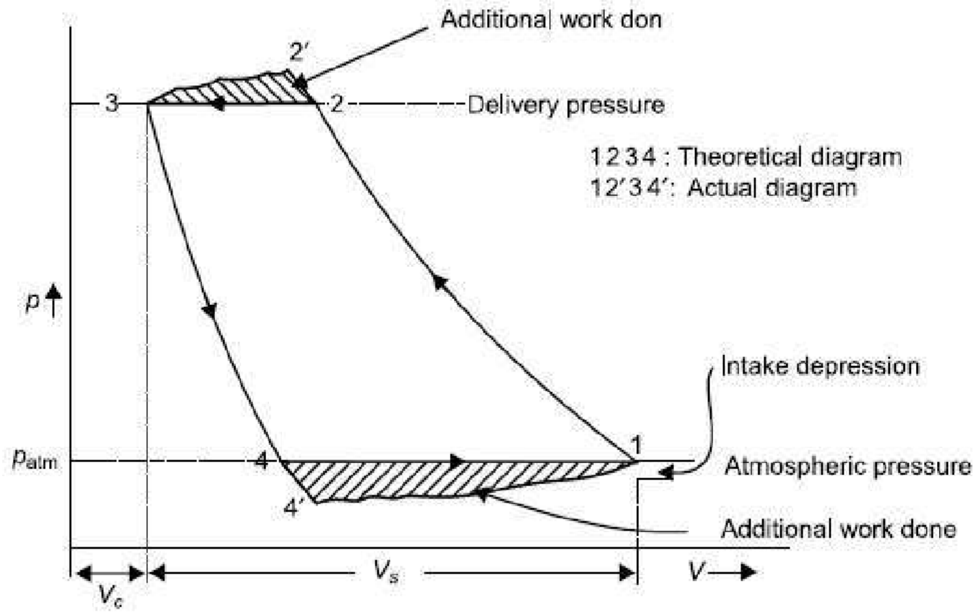
(a) Compression cycle without clearance (b) Compression cycle with clearance



Temperature entropy diagram

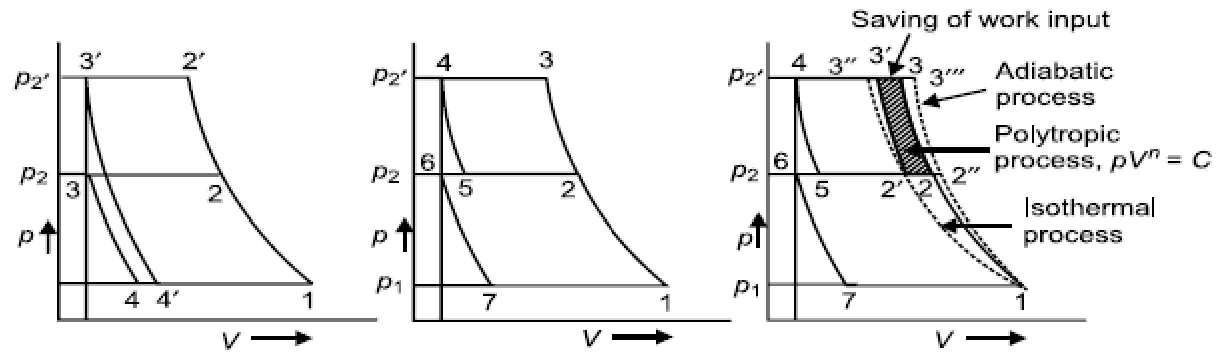
ACTUAL INDICATOR DIAGRAM

Theoretical indicator diagram of reciprocating compressor as shown in earlier discussion refers to the ideal state of operation of compressor. The practical limitations, when considered in the indicator diagram yield actual indicator diagram as shown in Fig



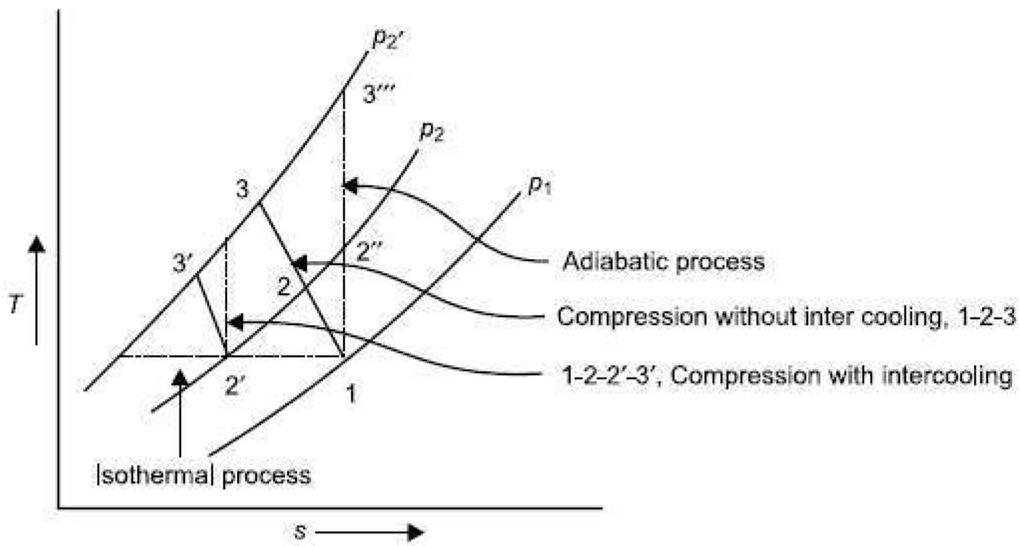
Actual *p-V* diagram varies from theoretical *p-V* diagram due to following: Compressor has mechanical types of valves so the instantaneous opening and closing of valves can never be achieved. Also during suction and discharge there occurs throttling due to reduction in area of flow across inlet and exit valve. 1234 shows theoretical indicator diagram and actual indicator diagram is shown by 12_34_ on *p-V* diagram. Compression process 1–2 ends at state 2. At state 2 exit valve should open instantaneously which does not occur and also due to restricted opening there shall be throttling causing drop in pressure. Due to time lag in opening of exit valve compression process is continued up to 2. Thus, additional work is done during delivery from compressor as shown by hatched area 2. After delivery stroke the inlet valve should theoretically open at 4 but does not open at this point instead is opened fully at 4. Shift from state 4 to 4_5 is there due to inertia in opening of valve throttling, gradual opening, and friction losses etc. Thus it is seen that during suction there occurs intake depression as shown in actual indicator diagram. Work required as shown in actual indicator diagram is more than theoretical diagram. In order to have compressor close to ideal compressor with minimum losses it shall be desired to have actual indicator diagram close to theoretical diagram, which requires less inertia and efficient operation of valves. Friction losses in piping's and across valves should be minimized.

MULTISTAGE COMPRESSION



(a) Effect of increase in pressure ration

(b) Multistage compression without intercooling



$$W_c = \left(\frac{n}{n-1}\right) p_1 V_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} + \left(\frac{p_{2'}}{p_2}\right)^{\frac{n-1}{n}} - 2\right]$$

ROTARY COMPRESSORS

Rotary compressors are those compressors in which rotating action is used for compression of fluid. Rotary air compressors have capability of running at high speeds up to 40,000 rpm and can be directly coupled to any prime mover such as electric motor, turbine etc. due to compact design, no balancing problem and less no. of sliding parts. Comparative study of rotary compressor with reciprocating compressor shows that rotary compressors can be used for delivering large quantity of air but the maximum pressure at delivery is less compared to reciprocating compressors. Generally, rotary compressors can yield delivery pressure up to 10 bar and free air delivery of 3000 m3/min. Rotary compressors are less bulky, and offer uniform discharge compared to reciprocating compressor even in the absence of big size receiver.

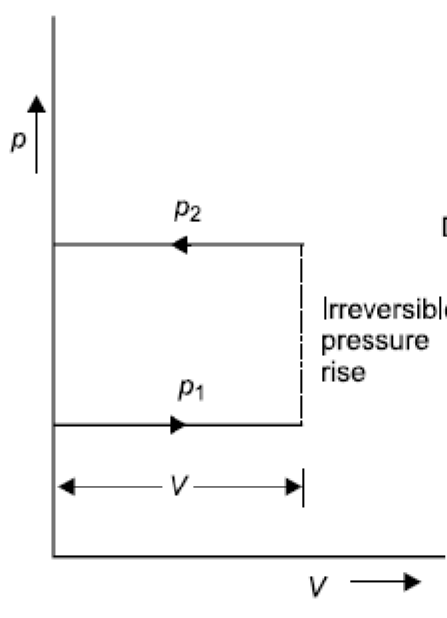
Lubrication requirement and wear and tear is less due to rotary motion of parts in rotary compressors compared to reciprocating compressors. Rotary compressors may work on the principle of positive displacement and dynamic action both. Rotary compressors having positive displacement may be of following types:

(i) Roots blower

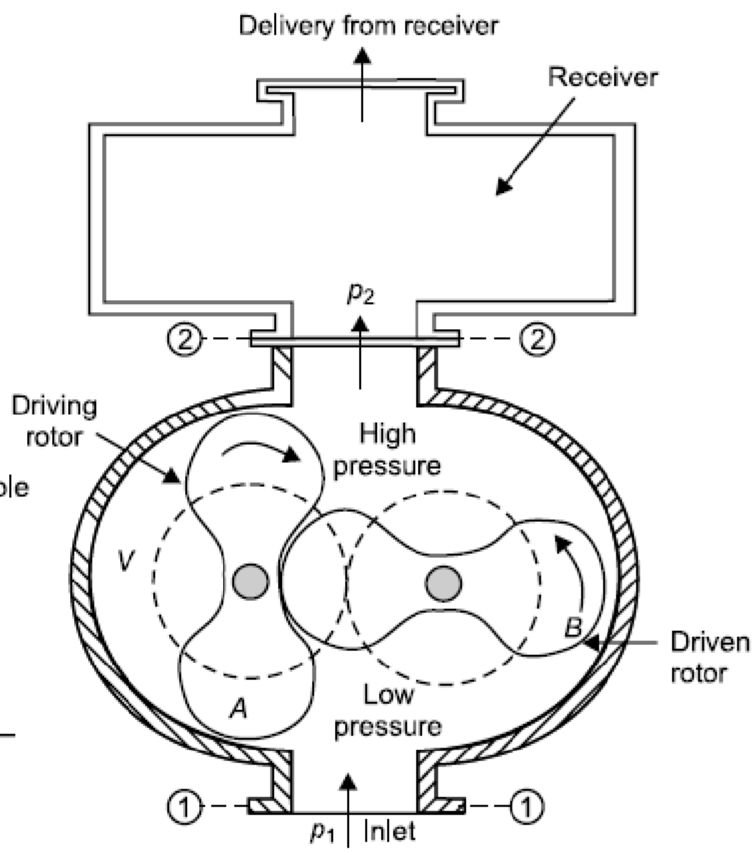
(ii) Screw type or helical type compressor

(iii) Vane type compressor

(i) *Roots blower:* Roots blower is a positive displacement type rotary compressor. It has two rotors having two or three lobes having epicycloid and hypocycloid or involute profiles such that they remain in proper contact. Figure 16.13 shows two lobe rotors in a roots blower. To prevent wear and tear two rotors have clearance in between. Out of two rotors one is driven by prime mover while other one is driven by first rotor. When two rotors rotate then their typical geometry divides the region inside casing into two regions i.e. high pressure region and low pressure region. Although there occurs slight leakage across the mating parts which can only be minimised not eliminated completely.



(a) p-V representation

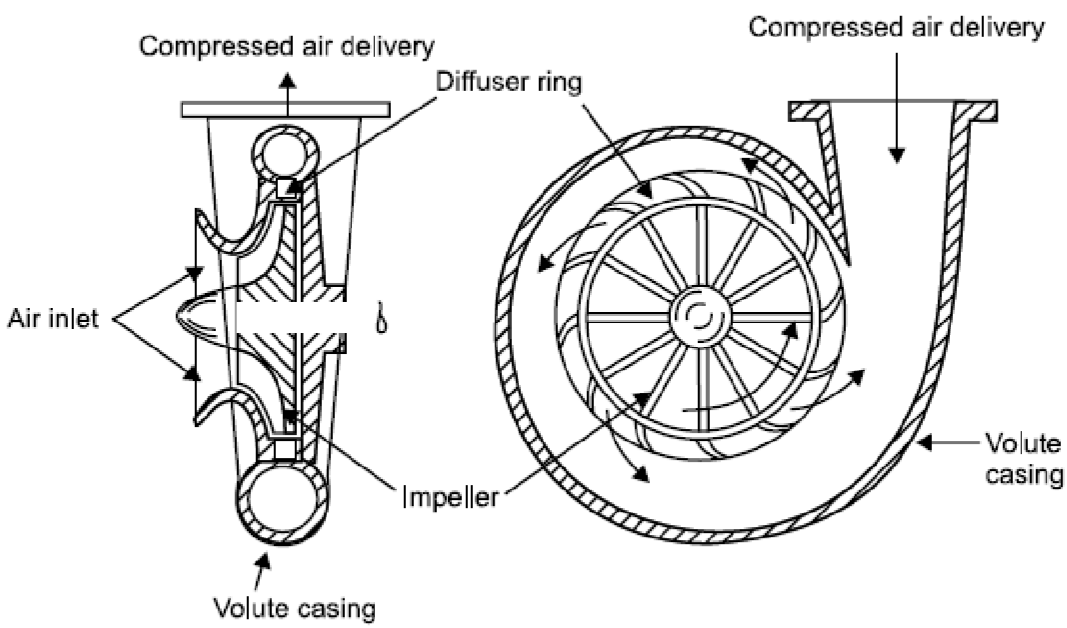


(b) Schematic of roots blower

$$\eta_{\text{roots}} = \left(\frac{\gamma}{\gamma-1}\right)\frac{\left\{ r^{\frac{\gamma-1}{\gamma}} - 1 \right\}}{\{r-1\}}$$

CENTRIFUGAL COMPRESSORS

Centrifugal compressor is a radial flow machine compressing the fluid due to the dynamic action of impeller. Centrifugal compressors have impeller mounted on driving shaft, diffuser and volute casing as shown in Fig. Centrifugal compressors have air inlet at the centre of impeller. The portion of impeller in front of inlet passage is called impeller eye



Impeller is a type of disc having radial blades mounted upon it. Compressor casing has a diffuser ring surrounding impeller and the air enters the impeller eye and leaves from impeller tip to enter diffuser ring. Volute casing surrounds the diffuser ring. Volute casing has cross section area increasing gradually up to the exit of compressor. These impellers of centrifugal compressors may also be of double sided type such that air can enter from two sides (both) of impeller. Thus double sided impeller shall have double impeller eye compared to single impeller eye as shown in Fig.

Exercise :-

1 Classify the compressors.

2 Discuss the applications of compressed air to highlight the significance of compressors.

3 Describe the working of single stage reciprocating compressor.

4 Discuss the indicator diagram for reciprocating compressor. Also describe the factors responsible for deviation of hypothetical indicator diagram to actual indicator diagram.

5 Obtain the volumetric efficiency of single stage reciprocating compressor with clearance volume and without clearance volume.

6 Discuss the effects of clearance upon the performance of reciprocating compressor.

7 Define isothermal efficiency. Also discuss its significance.

8 What do you understand by multistage compression? What are its' merits over single stage compression?

Numerical problems

1 A single stage single cylinder reciprocating compressor has 60 m3/hr air entering at 1.013 bar, 15°C and air leaves at 7 bar. Compression follows polytropic process with index of 1.35. Considering negligible clearance determine mass of air delivered per minute, delivery temperature, indicated power and isothermal efficiency. [1.225 kg/min, 202.37°C, 4.23 kW, 77.1%]

2 A reciprocating compressor of single stage and double acting type has free air delivered at 14 m3/min measured at 1.013 bar, 288 K. Pressure and temperature at suction are 0.95 bar and 305 K. The cylinder has clearance volume of 5% of swept volume. The air is delivered at pressure of 7 bar and expansion and compression follow the common index of 1.3. Determine the indicated power required and volumetric efficiency with respect to free air delivery. [63.55 kW, 72.4%]

3 A single stage double acting reciprocating compressor delivers 14 m3/min measured at suction states of 1 bar and 20°C. Compressor runs at 300 rpm and air is delivered after compression with compression ratio of 7. Compressor has clearance volume of 5% of swept volume and compression follows polytropic process with index 1.3. Determine the swept volume of cylinder and indicated power in hp. [0.028 m3, 76.86 hp]

4 A single stage single acting reciprocating air compressor handles 0.5 m3/min of free air measured at 1 bar. Compressor delivers air at 6.5 bar while running at 450 rpm. The volumetric efficiency is 0.75, isothermal efficiency is 0.76 and mechanical efficiency is 0.80.

Determine indicated mean effective pressure and power required to drive the compressor. [0.185 MPa, 3.44 hp]

5 A single stage single acting reciprocating air compressor compresses air by a ratio of 7. The polytropic index of both compression and expansion is 1.35. The clearance volume is 6.2% of cylinder volume. For volumetric efficiency of 0.8 and stroke to bore ratio of 1.3 determine the dimensions of cylinder. [14.67 cm and 19.08 cm]

Unit -5

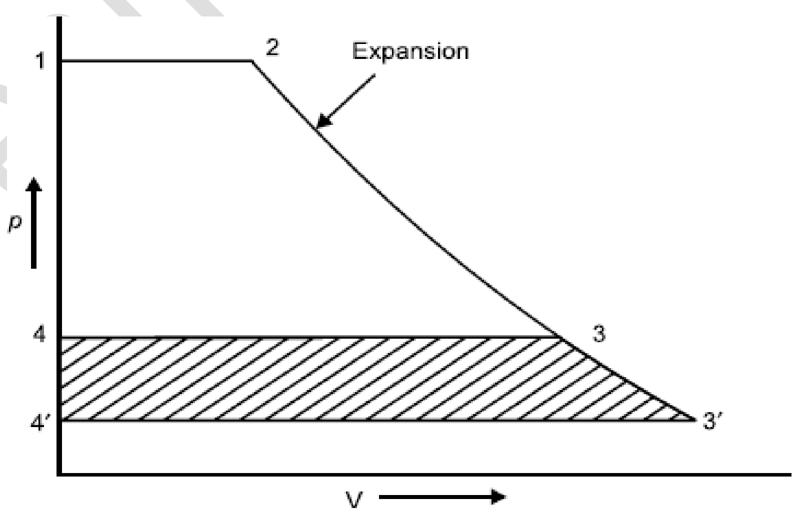
Steam condenser

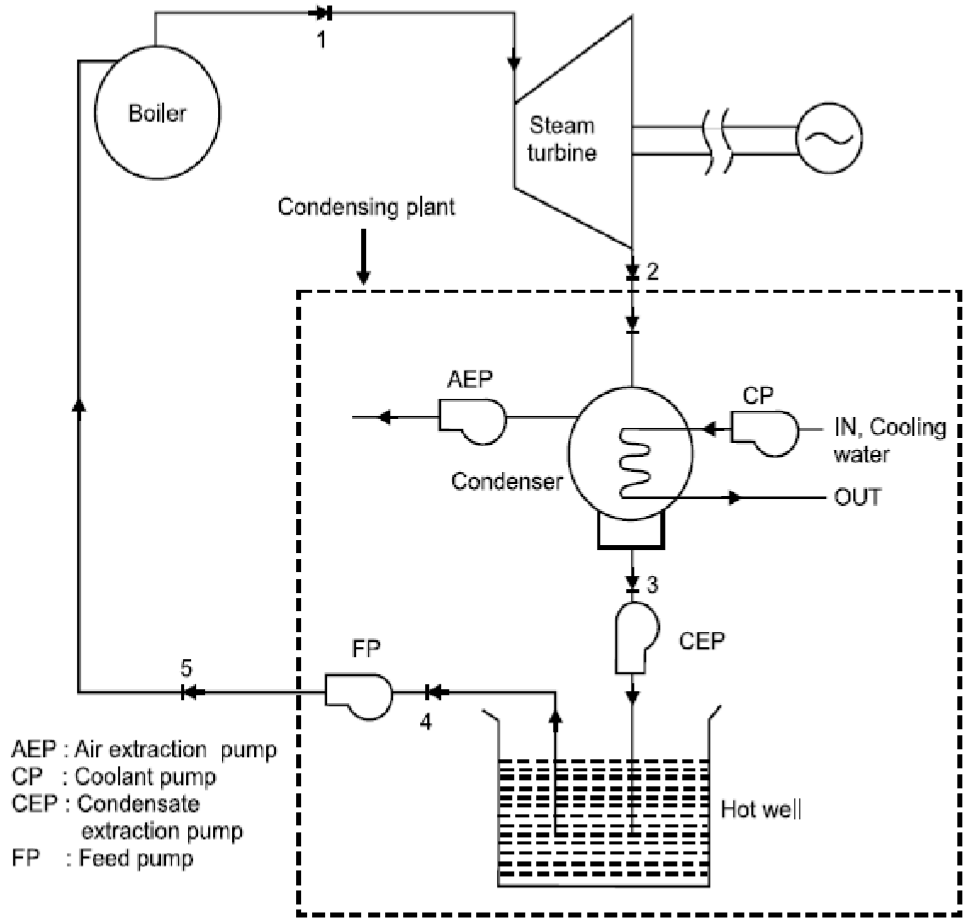
INTRODUCTION

Condenser is one of the essential components of steam power plants as it facilitates condensation of steam at given conditions with minimum expenditure of energy and minimum loss of heat and finally gives condensate which can be recirculated by feed pump to boiler for steam generation. Condenser generally operates at pressure less than atmospheric pressure. In the steam power plant the use of condenser permits expansion in steam turbine even upto less than atmospheric pressure and subsequently condensing steam to yield condensate for recirculation thus improving plant efficiency and output. Expansion in steam turbine/engine cannot be extended to pressures less than atmospheric in the absence of condenser.

"Condenser can be defined as device used for condensation of steam at constant pressure; generally pressure is less than atmospheric pressure". Condenser is thus a closed vessel which is generally maintained at vacuum and cold fluid is circulated for picking heat from steam to cause its condensation. Use of Condenser offers advantages such as hotter feed water for being sent to boiler',

'removal of air and non-condensable dissolved gases from feed water', 'recovery of condensate reduces treated water requirement', 'expansion up to sub atmospheric conditions and capital cost is reduced by recycling of feed water' etc. Increase in expansion work due to use of condenser is shown in Fig. *p-V* diagram.





Schematic for steam power plant having condensing plant

Discharge from steam turbine passes into condenser where it is condensed using cooling water being circulated employing coolant pump. Condensate being at pressure less than atmospheric pressure is to be sucked out using condensate extraction pump. Condensate is extracted and sent to hot well from where it is pumped to boiler using feed pump. Dissolved gases and air etc. if any are extracted out from condenser using air extraction pump. This air or vapour may be present because of air leaking into vacuum system and air coming with steam. Cooling water for supply to condenser is taken either from some river or from cooling tower. Cooling water requirement may be up to 100 kg water per kg of steam or even more depending upon the type of condenser and its capacity. Cooling tower cools the hot cooling water leaving condenser to get cooled by evaporation of water and heat exchange with air. Water evaporated or lost in cooling tower is compensated by the make up treated water available from feed water treatment plant.

CLASSIFICATION OF CONDENSER

Condenser can be broadly classified on the basis of type of heat exchange i.e. direct or indirect contact condensers.

(i) Direct contact type or Mixing type or Jet condenser

(ii) Indirect contact type or Non-mixing type or Surface condenser

(iii) Evaporative condenser

Jet condensers have direct contact between steam and cooling fluid thereby causing contamination of condensate. Surface condensers have indirect heat exchange through metal interface and the two fluids do not come in direct contact to each other. Evaporative condensers use evaporation of water for heat extraction and is well suited for dry weather so that evaporation is not difficult. Due to direct contact of two fluids the circulating water requirement is much less in jet condenser as compared to other types of condensers. Space requirement and size of condenser etc. are also less with jet condensers. Surface condenser is advantageous over direct contact type condensers because any type of cooling fluid can be used in it and also there is no scope of contamination etc. Different types of condensers are discussed ahead.

(i) *Jet condenser:* In jet condenser the steam to be condensed and cooling water are intimately mixed by breaking up of water in the form of spray and allowing small sized water particles to fall down through the body of steam. The water may also be discharged out through suitably shaped nozzles into body of steam. Thus it is desired to atomize water into small sized particles so that increased surface area is available for heat exchange between hot and cold fluid. Number of arrangements for flow of steam and water are available such as; counter flow type having steam entering from bottom and flowing upwards while water enters from top and falls downwards with air pump connected on top where air is colder etc. Jet condenser may be further classified based on relative movement of two fluids, and based on arrangement used for removal of condensate. Based on relative moment of two fluids jet condenser can be,

(a) Counter flow jet condenser

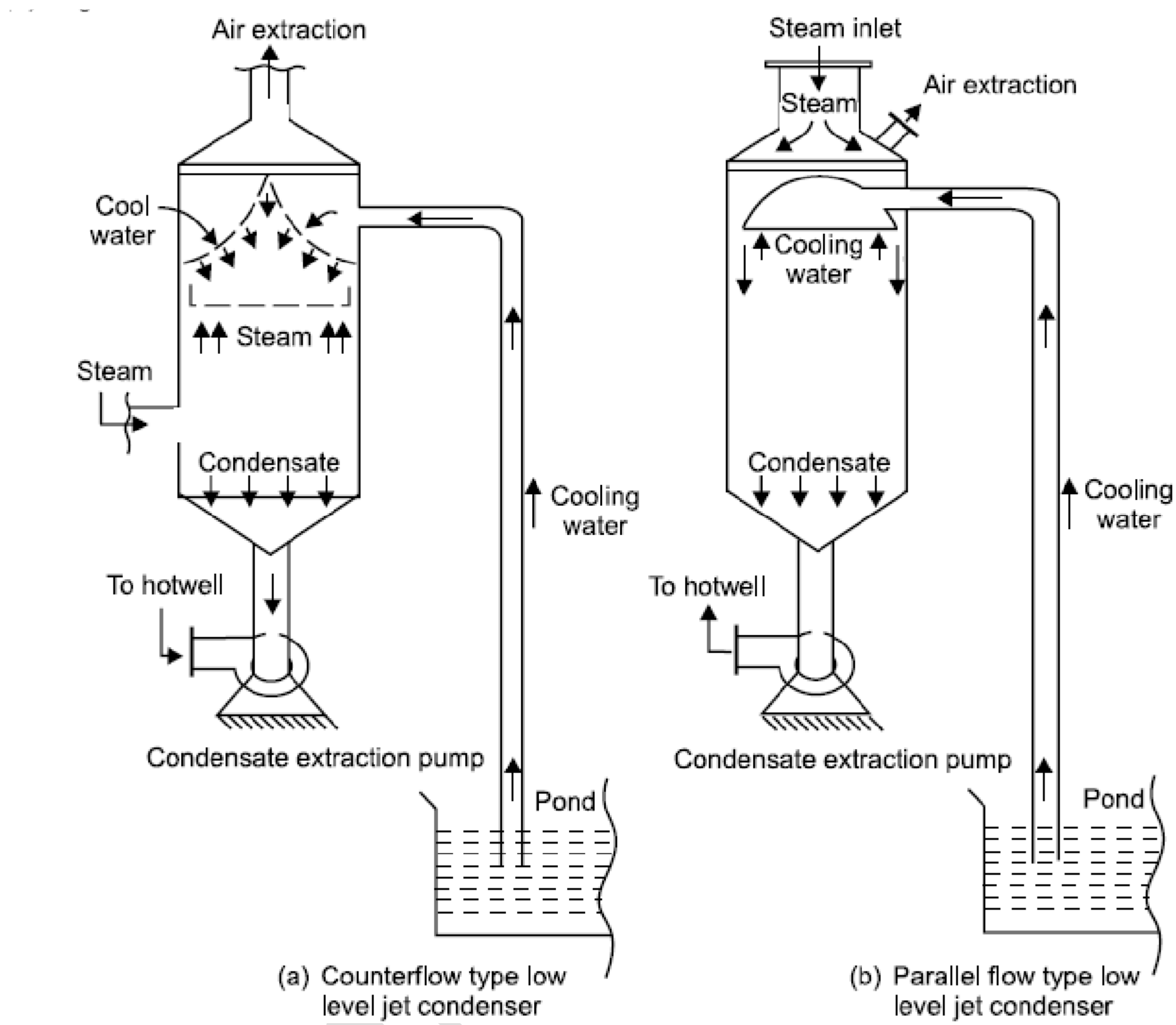
(b) Parallel flow jet condenser

Based on arrangement for removal of condensate jet condenser can be,

(a) Low level jet condenser

(b) High level jet condenser

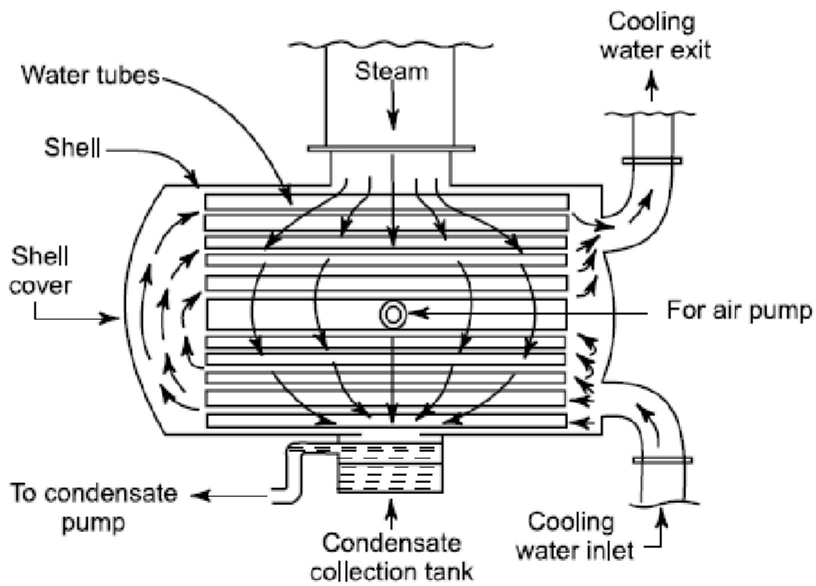
(c) Ejector condenser



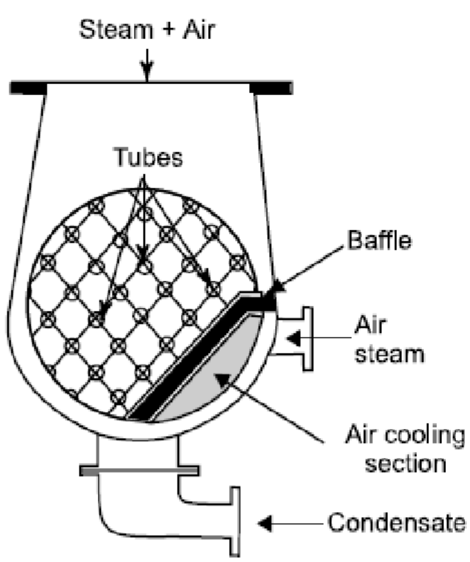
Schematic of low level jet condenser

The heat transfer occurs between two fluids through surface in between. Generally, cooling water flows through the pipes/tubes and steam surrounds them. These condensers are preferred in the locations where large quantity of poor quality cooling fluid (impure water) is available and condensate is to be recirculated. Surface condensers can be classified based on number of passes of condenser i.e. single pass or multipass. Number of times the cooling water crosses any transverse section is called a pass. Surface condensers may be of 'down flow type' or 'central flow type' depending on the type of flow of condensate and tube arrangement. Typical surface condenser having two passes, down flow type and central flow type arrangement are shown in Fig

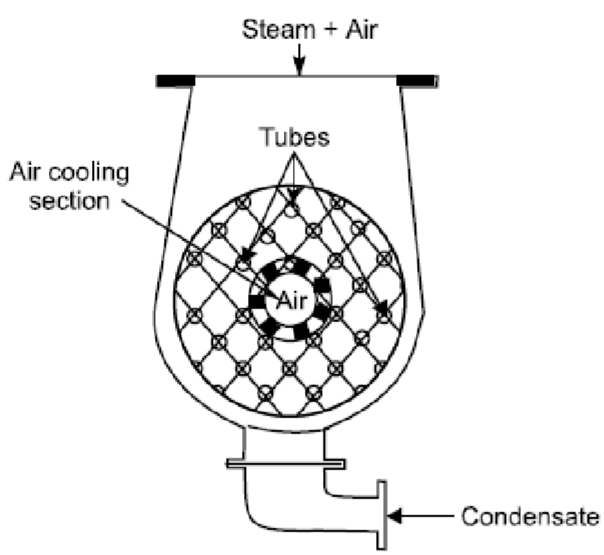
Two pass surface condenser has cooling water entering from one end and coming out after twice traversing through the tubes (generally, brass) containing water and surrounded by steam to be condensed. Condensate gets collected at bottom and is subsequently sucked by condensate extraction pump. Steam is admitted from the top. Cooling water may be picked directly from river/pond/cooling tower. For extraction of air the provision is made for air pump. Thus, this type of condenser has three pumps i.e. one for circulating cooling water, second for condensate extraction and third for air extraction. In surface condenser the space occupied by tubes in shell is about 10% of shell volume. Steam is not passed through the tubes because at this steam pressure the specific volume of steam is large requiring large number of tubes.



(a) Two pass surface condenser



(b) Down flow condenser



(c) Central flow surface condenser

Down flow condenser has steam and air entering from top and flowing downwards across the bundle of tubes having cooling water flowing through them. Air is extracted from bottom and before being handled by air pump it is flown through air cooler so as to reduce the temperature of air. Low temperature of air enhances the air handling capacity of pump. With the flow of steam down and simultaneous heat exchange the condensate is taken out by condensate extraction pump.

Central flow condenser has air cooling section in the center of condenser. Steam enters from top and passes over the tube banks of similar type as in case of down flow condenser. As air is being sucked from center so the flow of steam is radially inwards towards the center. During this flow steam passes over tubes. Condensate is collected from bottom. In this type of condenser there is better contact between steam and tubes because of radial flow of steam in whole of condenser, thus arrangement is better as compared to down flow condenser. In different designs of condenser it is always attempted to have maximum heat transfer between two fluids. Also air extraction should be done effectively. Thus designer of condenser should keep following things in consideration for making a better design surface condenser.

(i) Steam should be uniformly distributed over cooling water tubes. i.e. cooling surface.

(ii) Distribution of steam should be such that there is minimum pressure loss.

(iii) Number of tubes should be minimum. Water must be flown inside tubes and steam should surround them.

(iv) Tubes should be cleaned from inside and outside both. Although on external surface the steam surrounding tubes prevents deposition. For internal cleaning of tubes mechanical or chemical means of cleaning be used at frequent intervals.

(v) Leakage of air into condenser (due to vacuum) should be prevented as it reduces the work output. Also this reduces the heat transfer rate. Even if there is leakage of air, arrangement should be made for quick and effective removal of air with minimum work input.

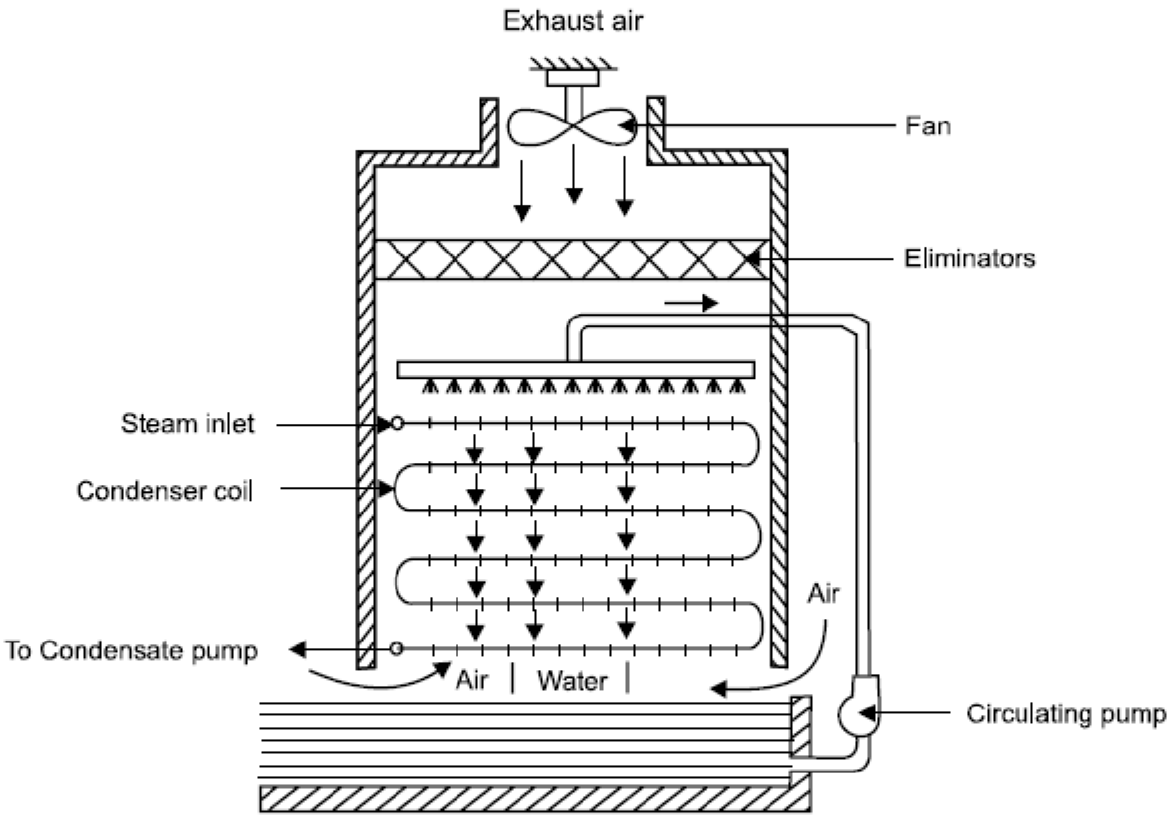
(vi) Air should be cooled to maximum extent inside condenser before being thrown out as this shall cause condensation if possible within condenser and thus reduce loss of condensate. Also the cool air shall enhance air handling capacity of pump.

(vii) Rate of circulation of cooling water should be such that the range of temperature variation in cooling water lies near the optimum temperature range. Generally, the cooling water temperature rise is limited to 10°C for having maximum heat exchange between two fluids.

(viii) Material of tubes is generally taken as brass. Tube material should be such as to offer maximum heat transfer rate i.e. high thermal conductivity. Generally, surface condensers are bulky and require large space.

(ix) Cost of surface condenser should be kept low. Capital cost, running and maintenance cost should be maintained as low as possible. Generally, these costs are high in case of surface condenser as compared to other types of condensers.

Evaporative condenser: Evaporative condensers are generally used where the availability of water is very poor. Figure below shows the schematic of such type of condenser where water falls from top through the nozzles over the condenser coil. Water picks up heat from the steam flowing through condenser coil and gets warmed up. This water is recirculated by circulation pump. Air flow inside condenser is maintained by using exhaust fan. This flow of air across condenser coil may be natural or forced to enhance the cooling rate.

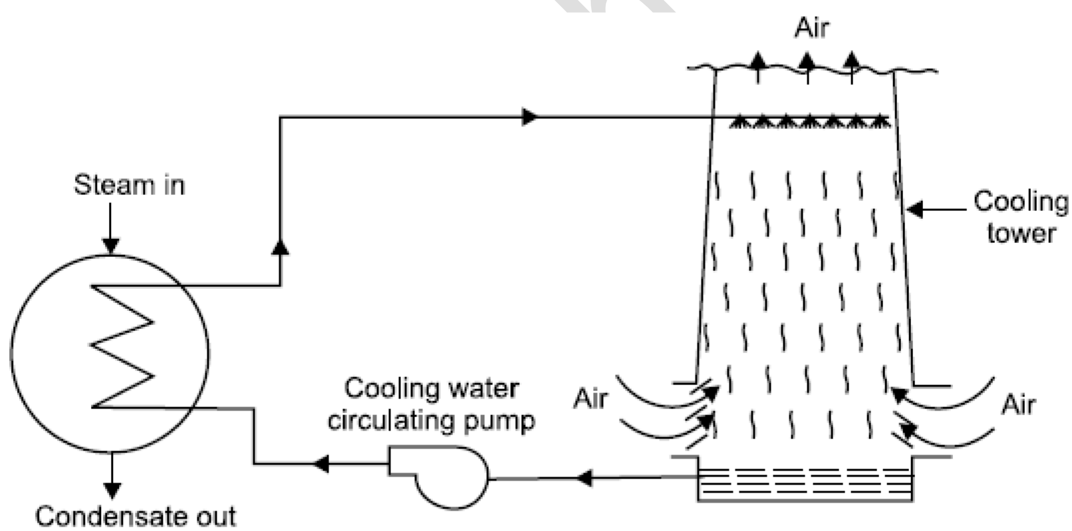


Evaporative condenser

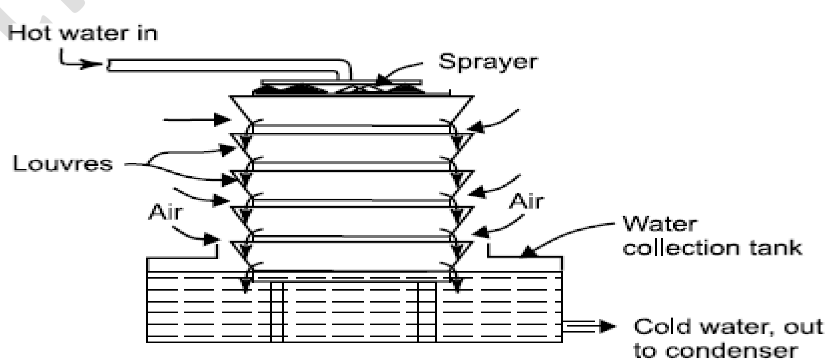
Water gets evaporated and evaporated vapours are taken by air leaving condenser. Heat required for evaporation is extracted finally from the steam flowing inside tubes and thus causing its phase transformation. For preventing the exit of water vapours with air going out the separator/eliminator is put on the top before the final exit by which water vapour are recovered up to certain extent. Evaporative condensers are named so because the technique of evaporation is used for realizing the cooling. Amount of water to be sprinkled on condenser tubes should be just sufficient to maintain tube surface in thoroughly wet state. In case of air being humid the vaporizing capacity of wet air gets reduced compared to dry air and so the performance of evaporative condenser deteriorates when humidity in atmosphere is high. Evaporative condenser is advantageous over the surface condenser as the vacuum maintained in evaporative condenser is not very high and the water requirement is small. These condensers are generally used in small capacity power plants where shortage of water supply is there.

COOLING TOWER

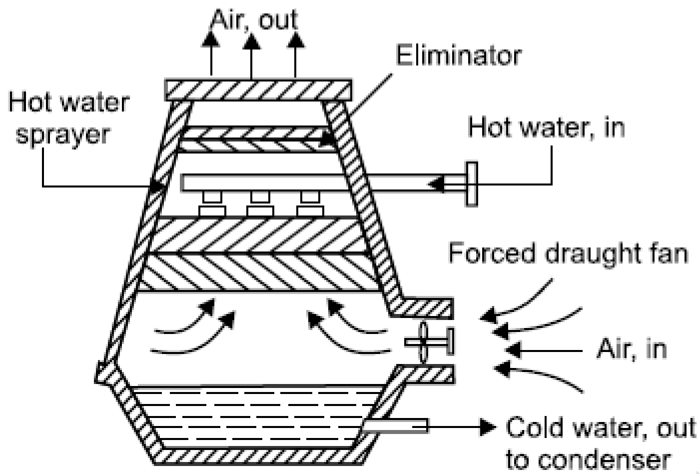
Cooling tower is similar to evaporative condenser where water used for cooling is being cooled effectively. Water used for cooling becomes hotter after extracting heat from condenser steam and needs to be cooled down if it is to be recycled. Cooling towers are preferably used where the water supply is limited and cooling water has to be recirculated without being thrown out. Cooling tower is such an arrangement made of wood or metal structure having baffles inside to facilitate better heat exchange between hot water falling down and atmospheric air blowing across it. Generally, hot water is admitted from top and is broken into small size (atomized) while falling down. Air enters tower at bottom and flows upward either due to natural draught or forced draught as the case may be. Air picks up heat by intimate contact with hot water particles and leaves cooling tower from exit passage at top. Cooled water falls down and is collected in a tank at bottom of cooling tower. The heat transfer from hot water to air occurs due to evaporative cooling of water and convective heating of air both. The effectiveness of cooling tower diminishes in humid weather conditions due to reduced capacity of air. Dry air shall offer better cooling effectiveness as compared to moist air. During cooling there occurs some loss of water as it is carried away by air. This water loss may be from 1 to 4% due to evaporation and drift losses.



(a) Schematic of cooling tower



(b) Atmospheric cooling tower



(c) Mechanical draught (forced) cooling tower

Figure shows schematic of different cooling towers. The performance of cooling tower depends largely upon the duration of contact between water particle and air, surface area of contact between water particle and air, humidity of air and relative velocity of air and water flow etc

Exercise:-

1 What do you understand by condenser? Discuss its significance.

2 How does condenser improve performance of steam power plant?

3 Discuss different types of condenser briefly.

4 Differentiate between surface condenser and jet condenser.

5 Give a sketch of barometric jet condenser and explain its working.

6 Discuss the effect of air leakage upon the performance of condenser.

7 How the air leaking into condenser is extracted out? Explain.

8 Describe the factors affecting the efficiency of condensing plant.

9 Discuss the relevance of Dalton's law of partial pressures in condenser calculations.

10 What do you understand by cooling towers? Explain their utility.

11 Determine the vacuum efficiency of a surface condenser having vacuum of 715 mm of Hg and temperature of 32°C. The barometer reading is 765 mm of Hg. [98%]

12 A surface condenser having vacuum of 715 mm Hg and temperature of 32°C has cooling water circulated at 800 kg/min. The cooling water entering condenser becomes warmer by 14°C. The condensate is available from condenser at 25 kg/min. The hot well temperature is 30°C. Barometer reading is 765 mm of Hg. Determine the mass of air in kg/m3 of condenser volume and dryness fraction of steam entering. [0.022 kg/m3, 0.84]

13 A surface condenser has vacuum of 71 cm Hg and mean temperature of 35°C. The barometer reading is 76.5 cm Hg. The hot well temperature is 28°C. Steam enters condenser at 2000 kg/hr and requires cooling water at 8°C at the rate of 1000 kg/min. Cooling water leaves condenser at 24°C. Determine

(i) the vacuum efficiency of condenser,

(ii) the undercooling in condenser

(iii) corrected vacuum in reference to standard barometer reading, (iv) the condenser efficiency.

[0.982, 7°C, 70.5 cm Hg, 0.505]

14 In a surface condenser steam enters at 40°C and dryness fraction of 0.85. Air leaks into it at 0.25 kg/min. An air pump is provided upon the condenser for extracting out air. Temperature at suction of air pump is 32°C while condensate temperature is 35°C. Determine.

(i) the reading of vacuum gauge

(ii) the volume handling capacity of air pump in m3/hr

(iii) the loss of condensate in kg/hr.

[705 mm Hg, 500 m3/hr, 16.9 kg/hr]

15 A steam turbine discharges steam into a surface condenser having vacuum of 700 mm Hg. The barometer reading is 760 mm Hg. Leakage into condenser is seen to be 1.4 kg/min. The air pump is employed for extracting out air leaking in. Temperature at the inlet of air pump is 20°C. The air pump is of reciprocating type running at 300 rpm and has L : D ratio of 2 : 1. Determine,

(i) the capacity of air pump is m3/hr

(ii) the dimensions of air pump

(iii) the mass of vapour going out with air in air pump, kg/hr.

[1250 m3/hr, bore: 35.36 cm, stroke: 70.72 cm, 21.5 kg/hr]

16 A surface condenser handles condensate at 70.15 cm Hg when barometer reads 76 cm Hg. Steam entering at 2360 kg/hr requires cooling water at 6.81 _ 102 kg/hr, 10°C. Cooling water leaves condenser at 27.8°C while condenser has mean temperature of 37°C. Air leaks into condenser at 0.3 kg/min. Determine,

(i) the mass of vapour going out with air per hour

(ii) the state of steam entering.

[119 kg/hr, 0.89]

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