UNIT 6 STEAM CONDENSERS

Structure

6.1 INTRODUCTION

The actual Rankine cycle used in modern power plants has many components, but the feed pump, boiler or steam generator, steam turbine and condenser are the four components which are common to all power plants. In this cycle, water is heated in the steam generator to produce higher temperature and high pressure steam. This steam is then expanded in a turbine to produce power. The steam from the turbine is then condensed back into water in the condenser. The pump then returns the water to the steam generator.

Thus, the main purposes of the condenser are to condense the exhaust steam from the turbine for reuse in the cycle and to maximise turbine efficiency by maintaining proper vacuum. As the operating pressure of the condenser is lowered (vacuum is increased), the enthalpy drop of the expanding steam in the turbine increases. This will increase the amount of available work from the turbine (electrical output). By lowering the condenser operating pressure, the following will occur :

(a) Increased turbine output

(b) Increased plant efficiency

(c) Reduced steam flow (for a given plant output)

It is therefore very advantageous to operate the condenser at the lowest pressure (highest vacuum). However, as we have seen in Unit 5 ambient conditions play a major role in the operating conditions of he condenser.

Objectives

After studying this unit, you should be able to

- define what is condenser,
- explain the condenser usages and applications, and
- know about the cooling towers and cooling ponds.

6.2 CONDENSER TYPES

There are two primary types of condensers that can be used in a power plant :

(a) Direct contact

(b) Surface

Direct contact condensers condense the turbine exhaust steam by mixing it directly with cooling water. The older type Barometric and Jet type condensers operate on similar principles. Steam surface condensers are the most commonly used condensers in modern power plants. The exhaust steam from the turbine flows on the shell side (under vacuum) of the condenser, while the plant's circulating water flows in the tube side. The source of the circulating water can be either a closed-loop (i.e. cooling tower, spray, pond, etc.) or once through (i.e. from a lake, ocean or river). The condensed steam from the turbine, called condensate, is collected in the bottom of the condenser, which is called a hot well. The condensate is then pumped back to the steam generator to repeat the cycle.

6.3 STEAM SURFACE CONDENSER OPERATION

The heat transfer mechanism in a surface condenser is that the saturated steam condenses on the outside of the tubes and the circulating water inside the tubes gets heated. Thus, for a given circulating water flow rate, the water inlet temperature to the condenser determines the operating pressure of the condenser. As this temperature is decreased, the condenser pressure will also decrease. As described below, this decrease in the pressure will increase the turbine power output and cycle efficiency.

6.3.1 Steam Surface Condenser Configuration

Steam surface condensers can be broadly categorised by the orientation of the steam turbine exhaust to the condenser.

Most common are side and down exhaust. In a side exhaust condenser, the condenser and turbine are installed adjacent to each other, and the steam from the turbine enters from the side of the condenser. In a down exhaust condenser, the steam from the turbine enters from the top of the condenser and the turbine is mounted on a foundation above the condenser.

Condensers can be further delineated by the configuration of the shell and tube sides.

(a) Number of tube side passes

(b) Configuration of the tube bundle and water boxes

Most steam surface condenses have either one or multiple tube side passes. The number of passes is defined as how many times circulating water travels the length of the condenser inside the tubes. Condensers with a once through circulating water system are often one pass. Multiple pass condensers are typically used with closed-loop systems.

The tube side may also be classified as divided or non-divided. In a divided condenser, the tube bundle and water boxes are divided into sections. One or more sections of the tube bundle may be in operation while others are not. This allows maintenance of sections of the tube side while the condenser is operating. In a non-divided tube side, all the tubes are in operation at all times.

Shell Sides

The shell sides of a steam surface condenser can be classified by its geometry. Examples of types are :

(a) cylindrical, and

(b) rectangular

The choice of the above configuration is determined by the size of the condenser, plant layout, and manufacturer preference. Steam surface condensers can be multiple shell and multiple pressure configurations, as well.

6.3.2 Water-cooled Surface Condenser

The diagram given in Figure 6.1 depicts a typical water-cooled surface condenser generally used in power stations to condense the exhaust steam from a *steam turbine*. There are many fabrication design variations possible depending on the manufacturer, the size of the steam turbine, and other site-specific conditions.

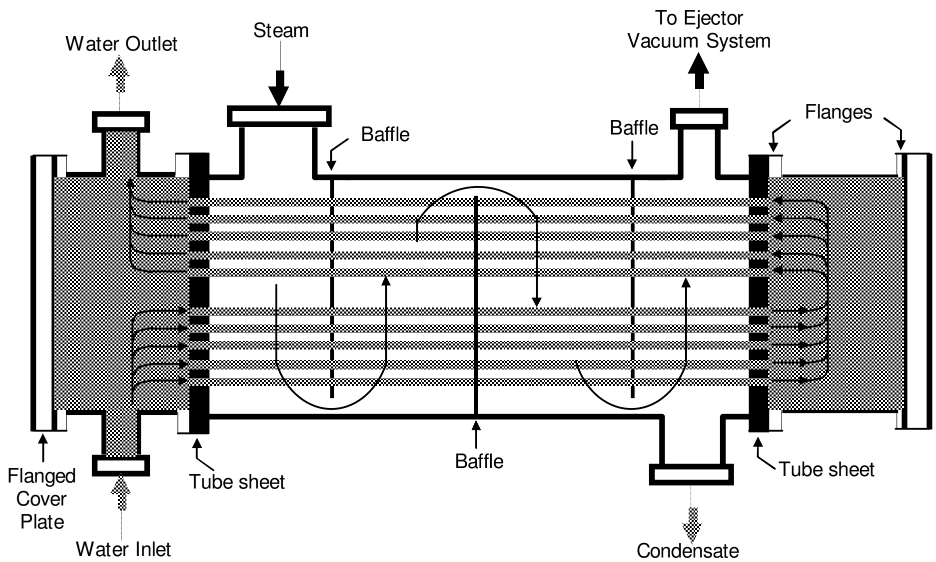

Figure 6.1 : Water-cooled Surface Condenser (Courtesy : Wikipedia)

Shell

The shell is the condenser's outermost body and contains the heat exchanger tubes. The shell is fabricated from *carbon steel* plates and is stiffened as needed to provide rigidity for the shell. Based on design considerations, intermediate plates are installed to serve as baffle plates that provide the desired flow path of the condensing steam. These plates also provide support that help prevent sagging of long tube lengths.

At the bottom of the shell, where the condensate collects, an outlet is installed. In some designs, a sump (often referred to as the hot well) is provided. Condensate is pumped from the outlet of the hot well for reuse as boiler feed water.

For most water-cooled surface condensers, the shell is under *vacuum* during normal operating conditions.

6.3.3 Vacuum System

For water-cooled surface condensers, the shell's internal vacuum is most commonly created and maintained by an external *steam jet ejector* system. Such an ejector system uses steam as the motive fluid to remove any non-condensible gases that may be present in the surface condenser. The *Venturi effect*, which is particular case of *Bernoulli's* *principle*, applies to the operation of steam jet ejectors. For the ejector shown in Figure 6.2 the motive fluid is steam.

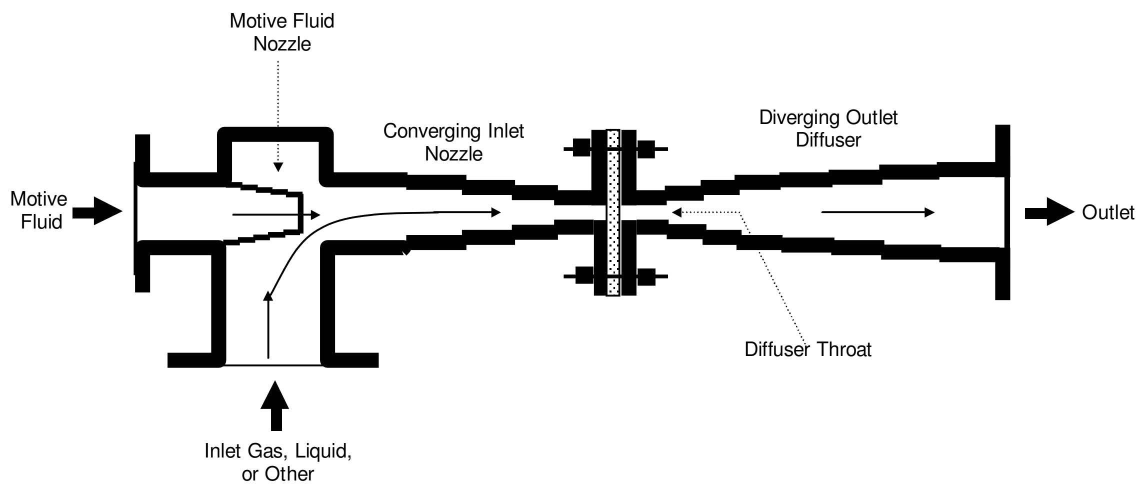

Figure 6.2 : Diagram of a Typical Modern Steam Injector or Ejector (Courtesy : Wikipedia)

Motor driven mechanical *vacuum pumps*, such as the *liquid ring* type, are also popular for this service.

6.3.4 Tube Sheets

At each end of the shell, a sheet of sufficient thickness usually made of *stainless steel* is provided, with holes for the tubes to be inserted and rolled. The inlet end of each tube is also bell-mouthed for steam-lined entry of water. This is to avoid eddies at the inlet of each tube giving rise to erosion, and to reduce flow friction. Some makers also recommend plastic inserts at the entry of tubes to avoid eddies eroding the inlet end. In smaller units some manufactures use ferrules to seal the tube ends instead of rolling. To take care of length wise *expansion* of tubes some designs have expansion joint between the shell and the tube sheet allowing the letter to move longitudinally. In smaller units some sag is given to the tubes to take care of tube expansion with both end water boxes fixed rigidly to the shell.

6.3.5 Tubes

Generally the tubes are made of *stainless steel*, copper alloys such as brass or bronze, *cupro nickel*, or *titanium* depending on several selection criteria. The use of copper bearing alloys such as brass or cupro nickel is rare in new plants, due to environmental concerns of toxic copper alloys. Also depending on the steam cycle water treatment for the boiler, it may be desirable to avoid tube materials containing copper. Titanium condenser tubes are usually the best technical choice, however, it is very expensive. The tube lengths range to about 55 ft (15 m) for modern power plants, depending on the size of the condenser. The size chosen is based on transportability from the manufacturers' site and ease of erection at the installation site. The outer diameter of condenser tubes typically ranges from 3/4 inch (19 mm) to 1-1/4 inch (13 mm), based on condenser cooling water fabrication considerations and overall condenser size.

6.3.6 Water Boxes

The tube sheet at each end with tube ends rolled, for each end of the condenser is closed by a fabricated box cover known as a water box, with flanged connection to the tube sheet or condenser shell. The water box is usually provided with man holes on hinged covers to allow inspection and cleaning.

These water boxes on inlet side will also have flanged connections for cooling water inlet *butterfly valves*, small vent pipe with hand *valve* for air venting at higher level, and hand operated drain *valve* at bottom to drain the water box for maintenance. Similarly on the outlet water box the cooling water connection will have large flanges, *butterfly valves*, vent connection also at higher level and drain connection at lower level. Similarly *thermometer* pockets are located at inlet and outlet pipes for local measurements of cooling water temperature.

In smaller units, some manufacturers make the condenser shall as will as water boxes using *cast iron*.

6.4 CORROSION

On the cooling water side of the condenser :

The tubes, the tube sheets and water boxes may be made up of materials having different compositions and are always in contact with circulating water. This water, depending on its chemical composition, will act as an *electrolyte* between the metallic composition of tubes and water boxes. This will give rise to electrolyte *corrosion* which will start from more anodic materials first.

Sea Water Based Condensers

Sea water based condensers, in particular when sea water has added chemical *pollutants*, have the worst corrosion characteristics. River water with *pollutants* are also undesirable for condenser cooling water.

The corrosive effect of sea or river water has to be tolerated and remedial methods have to be adopted. One method is the use of *sodium hypochlorite* or *chlorine*, to ensure there is no marine growth on the pipes or the tubes. This practice must be strictly regulated to make sure the circulating water returning to the sea or river source is not affected.

On the steam (shell) side of the condenser :

The concentration of un-dissolved gases is high over air zone tubes. Therefore, these tubes are exposed to higher corrosion rates. Sometimes these tubes are affected by stress corrosion cracking, if originally stress is not fully relieved during manufacturer. To overcome these effects of corrosion some manufacturers provide higher corrosive resistant tubes in this area.

6.5 EFFECTS OF CORROSION

As the tube ends get corroded there is the possibility of cooling water leakage to the steam side contaminating the condensed steam or condensate, which is harmful to *steam generators*. The other parts of water boxes may also get affected in the long run requiring repairs or replacements involving long duration shut-downs.

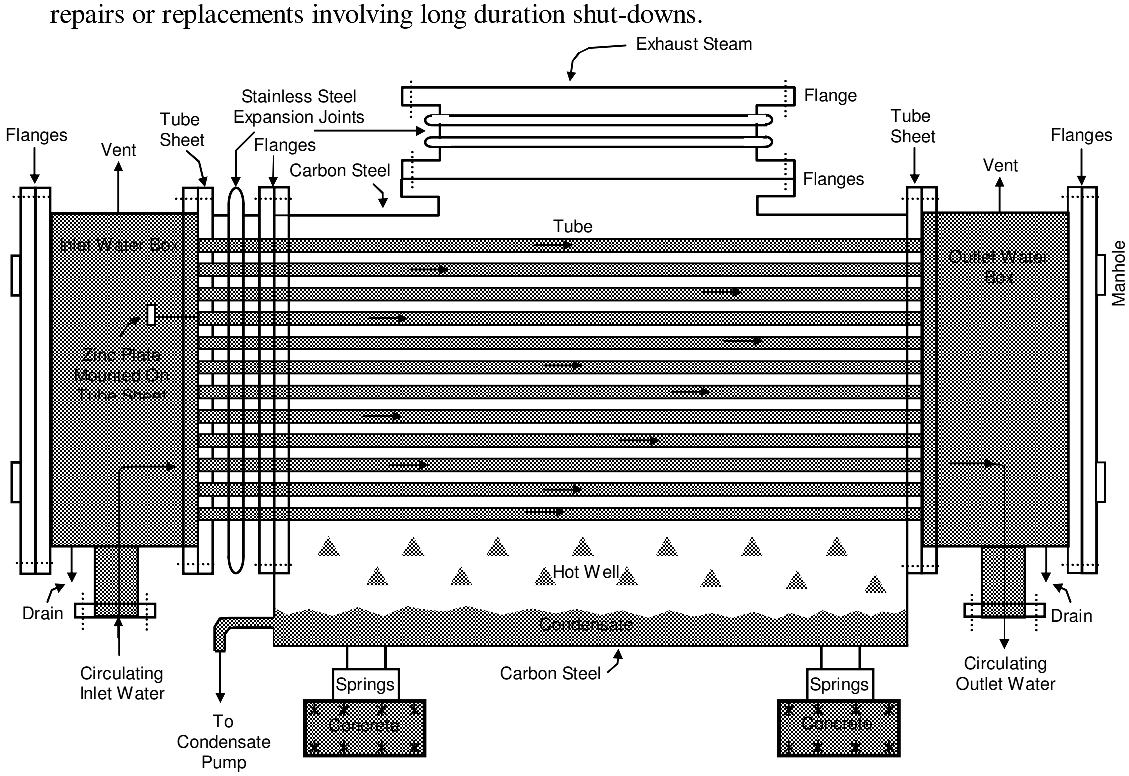

Figure 6.3 : Power Plant Condenser (Courtesy : Wikipedia)

6.5.1 Protection from Corrosion

Cathodic protection is typically employed to overcome this problem. *Sacrificial anodes* of *zinc* (being cheapest) plates are mounted at suitable places inside the water boxes. These *zinc* plates will get corroded first being in the lowest range of anodes. Hence, these *zinc* anodes require periodic inspection and replacements. This involves comparatively less down time. The water boxes made of steel plates are also protected inside by epoxy paint.

6.6 BAROMETRIC CONDENSERS

It is also known as high level counter flow jet condenser. In this condenser, the shell is placed at a height about 10.363 metres above hot well and thus the necessity of providing an extraction pump can be obviated. However, provision of own injection pump has to be made if water under pressure is not available.

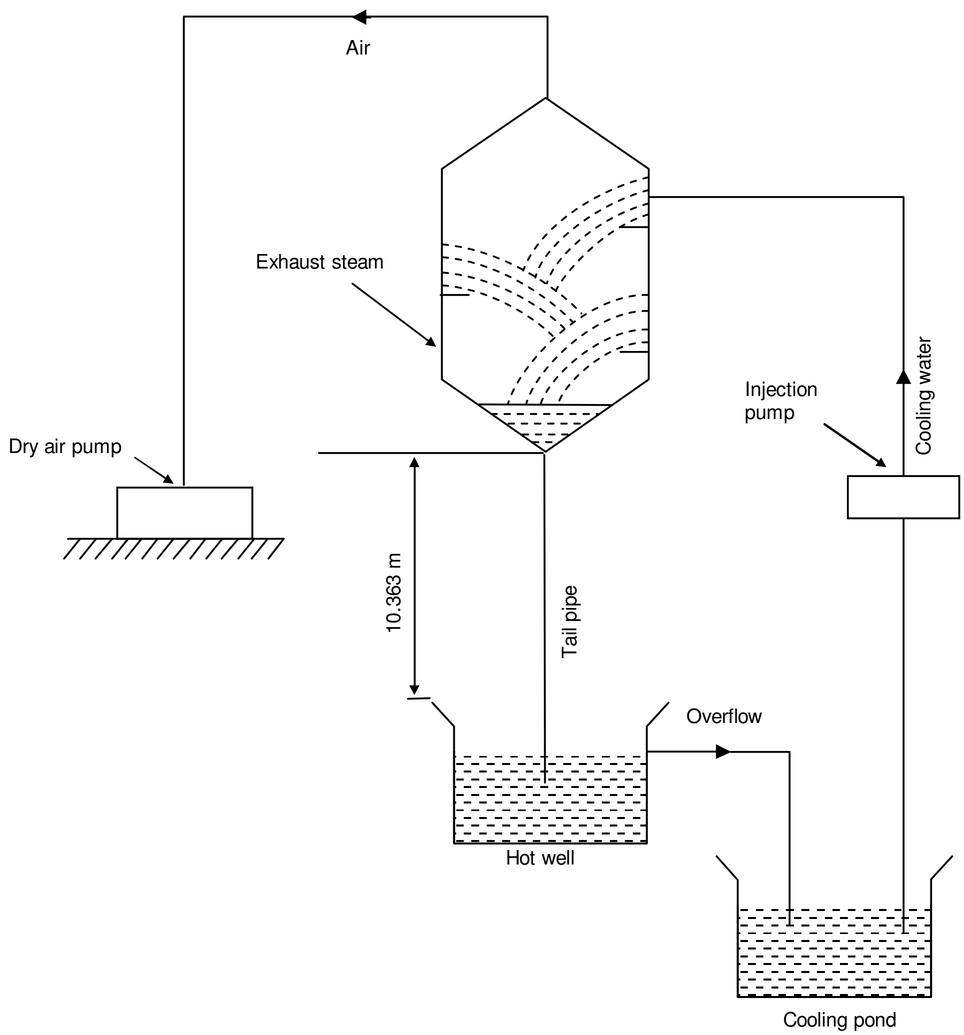

Figure 6.4 : Barometric Condenser

6.6.1 Principle of Operation

As shown in Figure 6.5, Multi-Jet Barometric Condensers are generally employed where low cost water is available in ample quantity. It is the simplest design of all barometric condensers, and requires no auxiliary air pump or pre-cooler. It is probably the ideal type where local conditions are constant and there is little air leakage. The Multi-Jet Barometric Condenser is also used where the vacuum handled is not high and a moderately large terminal difference is permissible.

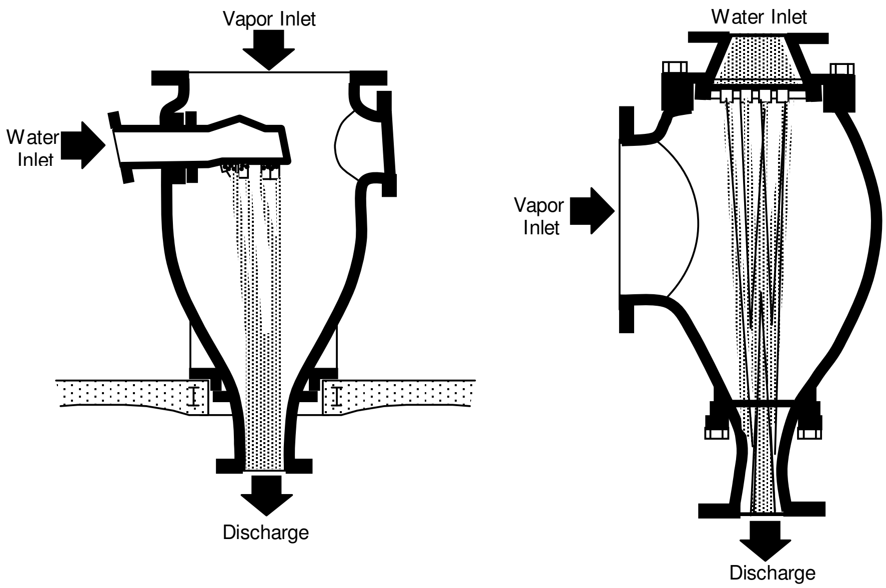

Figure 6.5 : Multi-Jet Barometric Condensers (Courtesy : Schutte and Koerting)

Figure 6.6 shows a Multi-Jet Spray type Barometric Condenser which are generally employed where large capacities are required and where wide fluctuations in water temperature or steam load occur. The flexibility of operation achieved by this condenser is apparent from its design. For full vapour load the rated water capacity is passes through both the spray and jet nozzles. If the load or water temperature decreases, it is possible to throttle the water to the spray nozzles and ultimately turn them off completely. In the latter case, the condenser is operating similar to the Multi-Jet type, but with a minimum of injection water under the given conditions.

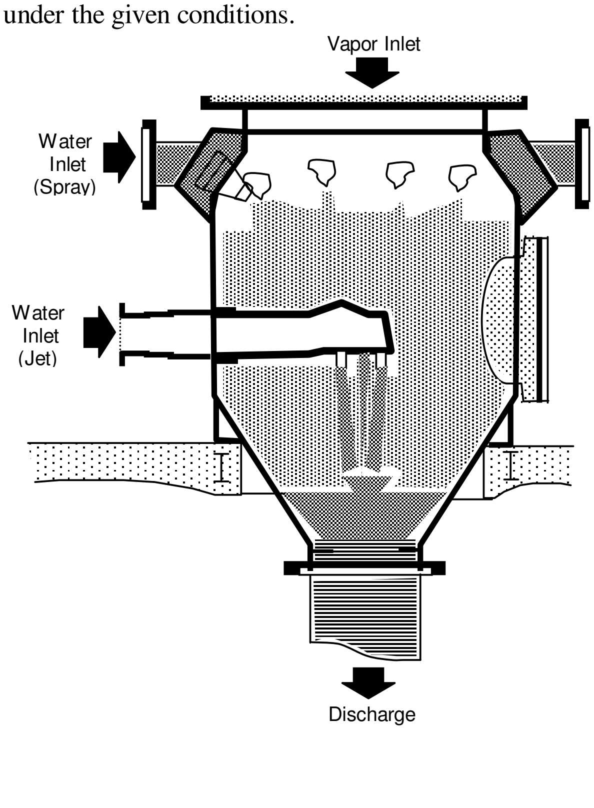

Figure 6.6 : Multi-Jet (Spray Type) Barometric Condenser (Courtesy : Schutte and Koerting)

6.7 COOLING TOWERS

Cooling water is a very important part of many cooling systems. Typical cooling circuit involving cooling tower is shown in Figure 6.7. The primary task of a cooling towers is to reject heat into the atmosphere. It represents a relatively inexpensive and dependable means of removing low-grade heat from cooling water. Hot water from heat exchanges is sent to the cooling tower. The cooled water exists the cooling tower and is sent back to the exchangers or to other units for further cooling. The make-up water source is used to replenish water lost due to evaporation.

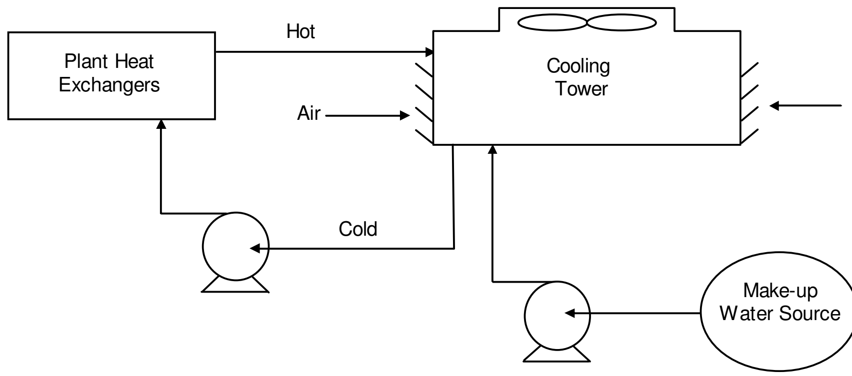

Figure 6.7 : Cooling Water System (Courtesy : BEE India)

6.7.1 Cooling Tower Types

Cooling towers fall into two main categories :

(a) Natural draft, and

(b) Mechanical draft.

Natural Draft

Natural draft towers use very large concrete chimney to introduce air through the media. Due to the large size of these towers, they are generally used for water flow rates above 45,000 m^3/hr. These types of towers are used only by utility power stations.

Mechanical Draft

Mechanical draft towers utilise large fans to force or such air though circulated water. The water falls downward over fill surface, which help increase the contact time between the water and the air – this helps maximise heat transfer between the two. Cooling rates of mechanical draft towers depends upon their fan diameter and speed of operation. Since, the mechanical draft cooling towers are much widely used, more detailed discussion of the same follows.

6.7.2 Mechanical Draft Towers

Mechanical draft towers are available in the following airflow arrangements :

(a) Counter flows induced draft

(b) Counter flow forced draft

(c) Cross flow induced draft

In the counter flow induced draft design, hot water enters at the top, while the air is introduced at the bottom and exists at the top. Both forced and induced draft fans are used. In cross flow induced draft towers, the water enters at the top and passes over the fill. The air, however, is introduced at the side either on one side (single-flow tower) or opposite sides (double-flow tower). An induced draft fan draws the air across the wetted fill and expels it through the top of structure.

Figure 6.8 illustrates various cooling towers types. Mechanical draft towers are available in a large range of capacities. Normal capacities range from approximately 10 tons, 2.5 m^3/hr flow to several thousand tons and m^3/hr. Towers can be either factory built or field erected – for example concrete towers are only field erected.

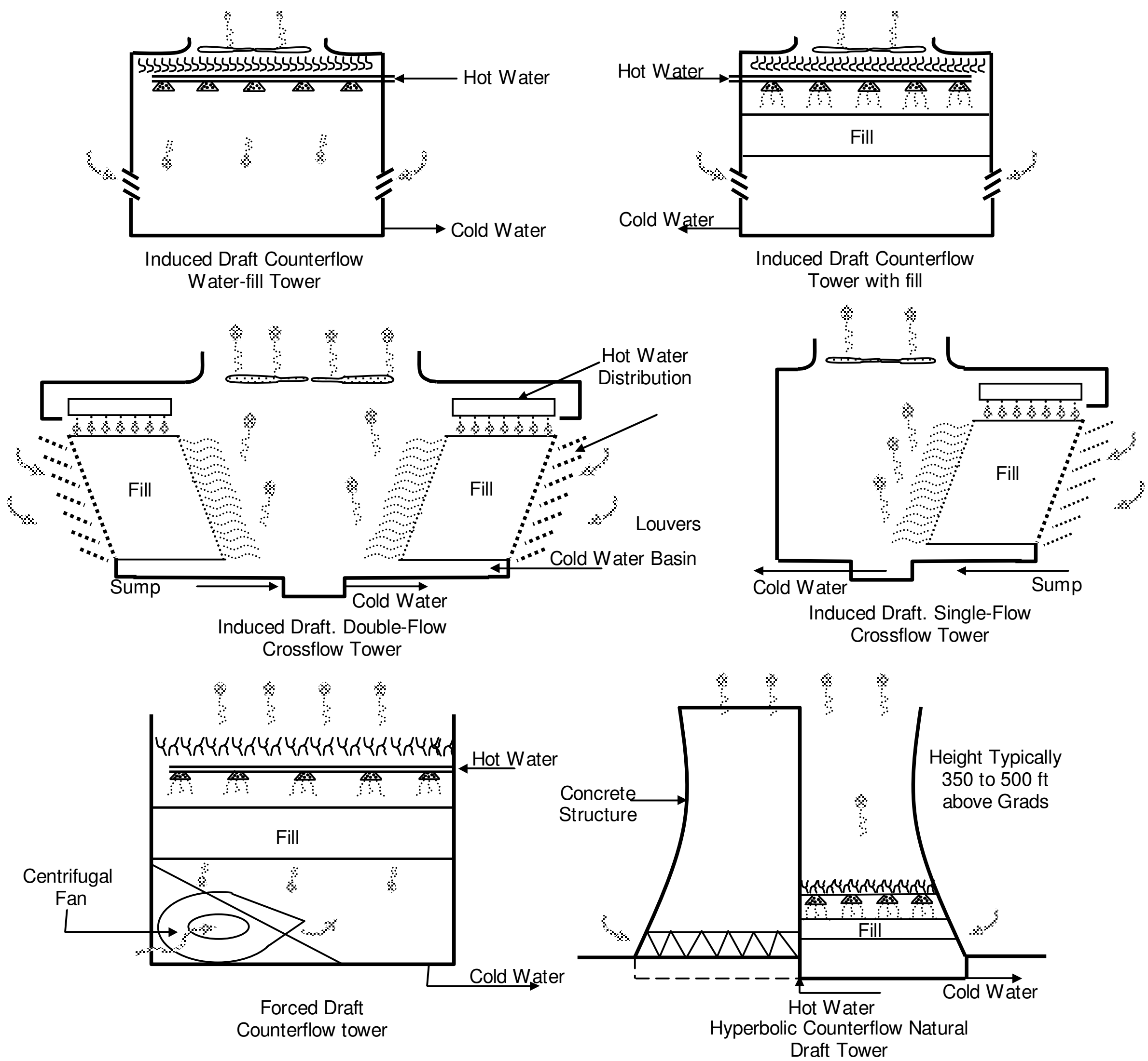

Figure 6.8 : Types of Cooling Towers (Courtesy : BEE India)

Many towers are constructed so that they can be grouped together to achieve the desired capacity. Thus, many cooling towers are assemblies of two or more individual cooling towers or "cells". The number of cells they have, e.g. an eight-cell tower, often refers to such towers. Multiple-cell towers can be lineal, square or round depending upon the shape of the individual cells and whether the air inlets are located on the sides or bottoms of the cells.

6.7.3 Components of Cooling Tower

The basic components of an evaporative towers are : Frame and casing, fill, cold water basin, draft eliminators, air inlet, louvers, nozzles and fans.

Frame and Casing

Most towers have structural frames that support the exterior enclosures (casings), motors, fans and other components. With some smaller designs, such as some glass fibre units, the casing may essentially be the frame.

Fill

Most towers employ fills (made of plastic or wood) to facilitate heat transfer by maximising water and air contact. Fill can either be splash or film type. With splash fill, water falls over successive layers of horizontal splash bars, continuously breaking into smaller droplets, while also wetting the fill surface. Plastic splash fill promotes better heat transfer than the wood splash fill.

Film fill consists of thin, closely spaced plastic surfaces over which the water spreads, forming a thin film in contact with the air. These surfaces may be flat, corrugated, honeycombed or other patterns. The film type of fill is the more efficient and provides same heat transfer in a smaller volume than the splash fill.

Cold Water Basin

The cold water basin, located at or near the bottom of the tower, receives the cooled water that flows down through the tower and fill. The basin usually has a sump or low point for the cold water discharge connection. In many tower designs, the cold water basin is beneath the entire fill.

In some forced draft counter flow design, however, the water at the bottom of the fill is channeled to a perimeter through that functions as the cold water basin. Propeller fans are mounted beneath the fill to blow the air up through the tower. With the design, the tower is mounted on legs, providing easy access to the fans and their motors.

Draft Eliminators

These capture water droplets entrapped in the air stream that otherwise would be lost to the atmosphere.

Air Inlet

This is the point of entry for the air entering a tower. The inlet may take up an entire side of a tower – cross flow design – or be located low on the side or the bottom of counter flow designs.

Louvers

Generally, cross-flow towers have inlet louvers. The purpose of louvers is to equaliser air flow into the fill and retain the water within the tower. Many counter flow tower designs do not require louvers.

Nozzles

These provide the water sprays to wet the fill. Uniform water distribution at the top of the fill is essential to achieve proper wetting of the entire fill surface. Nozzles can either be fixed in place and have either round or square spray patterns or can be part of a rotating assembly as found in some circular cross-section towers.

Fans

Both axial (propeller type) and centrifugal fans are used in towers. Generally, propeller fans are used in induced draft towers and both propeller and centrifugal fans are found in forced draft towers. Depending upon their size, propeller fans can either be fixed a variable pitch.

A fan having non-automatic adjustable pitch blades permits the same fan to be used over a wide range of kW with the fan adjusted to deliver the desired air flow at the lowest power consumption. Automatic variable pitch blades can vary air flow in response to changing load conditions.

6.7.4 Tower Materials

In the early days of cooling tower manufacturer, towers were constructed primarily of wood. Wooden components included the frame, casing, louvers, fill and often the cold water basin. If the basin was not of wood, it likely was of concrete.

Today, tower manufacturers fabricate towers and tower components from a variety of materials. Often several materials are used to enhance corrosion resistance, reduce maintenance and promote reliability and long service life. Galvanised steel, various grades of stainless steel, glass fibre and concrete are widely used in tower construction as well as aluminium and various types of plastics for some components.

Wood towers are still available, but they have glass fibre rather than wood panels (casing) over the wood framework. The inlet air louvers may be glass fibre, the fill may be plastic, and the cold water basins may be steel.

Larger towers sometimes are made of concrete. Many towers – casings and basins – are constructed of galvanised steel or where a corrosive atmosphere is a problem, stainless steel. Sometimes a galvanised tower has a stainless steel basin. Glass fibre is also widely used for cooling tower casings and basins, giving long life and protection from the harmful effects of many chemicals.

Plastics are widely used for fill, including PVC, polypropylene and other polymers. Treated wood splash fill is still specified for wood towers, but plastic splash fill is also widely used when water conditions mandate the use of splash fill. Film fill, because it offers greater heat transfer efficiency, is the fill of choice for applications where the circulating water is generally free of debris that could plug the fill passage ways. Plastics also find wide use as nozzle materials. Many nozzles are being made of PVC, ABS, polypropylene and glass-filled nylon. Aluminium, glass fibre and hot-dipped galvanised steel are commonly used fan materials. Centrifugal fans are often fabricated from galvanised steel. Propeller fans are fabricated from galvanised, aluminium or moulded glass fibre reinforced plastic.

6.8 COOLING PONDS

Cooling of condenser coolant can be achieved by using artificial or natural ponds or lakes to re-cool the water. Such water bodies are known as cooling ponds. According to "European Nuclear Society" a power plant with an electric output of 1,300 MW needs a pond with a cooling surface of about 10 km^2 to be able to maintain a cooling water temperature of 21^{o}C at humid air temperature of 8^{o}C (12^{o}C dry, relative humidity 57%).

6.9 SOURCES OF AIR IN CONDENSERS

Due to the fact that a surface condenser operated under vacuum, non-condendsable gases will migrate towards the condenser. The non-condensible gases consist of mostly air that has leaked into the cycle from components that are operating below atmospheric pressure (like the condenser). These gases can also result from decomposition of water into oxygen and hydrogen by thermal or chemical reactions. These gases must be vented from the condenser for the following reasons :

(a) The gases will increase the operating pressure of the condenser. Since the total pressure of the condenser will be the sum of partial pressure of the steam and the gases, as more gas is leaked into the system, the condenser pressure will rise. This rise in pressure will decrease the turbine output and efficiency.

(b) The gases will blanket the outer surface of the tubes. This will severely decrease the heat transfer of the steam to the circulating water. Again, the pressure in the condenser will increase.

(c) The corrosiveness of condensate in the condenser increases as the oxygen content increases. Oxygen causes corrosion, mostly in the steam generator. Thus, these gases must be removed in order to extend the life of cycle components.

6.9.1 Steam Surface Condenser Air Removal

The two main devices that are used to vent the non-condensible gases are Steam Jet Ejectors (Figure 6.2) and Liquid Ring Vacuum Pumps. Steam Jet Air Ejectors (SJAE) use high pressure motive steam to evacuate the non-condensible from the condenser (jet pump). Liquid ring vacuum pumps use a liquid compressant to compress the evacuated non-condiensibles and then discharges them to the atmosphere.

To aid in the removal of the non-condensible gases, condensers are equipped with an air-cooler section. The air-cooler section of the condenser consists of a quantity of tubes that are baffled to collect the non-condensible.

Cooling of the non-condensible reduces their volume and the required size of the air removal equipment.

Air removal equipment must operate in two modes : hogging and holding. Prior to admitting exhaust steam to a condenser, all the non-condensible must be vented from the condenser. In hogging mode, large volumes of air are quickly removed from the condenser in order to reduce the condenser pressure from atmospheric to a predetermined level. Once the desired pressure is achieved, the air removal system can be operated in holding mode to remove all non-condensible gases.

Exercise 1

(a) What are the important roles played by the condenser in a power plant?

(b) Give the classification of condensers.

(c) Using a neat sketch explain the construction and working of a surface condenser.

(d) What is the need to have a vacuum system in condenser? Indicate some methods of maintaining vacuum in condensers?

Exercise 2

(a) What are barometric or jet type condensers? How do they differ from surface condenser?

(b) Draw a neat sketchy explain the construction and working of a multi jet-type condenser.

(c) Discuss the need for cooling towers and cooling ponds?

(d) How are cooling towers classified?

Exercise 3

(a) Describe the construction of any one type of natural draft type cooling tower using a neat sketch.

(b) Briefly describe the construction and working of any one type of induced draft type cooling tower.

(c) Give a detailed account of components of a cooling tower.

(d) What are the materials used in different parts of a cooling tower?

SAQ 1

A steam turbine uses 14000 kg of steam per hour and develops 2600 kW. The steam enters the turbine at 40 bar, 400^{o}C. The exhaust steam is condensed at 725 m Hg when the barometer reads 755 mm. The condensate temperature is 30^{o}C as it leaves the condenser. The cooling water temperature rises from 8^{o}C to 18^{o}C. Determine :

(i) the quality of steam entering the condensers, and

(ii) the quantity of circulating cooling water.

6.10 SUMMARY

In this unit, we have discussed about, what is a condenser? Where it is actually useful? What are its advantages and applications? Actually condenser is a unit or a system to condenser the exhaust steam from the turbine to reuse to maximise turbine efficiency. It is a part of system of power plant. Condensers are mostly used in power plants or steam power plants. In this unit, we have also discussed about cooling towers, cooling ponds, etc.

6.11 KEY WORDS

Condenser : It is system in the power plant used to condenser the exhaust steam from the turbine to reuse to maximise turbine efficiency.

Cooling Tower : It rejects heat of water into the atmosphere.

Cooling Ponds : Cooling of condenser coolant can be achieved by using artificial or natural ponds or lakes to re-cool the water.

6.12 ANSWERS TO SAQs

SAQ 1

(i) Quality of steam entering condenser

Condenser pressure = 755 – 725 = 30 mm Hg

$$= \frac{30}{1000} \times \frac{13.6}{10} = 0.0408 \text{ bar} \quad \text{(or)} \quad 4.08 \text{ kPa}$$

From steam tables at 4.08 kPa (0.0408 bar)

$$h_f = 121.5 \text{ kJ/kg}$$

$$h_{fg} = 2432.9 \text{ kJ/kg}$$

At 40 bar, 400^{o}C

$$h = 3213 \text{ kJ/kg}$$

Work done in the turbine (given) = 2600 kW

$$\text{Enthalpy drop in turbine/s} = \frac{14000}{3600}[3213 - (121.5 + x + 2432.9)]$$

i.e. $$2600 = \frac{14000}{3600}[3213 - (121.5 + x \,.\, 2432.9)]$$

solving $x = 0.995$

(ii) Quantity of circulating water

m_s Heat lost by condensing steam = Heat gained by cooling water

$$m_s\,[h_f + x\,h_{fg} - h_c] = m_w\,C_{p_w}\,(t_{w2} - t_{w1})$$

$$m_w = \frac{m_s\,[h_f + x\,h_{fg} - h_c]}{C_{p_w}\,(t_{w2} - t_{w1})}, \qquad h_c = h_f \text{ at } 31^oC = 130 \text{ kJ/kg k}$$

$$= \frac{1400\,[121.5 + 0.995 \times 2432.9 - 130]}{4.186 \times 10}$$

$$= 806767.7 \text{ kg/hr}$$