Institute: Jnan Chandra Ghosh Polytechnic

Deptt.: Mechanical Engineering

Subject: Thermal Engg.-II

Topic dicussed: Steam Condenser.

Teacher: RATAN SIKDAR

20.1. CONDENSER AND ITS UTILITY

The efficiency of a steam power plant working on Carnot cycle is given by

$$\eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

where T_1 is the temperature at which heat is supplied and T_2 is the temperature at which heat is rejected. This expression reveals that for obtaining maximum efficiency, it is necessary that the difference between the temperature T_1 and the temperature T_2 should be as large as possible. The temperature T_1 can have the maximum optimum value consistent with metallurgical considerations and so for maximum efficiency, the temperature T_2 should have the minimum value. There is a definite relation between steam temperature and pressure. Low exhaust temperature means low exhaust pressure. Steam cannot be exhausted to atmosphere if it is expanded in the steam turbine or engine to a back pressure which is lower than the atmospheric pressure. However, the steam by exchanging heat with water in a vessel can be condensed resulting in a fall in its temperature and pressure. However, the condensation of steam will cause reduction in pressure only when water is contained in a closed vessel. With the vessel open to atmosphere the condensation will of course be there but the pressure will not drop below the atmospheric pressure.

The closed vessel in which steam is condensed by abstraction of heat and in which vacuum is maintained is called *condenser*.

Condensation of steam enables expansion of steam to a lower back pressure. The available enthaply drop increases. Consequently more work is done and the plant efficiency improves.

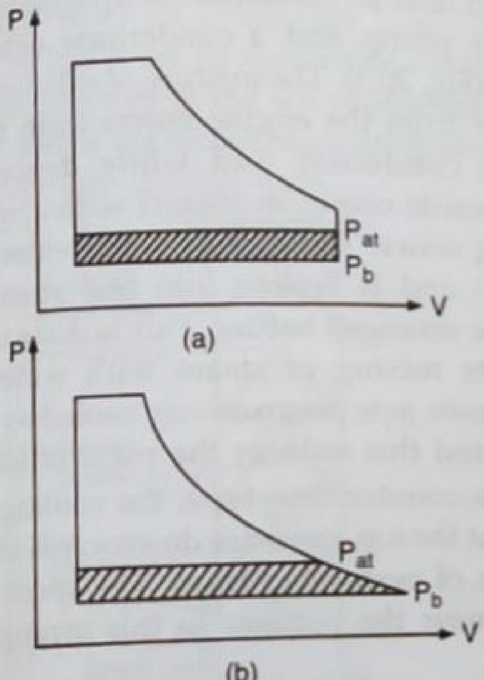
Due to increased cost involved in the creation and maintenance of higher vacuum, a limit is imposed beyond which the reduction of back pressure does not prove economical. For steam engines the lowest practical exhaust pressure is 65 cm of mercury vacuum. The steam engines being of positive displacement have to provide piston displacement equivalent to volume of exhaust steam and as such the cylinder dimensions impose a limit on the engine condenser pressure. Steam turbines being steady flow machines may be designed to operate at 73.25 cm of mercury vacuum or even more depending upon the capacity of the plant and cooling water available.

The hatched areas in Fig. 20.1(*a*) and 20.1(*b*) represent the increase in work done by a steam engine and a steam turbine by exhausting the steam into a condenser.

The following are the advantages obtained by incorporating a condenser in a steam engine or steam turbine plant :

(1) Improvement in the efficiency of the plant due to increased available enthalpy drop.

(2) Reduction in steam consumption per kW/hour. Increase in vacuum from 71 to 73.5 cm. of Hg gives about 45% reduction in steam consumption.



P_{at} = Atmospheric pressure
P_b = Condenser pressure

Fig. 20.1. Increase in work

(3) The condensed steam, called *condensate* collected in the hot well may be pumped back to the boiler as feed water. Recovery of condensate reduces the make up water that must be added to the system from 100% when non-condensing to 1.5% when condensing. For steam power plants where sufficient quantity of good quality boiler feed water is not available, recovery of condensate is very important. For marine practice where sea water is treated before being used in the boiler, recovery is a necessity.

(4) To prevent the encrustation of boiler, the feed water if not available in pure form has to be treated first in the water softening plant. The recovered condensate reduces the capital and running cost of the water softening plant.

(5) Provision for the supply of hot water to the boiler results in fuel economy and safety from thermal stresses.

20.2. ELEMENTS OF A CONDENSING PLANT

Fig. 20.2 shows the essential elements which comprise a condensing unit:

(1) A closed vessel in which steam is condensed.

(2) A condensate pump to extract the condensed steam from the condenser and feed it to hot well.

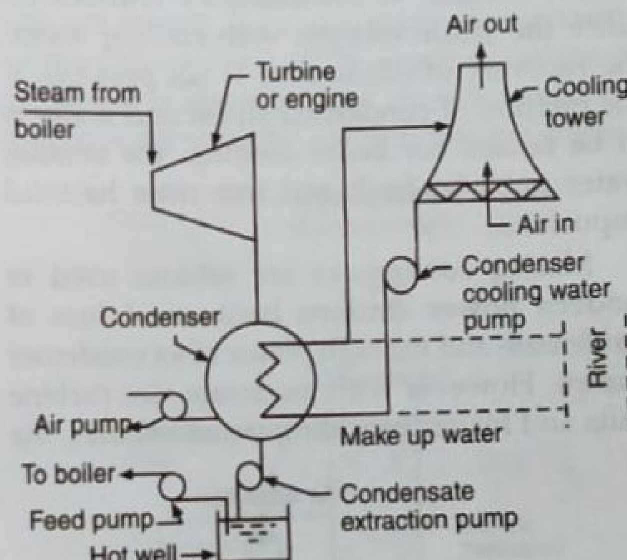


Fig. 20.2. Elements of a condensing unit

(3) A dry air pump to remove air and non-condensable gases. Sometimes a single pump known as wet air pump serves to remove both air and condensate.

(4) A feed water pump to force the condensate from the hot well to the boiler.

(5) A cooling water pump for circulating cooling water.

(6) An arrangement such as cooling tower or spray pond to recool the circulating water after it gets heated in the condenser. This is necessary when the supply of cooling water is scarce and same water has to be used over and over again for cooling purposes.

(7) An atmospheric relief valve for relieving the pressure in the condenser when the condenser does not function properly. The steam then escapes through the valve and engine operates as non-condensing.

20.3. TYPES OF CONDENSERS

The condensers can be classified into two groups namely jet condensers and surface condensers. These two types are discussed briefly in the following sections.

(A) *Mixing* or *jet condensers.* There is a direct contact between the steam and cooling water and the heat exchange is by direct conduction. The steam quickly condensers in water introduced in the form of spray or jet and the stream of warm water (condensed steam + water) is continuously withdrawn. Since the steam escapes with cooling water, the recovery of condensate is not possible. If the mixture of condensed steam and water is to be reused for boiler feeding, the cooling water must be fresh and free from harmful impurities.

Mixing condensers are seldom used in modern power stations because of loss of condensate and the high power of jet condenser pumps. However with moderate size turbine units and for reciprocating steam engines, the jet condensers are used especially where an abundant supply of good feed water is available.

The jet condensers are divided into:

(*a*) Parallel flow in which the steam and the cooling water flow are in the same direction.

(*b*) Counter flow in which steam flows in the opposite direction to the cooling water.

Depending upon the arrangement of the removal of condensate, the jet condensers are further subdivided into the following three categories:

(*i*) *Low level jet condenser.* A low water level parallel flow jet condenser is equipped with a dry air pump and a condensate extraction pump (Fig. 20.3). The mixture of exhaust steam and air from the engine enters from the top of the condenser and while descending downwards comes in contact with a spray of cooling water. The cooling water enters from the top and is broken into fine streams by suitable arranged baffles. This is done to have intimate mixing of steam with water. The condensate gets progressively cooled as it goes down and this reduces the plant efficiency.

In a counter flow type, the cooling water enters at the top, cascades downwards through a series of perforated trays. The spent steam enters near the bottom. In this arrangement

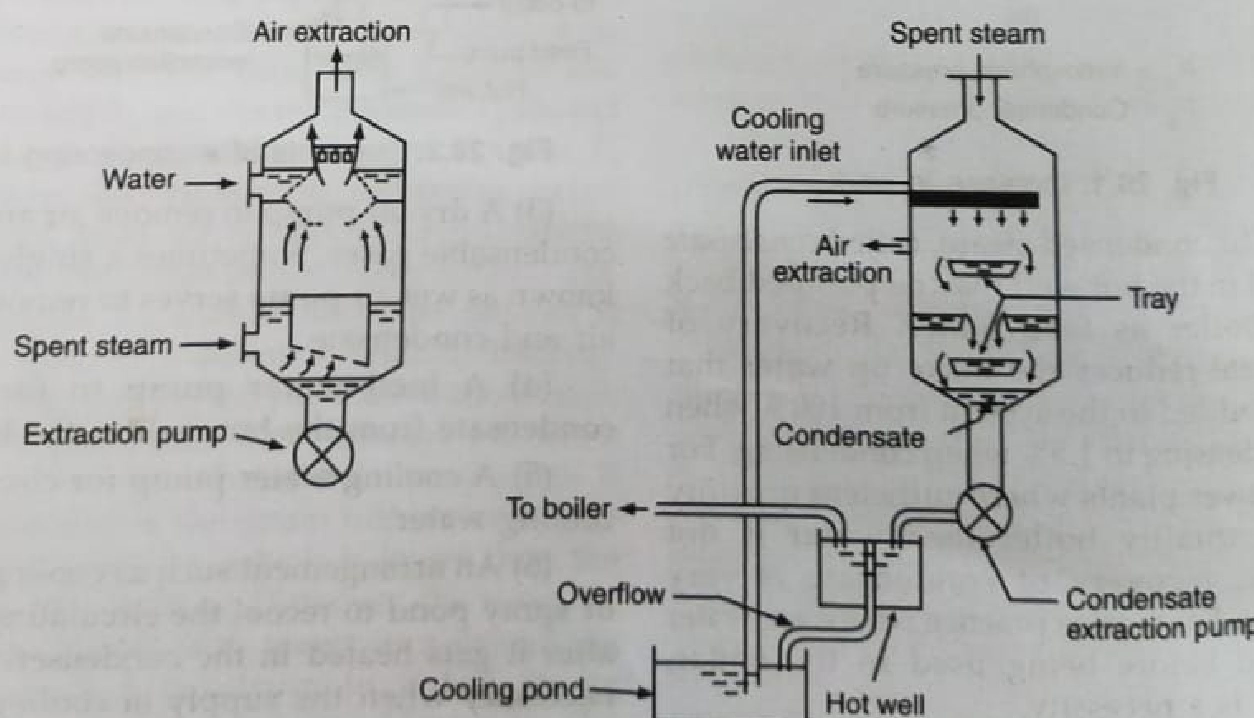


Fig. 20.3. Jet condensers (Low-Level)

The condenser is used for moderate vacuum and dispenses with extraction pump.

(B) ***Surface condensers.*** The heat is convectively transferred through a wall interposed between steam and water. The steam is drawn across a nest of tubes which are arranged in certain pattern and are maintained at a temperature lower than that of steam by a flow of cooling water through them.

Because the steam and circulating water do not mix, the condensate can be recovered. Moreover cooling water need not be up to a high standard of purity. This fact is of great advantage for ships which can carry only a limited amount of pure treated water for steam raising and use sea water for cooling purposes. All the marine installations are equipped with surface condensers.

The surface condensers may be classified according to:

(*a*) direction of flow of condensate and arrangement of tubing : down flow, central flow and inverted flow type surface condensers

(*b*) number of passes of water : single pass or multipass

(*c*) shape of shell which may be circular, oval or *U* shaped

Fig. 20.6 shows a two pass down flow surface condenser. The two pass arrangement is compact, more efficient in the process of heat exchange and is to be preferred when the supply of cooling water is limited. The suction of the extraction pump, installed at the bottom, causes the spent steam entering from the top to flow downwards over a nest of tubes. The cooling water enters at one end of the bottom-set of tubes, flows through them till it reaches the other end of the shell. The water then rises up and flows in the opposite direction through the upper half of the tubes and finally leaves through the outlet.

A section of tubes near the air pump suction is screened off by providing a baffle [Fig. 20.7(*a*)] This is done to reduce the amount of water vapour going along with air. Moreover the lowest temperature maintained in this section increases the density of air and so we need an extraction pump of a small capacity.

In the central flow type surface condenser [Fig. 20.7(*b*)] the air extraction pump is placed in the centre of the tube nest. The steam flowing radially towards the centre passes over the entire periphery of tubes and is extracted at the bottom.

In the inverted flow type surface condenser, the steam enters near the bottom and flows upwards since the air suction is at the top. After flowing near the outer surface the condensed steam falls downwards and leaves from the bottom where the condensate extraction pump is installed.

Requirements of a modern surface condenser : The following are the requirements of a

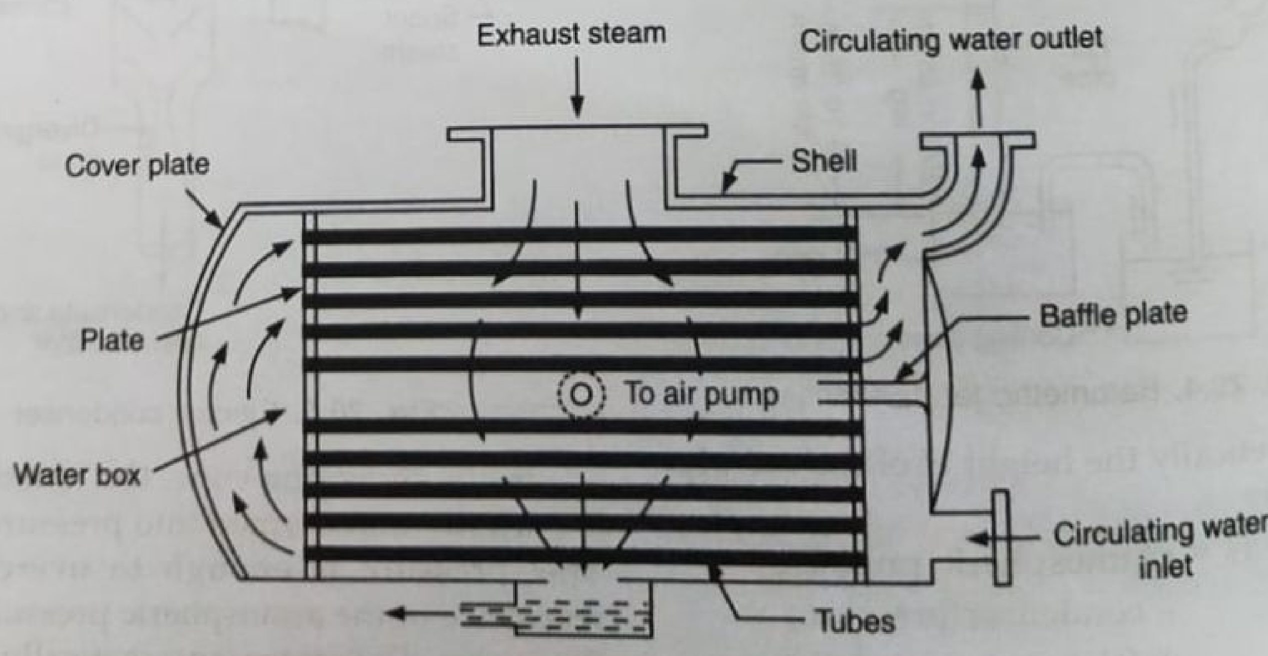


Fig. 20.6. Two-pass downflow surface condenser

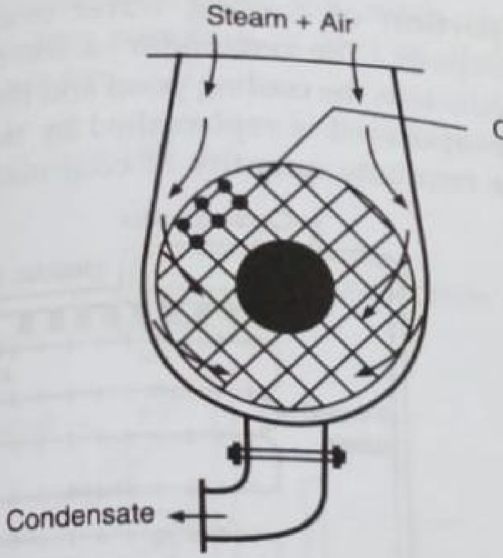


Fig. 20.7. (a) Central flow surface condender

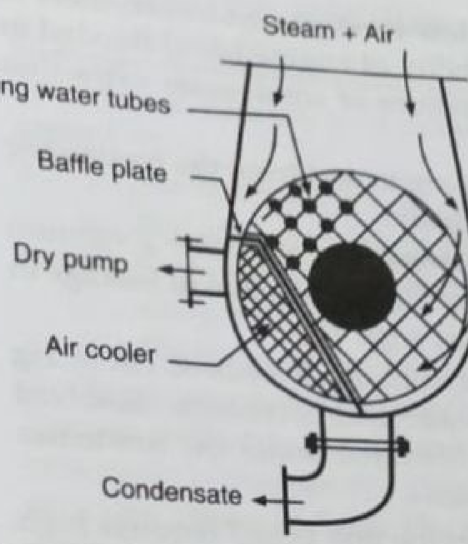


Fig. 20.7. (b) Down flow surface condender

modern surface condenser, sometimes referred to as an ideal condenser :

(1) The steam should be well distributed in the vessel and the pressure drop should be minimum.

(2) The steam should enter the condenser with least possible resistance.

(3) Circulating water should pass through the surface condenser with least friction but at a velocity consistent with high efficiency.

(4) The steam should lose only its latent heat and there should be no condensate depression (undercooling of condensate). To achieve this the quantity of water circulating through the tubes should be so regulated that temperature of leaving water is the same as the saturation temperature of steam.

(5) The water is to flow inside the tubes and vapour outside so that outside surface of the tubes (which is rather difficult to clean) does not get deposited with sediments. The cooling water, if dirty, would leave such deposits on the inside of the tubes. By removing the end cover plates and passing motor driven brushes, the inside surface of tubes can be cleaned.

(6) There should be no leakage of air into the condenser and if any, arrangements must be made to extract it rapidly and with least expenditure of mechanical energy. The presence of air in the condenser would destroy the vacuum and will hamper the rate of heat transfer from the steam to the coolant because of its poor conductivity.

(7) The air extraction should be at the coolest section of the tubes and the air exit should be shielded from the down flowing condensate by means of a baffle. This is to extract the air with a comparatively much smaller amount of water vapour, *i.e.*, without entailing much loss of potential condensate.

20.4. COMPARISON OF JET AND SURFACE CONDENSERS

Jet condenser : A jet condenser has the following advantages :

(1) More intimate mixing of steam and cooling water.

(2) Requires less quantity of circulating water to affect the steam condensation.

(3) Equipment simple and low in cost.

(4) Less building space needed.

(5) In barometric and ejecter condensers, condensate extraction pump is dispensed with and the low level jet condenser does not require cooling water pump.

The disadvantage of jet condenser are :

(1) There is waste of condensate.

(2) If the condensate has to be salvaged, the cooling water should be clean and free from harmful impurities.

(3) With low level jet condenser, there is greater possibility of engine being flooded in the event of failure of condensate extraction pump.

(4) The piping to and from the barometric condenser is costly.

(5) With barometric condenser a vacuum loss (1–1.5 cm of Hg) occurs due to leakage in the long exhaust pipe line.

(6) Vacuum seldom exceeds 66 cm of Hg as the cooling water always contains dissolved air which gets liberated under the condenser vacuum conditions.

(7) The air extraction pump requires high power which may be about two times of that required for surface condenser.

Surface condenser : A surface condenser has the following advantages :

(1) High vacuum can be attained and greater plant efficiency is achieved.

(2) Any kind of cooling water can be used and so the cost of water softening plant is considerably reduced.

(3) Chances of losing vacuum are minimum because water supply is not affected by drop in vacuum.

(4) The condensate can be salvaged and used for boiler feed.

(5) The arrangement can be conveniently adapted to weigh the condensate for tests in laboratory.

(6) Suitable for high capacity units.

The surface condenser is, however, bulky and so requires considerable floor space for its erection. Moreover, the unit has a high capital and maintenance costs.

20.5. EVAPORATIVE CONDENSER

The steam to be condensed enters a coiled finned pipe system at *A* (Fig. 20.8). The water from a cooling pond is pumped to a horizontal header *C* which is fitted with spray nozzles. The cooling water sprayed over the finned tubes gets evaporated. The steam loses its heat both to the cooling water and the current of air circulating over the water film. The heated air moves upwards carrying along with it a portion of cooling water evaporated into vapour. The remainder of the cooling water falls into the cooling pond and the loss of water evaporated is replenished by the addition of a requisite quantity of cold make up water.

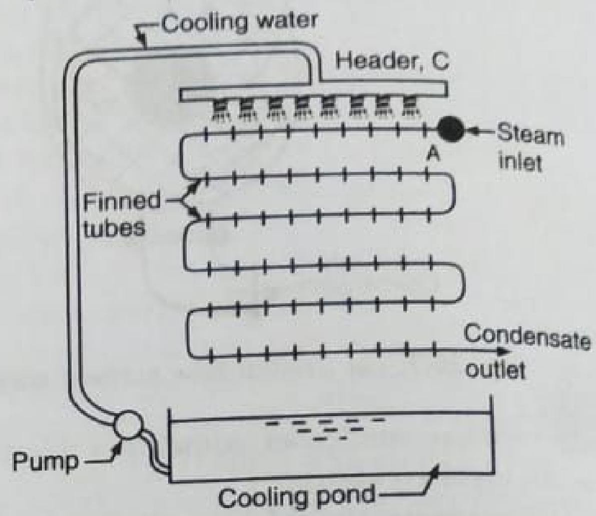


Fig. 20.8. Evaporative condenser

The arrangement is simple, cheap, does not require large quantity of cooling water and so needs a cooling water pump of small capacity.

The vacuum created is, however, not so high as in the surface condenser. Moreover the cloud of evaporated water is also a nuisance to the surroundings.

20.6. CONDENSER VACUUM

The vacuum obtainable from a condenser depends upon tightness of valves and joints, amount of air infiltration and the temperature of steam after condensation. The vacuum is not uniform throughout the condenser, being least at the air pump suction, high in the body of the condenser and still higher at the engine exhaust valve.

The degree of vacuum measured by means of a vacuum gauge (Fig. 20.9) can be expressed in the following different ways :

(*a*) Excess of atmospheric pressure over observed vacuum. A 65 cm of vacuum means that the pressure of atmosphere is 65 cm of Hg above the condenser pressure.

(*b*) Percentage of vacuum, *i.e.*, ratio of observed vacuum to atmospheric pressure. If the gauge reads 65 cm of Hg with the barometer reading standing at 75 cm, then percentage vacuum

$$= \frac{65}{75} \times 100$$

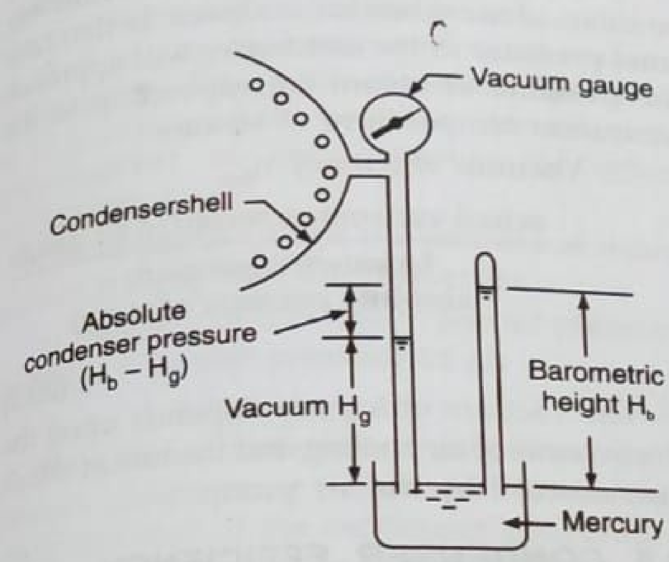


Fig. 20.9. Vacuum measurement

(c) Absolute pressure

Let H_b = barometric height in cm of Hg

H_g = vacuum gauge reading in cm of Hg

Then absolute pressure in the condenser

$$= (H_b - H_g) \text{ cm of Hg}$$

The vacuum in the condenser is thus a function of both absolute pressure as well as the barometric pressure. The barometric height is a variable quantity, changing from place to place. Accordingly the gauge reading would also vary, if the absolute pressure is to remain constant. For purposes of comparison it is more convenient to refer the vacuum readings to a standard barometric height of 76 cm of Hg.

$$\therefore \text{ Corrected vacuum} = 76 - (H_b - H_g) \quad ...(20.1)$$

Standard atmospheric pressure

$$= 76 \text{ cm of Hg} = 1.01325 \text{ bar}$$

$\therefore$ Pressure equivalent of 1 cm of Hg

$$= \frac{1.01325}{76} = 0.01333 \text{ bar}$$

20.8. VACUUM EFFICIENCY

The vacuum efficiency is a measure of the degree of perfection in achieving the aim of maintaining a desired vacuum in condenser. The vacuum efficiency may be defined as the ratio of actual vacuum as recorded by the vacuum gauge to the ideal vacuum.

Vacuum efficiency = η_{vac}

$$= \frac{\text{actual vacuum as recorded by gauge}}{\text{ideal vacuum}} \quad ...(20.2)$$

The ideal vacuum means the vacuum due to steam alone when air is absent. In that case total pressure in the condenser will approach the pressure of steam corresponding to the saturation temperature of steam.

∴ Vacuum efficiency η_{vac}

$$= \frac{\text{actual vacuum as recorded by gauge}}{\text{barometric pressure} - \text{absolute pressure of steam}} \quad ...(20.3)$$

The vacuum efficiency depends upon the effectiveness of air cooling and the rate at which it is removed by the air pump.

20.9. CONDENSER EFFICIENCY

The purpose of an ideal condenser is to remove only the latent heat so that temperature of condensate equals the saturation temperature corresponding to condenser pressure. In other words there is no under cooling of condensate. Further, the maximum temperature to which the cooling water can be raised is the condensate temperature. The condenser efficiency is then defined as the ratio of actual rise in the temperature of cooling water to the maximum possible rise.

$$\text{Condenser efficiency} = \frac{t_2 - t_1}{t_3 - t_1} \quad ...(20.4)$$

where t_3 = saturation temperature corresponding to condenser pressure, t_2 and t_1 are the outlet and inlet temperatures of cooling water.

20.10. DALTON'S LAW AND AIR-VAPOUR MIXTURE

Dalton's law forms the basis for the analytical treatment of the problems dealing with mixture of gases or of gas and vapour. The law states:

"The total pressure exerted by a mixture of gases or a mixture of gas and vapour (which have

no chemical action on each other) is equal to the sum of partial pressure of the constituents".

The partial pressure of each constituent of the mixture is the pressure exerted by the constituent taken separately if the quantity of the constituent occupies alone the same volume as that of the mixture and at the same temperature. Thus each constituent behaves as if it occupies the volume alone and is independent of the presence of other constituent.

In a condenser, there is a mixture of steam and air leaking into the condenser.

∴ Pressure of mixture = partial pressure of steam + partial pressure of air

$$p = p_s + p_a \qquad ...(20.5)$$

The total pressure p is measured by a vacuum gauge, *i.e.*, p = (barometric reading– gauge reading). If the condenser temperature is known then p_s can be read from the steam tables. By difference the partial pressure of air p_a can be obtained.

EXAMPLE 20.1

The following observations were recorded during a test on a steam condenser :

Recorded condenser vacuum
= *71 cm of Hg*

Barometric reading = *76.5 cm of Hg*

Mean condenser temperature
= *34 °C*

Temperature of hot well
= *28.5°C*

Condensate collected = *1800 kg/hour*

Flow rate of cooling water
= *57500 kg/hour*

Inlet temperature of cooling water
= *8.5°C*

Outlet temperature of cooling water
= *26°C*

Calculate: (a) vacuum corrected to standard barometer of 76 cm of Hg, (b) vacuum efficiency, (c) under cooling of condensate, (d) condenser efficiency, (e) state of steam entering the condenser and (f) mass of air present per cubic meter of condenser volume and the mass of air present per kg of uncondensed steam.

Solution : (*a*) Corrected vacuum

$$= 76 - (H_b - H_g)$$
$$= 76 - (76.5 - 71) = \mathbf{70.5\ cm\ of\ Hg}$$

(*b*) From steam tables, the absolute pressure of steam corresponding to condenser temperature of 34°C

$$= 0.053 \text{ bar}$$
$$= \frac{0.0532}{0.01333} = 3.99 \text{ cm of Hg}$$

Vacuum efficiency η_{vac}

$$= \frac{\text{actual vacuum as recorded by gauge}}{\text{barometric pressure} - \text{absolute pressure of steam}}$$

$$= \frac{71}{76.5 - 3.99}$$

$$= \frac{71}{72.51} = 0.979 \simeq \mathbf{98\%}$$

(*c*) Condensate under-cooling

= condenser temperature – temperature of hot well

$$= 34 - 28.5 = \mathbf{5.5°C}$$

(*d*) Absolute condenser pressure

= barometer reading – vacuum reading

$$= 76.5 - 71 = 5.5 \text{ cm of Hg}$$
$$= 5.5 \times 0.01333 = 0.0733 \text{ bar}$$

Saturation temperature corresponding to 0.0733 bar = 39.95°C

Therefore the maximum temperature to which cooling water can be raised is 39.95°C.

Condenser efficiency

$$= \frac{\text{actual rise in temperature of cooling water}}{\text{maximum permissible temperature rise}}$$

$$= \frac{26 - 8.5}{39.95 - 8.5} = \mathbf{55.7\%}$$

(*e*) From steam tables for a pressure of 0.0733 bar

$$h_f = 167.23 \text{ kJ/kg}$$

and $\quad h_{fg} = 2406 \text{ kJ/kg}$

The enthaply of condensate (h_c) corresponding to hot well temperature of 28.5°C is 119.4 kJ/kg.

Heat absorbed by cooling water

$= \text{Heat given up by steam}$

$$m_w\, c_w(t_2 - t_1) = m_s\left[(h_f + h_{fg}) - h_c\right]$$

$$57500 \times 4.186\ (26.0 - 8.5)$$

$$= 1800\ \left[(167.23 + x \times 2406) - 119.4\right]$$

or $2340 = 2406\ x + 47.83$

$$\therefore \quad x = \frac{2340 - 47.83}{2406} = 0.953$$

Thus steam at entry to the condenser has a dryness fraction of 0.953.

(*f*) At condenser temperature of 34°C, Partial pressure of steam,

$$p_s = 0.0532 \text{ bar}$$

∴ From Dalton's law, partial pressure of air

$$p_a = 0.0733 - 0.0532 = 0.0201 \text{ bar}$$

From characteristic gas equation,

$$pV = mRT$$

∴ Mass of air present per m^3 of condenser volume

$$= \frac{0.0201 \times 10^5 \times 1}{287 \times 307} = 0.0228 \text{ kg}$$

Volume of 1 kg of steam at 34°C = 26.61 m^3

Air associated with 1 kg of steam will have the same volume.

∴ Mass of air present per kg of uncondensed steam

$$= \frac{0.0201 \times 10^5 \times 26.61}{287 \times 307} = 0.607 \text{ kg}$$

EXAMPLE 20.2

A condenser deals with 1000 kg of steam per hour with a dryness fraction of 0.9. The mean condenser temperature is 45°C. The air associated with the steam in the condenser is 250 kg/hour. What would be the vacuum reading? Barometer reading is 75cm of Hg. Correct this vacuum to a standard barometer reading of 76 cm of mercury.

Solution : From steam tables :

Partial pressure of steam at 45°C,

$$p_s = 0.0958 \text{ bar}$$

Volume of 1 kg of steam at 45°C,

$$v_s = 15.28 \text{ m}^3$$

∴ Total volume of steam

$$= m \times (x \times v_s)$$
$$= 1000(0.9 \times 15.28)$$
$$= 13752 \text{ m}^3/\text{hr}$$

According to Dalton's law this is also the volume of 250 kg of air at 45°C.

From characteristic gas equation,

$$pV = mRT$$

partial pressure of air,

$$p_a = \frac{250 \times 287 \times (45 + 273)}{13752}$$
$$= 1659 \text{ N/m}^2 = 0.01659 \text{ bar}$$

∴ Total condenser pressure

$$= 0.0958 + 0.01659 = 0.11239 \text{ bar}$$
$$= \frac{0.11239}{0.01333} = 8.43 \text{ cm of Hg}$$

∴ Vacuum reading

$$= 75 - 8.43 = 66.57 \text{ cm of Hg}$$

Corrected vacuum

$$= 76 - (75 - 66.57)$$
$$= \mathbf{67.57} \text{ cm of Hg}$$

20.12. COOLING TOWERS AND COOLING PONDS

The cooling towers and cooling ponds are employed for cooling the hot water coming out of the condenser so that the resulting cooled water can be used again for circulation in the condenser. The cooling is affected by exposing the hot water to an atmosphere of air. The cooling tower becomes a necessity when the supply of cooling water is scarce and the same water has to be used over and over again for cooling purposes.

The cooling process in the cooling tower is normally affected by the following factors :

- temperature and humility of air,
- velocity with which the air enters the cooling tower,
- reach of air to different sections of the cooling tower,
- arrangement of plates/baffles inside the tower, and
- size and height of the tower.

The cooling towers operate on draught which may be natural, induced or forced.

Natural draught cooling tower : Water from the condenser is supplied to troughs and nozzles with the help of a pump installed at a height of about 8-10 m from the bottom. Water falls in the form of spray and meets the air which enters from the bottom. Water loses its heat to air and gets cooled. The cooled water is collected at the bottom and is returned to condenser for circulation. There are no moving parts in the natural draught cooling tower. Air flow through the shell is created by the density difference between the atmospheric air and the air inside the tower which has been warmed by the hot circulating water.

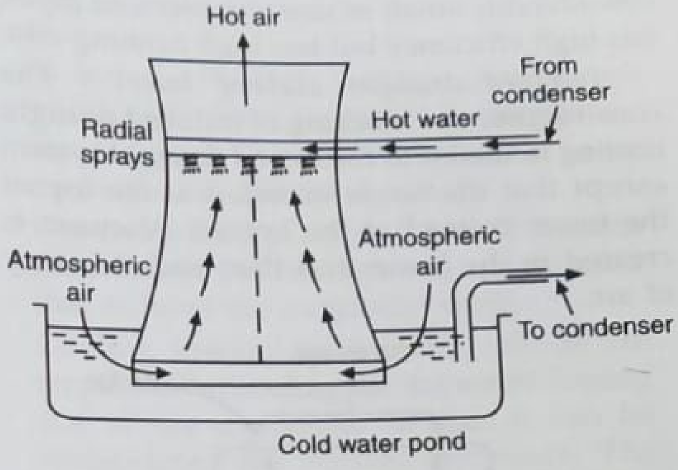


Fig. 20.11. Natural draught cooling tower

Some of the water during its fall is evaporated and is carried along by the heated air . The loss of water due to evaporation is made up by fresh water called *make up water.* The reduction in temperature of water is called *range.*

The performance of natural draught tower is affected by variation of atmospheric conditions and wind velocity.

Forced draught cooling tower : Hot water coming from the condenser enters the unit from the top and gets sprayed through nozzles. Water droplets falling downwards meet the air going upward. A good supply of air is made by a fan installed at the bottom of the tower. Spray eliminators are provided at the top and these entrap the water which is likely to go along with hot air leaving from the top.

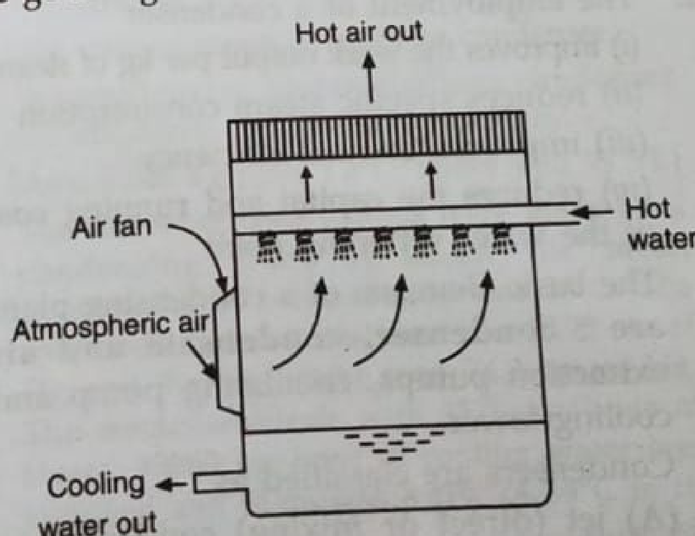


Fig. 20.12. Forced draught cooling tower

Compared to natural draught cooling tower, the forced draught system is considerably small in size of tower and pipes, has high efficiency but has high running cost.

Induced draught cooling tower : The construction and working of induced draught cooling is similar to the forced draught system except that the fan is installed at the top of the tower instead at the bottom. Vacuum is created in the tower and that leads to entry of air.

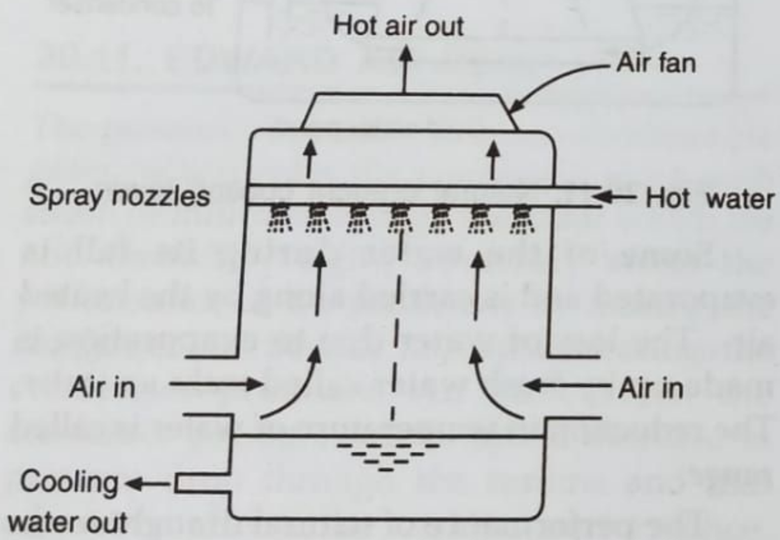


Fig. 20.13. Induced draught cooling tower

Cooling towers are generally of hyperbolic shape and are made of timber, steel or concrete. The timber towers have a short life, a limited cooling capacity, high maintenance cost and rot easily due to exposure to sun, wind, water etc. In contrast, the advantages of concrete cooling towers are: low maintenance, large capacity, increased stability, and improved draught and air circulation.

Cooling pond : The hot water coming from the condenser is sprayed into the cooling pond through nozzles. These nozzles are kept at a distance from each other so that there is no interference from between two sprays. Further, for effective cooling, the nozzles are fitted at a height of 1 to 2 m above the ground level. The evaporation from the water surface produces the cooling effect.

For the same duty, the surface area required in a cooling pond is about 30 times the size of cooling tower. Further, a good amount of water is lost by evaporation and by the wind blowing across the cooling pond.