Chapter Three

Steam Generators

3.1 Definition

A steam generator or a boiler is defined as a closed vessel in which water is converted into steam by burning of fuel in presence of air at desired temperature, pressure and at desired mass flow rate.

According to American society of Mechanical Engineers (A.S.M.E.), a steam generator or a boiler is defined as "a combination of apparatus for producing, finishing or recovering heat together with the apparatus for transferring the heat so made available to the fluid being heated and vaporized.

The boiler is the part of a steam power plant process that produces the steam and thus provides the heat.

A steam boiler as show in figure 3.1 fulfills the following statements:

- It is part of a type of heat engine or process
- Heat is generated through combustion (burning)
- It has a working fluid, heat carrier that transfers the generated heat away from the boiler.
- The heating media and working fluid are separated by wall.

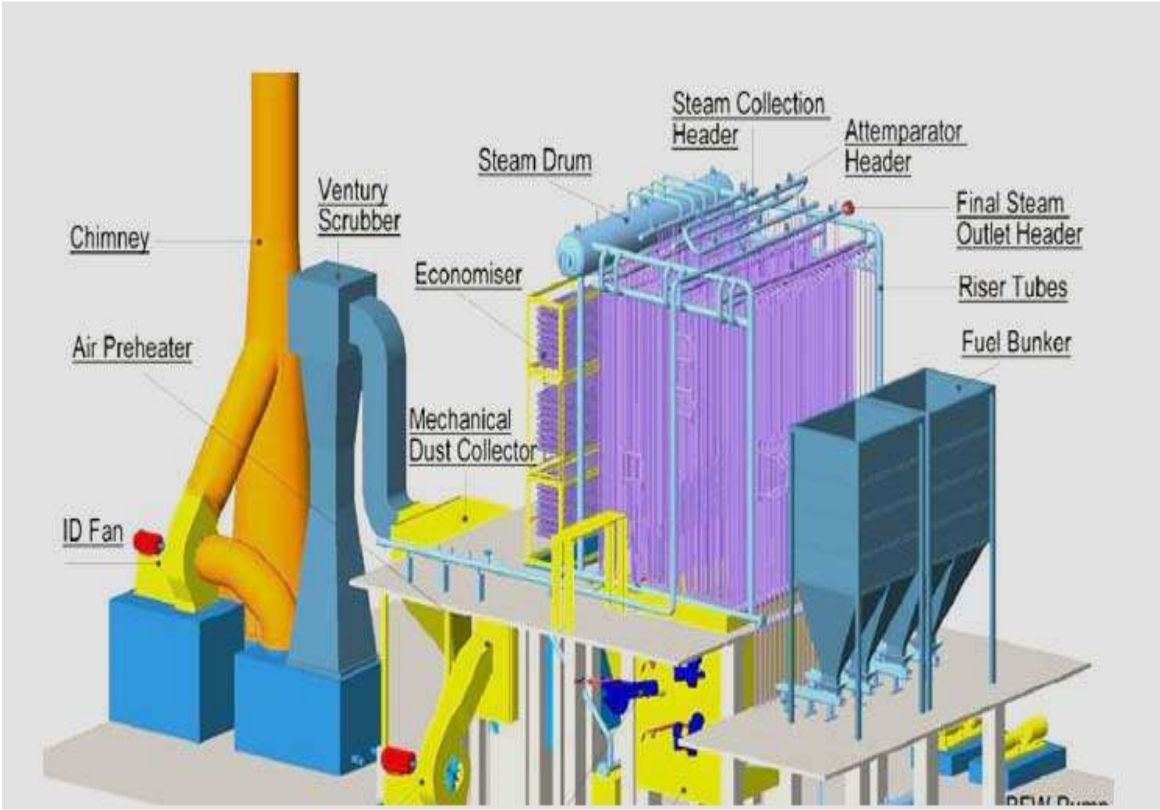


Figure 3-1: steam boiler

Principle: In case of boiler, any type of fuel burn in presence of air and form flue gases which are at very high temperature (hot fluid). The feed water at atmospheric pressure and temperature enters the system from other side (cold fluid). Because of exchange of heat between hot and cold fluid, the cold fluid (water) temperature raises and it form steam. The flue

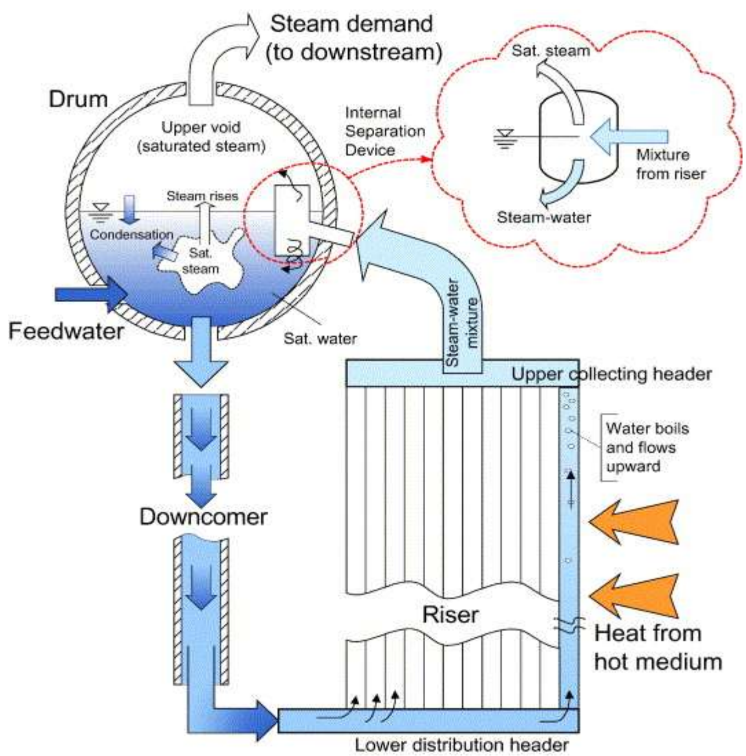


Figure 3-2: Principle of Boiler

gases (hot fluid) temperature decreases and at lower temperature hot fluid is thrown into the atmosphere via stack/chimney. The function of boiler is to facilitate the generation of steam by providing the necessary heat transfer surfaces as show in figure 3-2 , space for storage of water and steam, furnace for burning the fuel and necessary equipment's for control of safe operation the large variety of

The steam or hot water under pressure can then be used for transferring heat to a process that consumes the heat in the steam and turns it into work.

3.2 Main types of a modern boiler

In a modern boiler, there are two main types of boilers when considering the heat transfer means from flue gases to feed water, these type can be classified as follow:-

3.2.1 Fire tube boiler

The fire-tube boiler is sometimes called a "*smoke-tube boiler*" or "*shell boiler*". Flue gases from the furnace are conducted to flue passages, which consist of several parallel-connected tubes. The tubes run through the boiler vessel, which contains the feedwater. The tubes are thus surrounded by water as shown

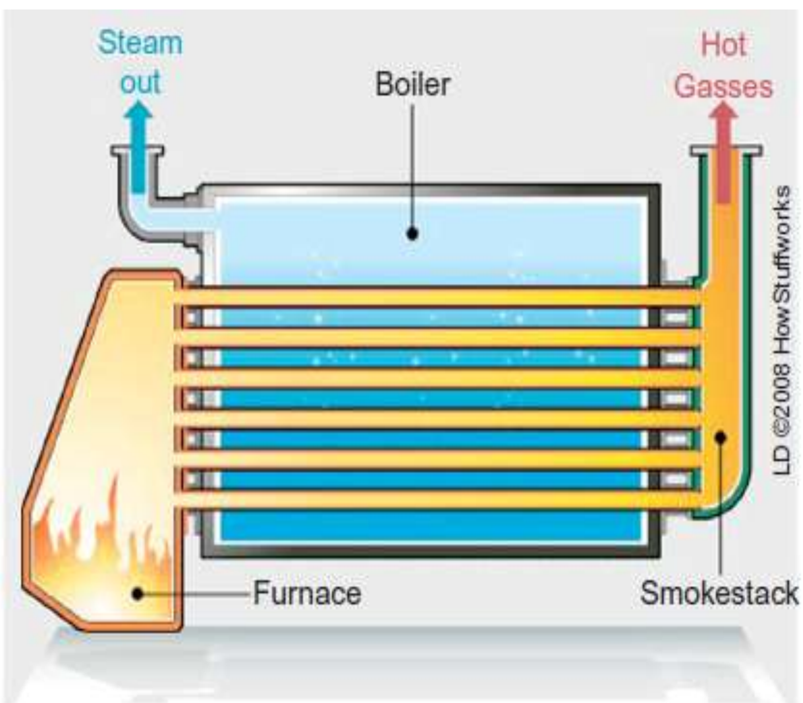


Figure 3-3: schematic of fire tube steam boiler

in figure 3-3. The heat from the flue gases is transferred from the tubes to the water in the container, thus the water is heated into steam. An easy way to remember the principle is to say that a fire tube boiler has "fire in the tubes". A fire tube boiler is simple and its initial cost is low and used in industrial plants to produce saturated steam up to (18 bar) pressure about (6 kg/s) capacity.

3.2.1.1 Advantages of Fire-Tube Boiler:

Following are the major advantages offered by fire tube boiler :

- Due to their availability as packaged systems, they can be easily relocated from one place to another.
- The construction and maintenance routine of a typical fire tube boiler happens to be very simple.
- Fire tube boilers usually consist of a single furnace tube and a burner. Hence, the control systems meant for heating purpose inside these boilers is kept very simple.
- Due to their comparatively low operating pressures, the accessories needed to support fire tube boiler systems can be obtained at very economical rates.
- These types of boiler systems are found to be very fuel efficient. Besides, their operation is very easy.
- They provide very cost-effective heating solutions.
- Their cleaning procedure is very simple.

3.2.1.2 Disadvantages of Fire-Tube Boiler:

Major disadvantages associated with fire tube boilers are mentioned below:

- As a general rule, the maximum output generated out of fire tube boiler is around 27 000 kg / h.
- The fire tube boiler systems are not capable of working with applications which involve high operating pressures i.e. beyond 250 psig. This limitation is experienced due to the large diameter cylindrical construction of fire tube boilers.
- Also, these boiler systems are not considered suitable for processes where high capacity steam is required.

3.2.2 Water tube boiler

The conditions are the opposite of a fire tube boiler. The water circulates in many parallel-connected tubes. The tubes are situated in the flue gas channel, and are heated by the flue gases, which led from the furnace through the flue gas passage. In a modern boiler, the water circulates in the tubes, which are welded together and form the furnace walls. Therefore the water tubes are directly exposed to radiation and gases from the combustion Figure 3-4. Similarly to the fire tube boiler, the water tube boiler received its name from having "water in the tubes". A modern utility boiler is usually a water tube boiler, because a fire tube boiler is limited in capacity and only feasible in small systems. Water tube boiler is classified as:

- Vertical tube boiler
- Horizontal tube boiler
- Inclined tube boiler

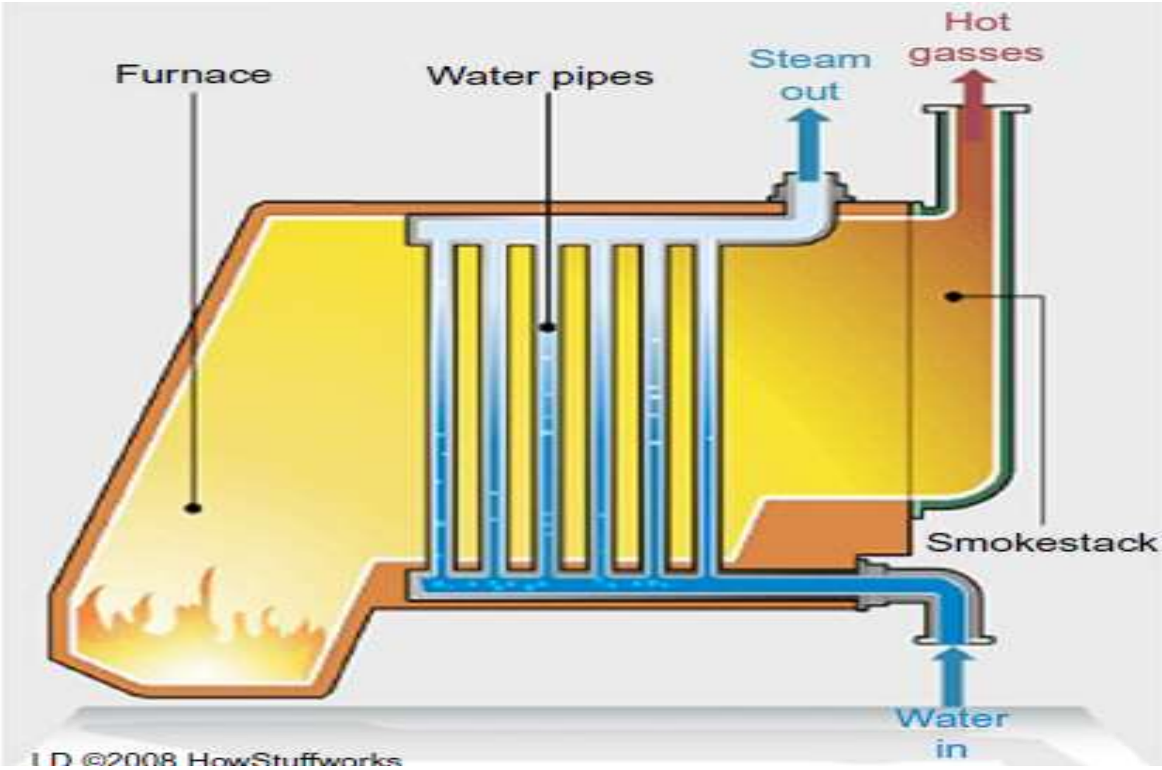


Figure 3-4: drawing describing the water tube boiler principle.

3.2.2.1 Advantages of Water Tube Boilers

- More amount of steam can be generated at high pressure.
- Heating surface is more; therefore steam is generated quickly in water tube boilers.
- Replacement of defective tube is easier.
- Simpler in construction.
- Cleaning and inspection is easy when compared to fire tube boilers.
- The various parts of the boiler can be separated easily; hence it can be transported easily from one place to another.

3.2.2.2 Limitations of Water Tube Boilers

These boilers are less suitable for use with impure and dirty water. Because of scale formation on tubes, overheating and bursting of the tubes is likely to occur.

- Skilled persons are required for inspection.
- The cost of maintenance is high when compared to fire tube boilers.

3.3 Comparison between Fire Tube and Water Tube Boilers:

Water Tube boiler	Fire Tube boiler
➢ Water is inside the tube and flue gases surrounded to it.	➢ Flue gases inside the tube and water surrounded to it.
➢ Operating pressure is up to 170-180 bar (high pressure boilers).	➢ Operating pressure is up to 25 bar (low and medium pressure boilers).
➢ Steam generation rate is very high (more than 3000 kg/hr)	➢ Less steam generation rate.
➢ Suitable for power plants.	➢ Suitable for small industries.
➢ Chance of explosion is more due to high steam pressure.	➢ Chance of explosion is less due to low steam pressure.
➢ Provide steam in power plants to develop electrical energy.	➢ Provide steam in chemical and pharmaceutical industries.
➢ Small chance of scale formation due to flue gases are in shell	➢ More chance of scale formation
➢ Example: Bobcock and Wilcox boiler	➢ Example: Vertical boiler, locomotive boiler, Lancashire boiler.

3.4 The Selection of Steam Generator:

- Quantity of steam or hot water required.
- Pressure, temperature, or steam quality required.
- Location and purpose of the installation.
- Type of fuel to be used.
- Availability of water

3.5 Classification of a Modern Boiler

Steam generators are classified as follows:

a. As per location of fire and water spaces :

- Fire Tube Boiler
- Water Tube Boiler

b. Based on circulation:

- Natural Circulation Boiler
- Forced/Assisted Circulation Boiler

c. Based on pressure requirement:

- Subcritical Boiler
- Supercritical Boiler

d. As per arrangement of steam and water spaces :

- Drum Type Boiler
- Once-through Boiler

e. Based on type of firing/heat transfer:

- Stoker-fired Boiler
- Fossil Fuel (Gas/Oil/Coal)-fired Boiler
- Fluidized-bed Boiler
- Waste Heat Recovery Boiler

3.6 Natural circulation boilers

3.6.1 General

The natural circulation is one of the oldest principles for steam/water circulation in boilers. Its use has decreased during the last decades due to technology advances in other circulation types. Natural circulation principle is usually implemented on small and medium sized boilers. Typically the pressure drop for a natural circulation boiler is about 5-10 % of the steam pressure in the steam drum and the maximum steam temperature varies from 540 to 560 °C.

3.6.2 Natural circulation principle

The water/steam circulation begins from the feed water tank, from where feed water is pumped. The feedwater pump Figure 3.5 raises the pressure of the feedwater to the wanted boiler pressure. In practice, the final steam pressure must be under 170 bar in order for the natural circulation to work properly. The feed water is then preheated in the economizer almost up to the boiling point of the water at the current pressure. To prevent the feed water from boiling in the economizer pipes the economizer temperature is on purpose kept about 10 degrees under the boiling temperature. From the economizer the feed water flows to the steam drum of the boiler. In the steam drum the water is well mixed with the existing water in the steam drum. This reduces thermal stresses within the steam drum.

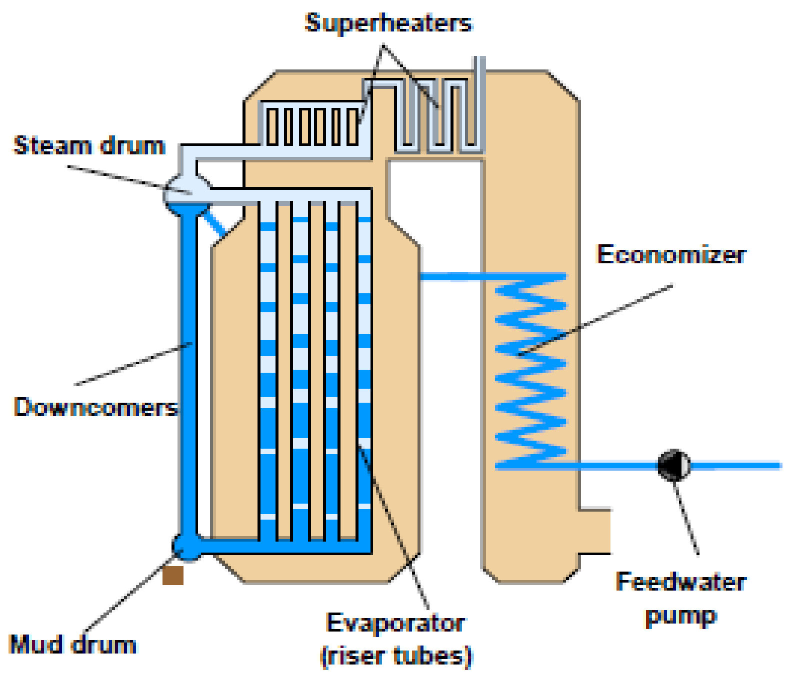


Figure 3.5: Natural circulation principle

The saturated water flows next from the steam drum through downcomer tubes to a mud drum (header). There are usually a couple of downcomer tubes, which are unheated and situated outside the boiler.

The name "mud drum" is based on the fact that a part of the impurities in the water will settle and this 'mud' can then be collected and removed from the drum.

The saturated water continues from the header to the riser tubes and partially evaporates. The riser tubes are situated on the walls of the boiler for efficient furnace wall cooling. The rises tubes are sometimes also called generating tubes because they absorb heat efficiently to the water/steam mixture. The riser tubes forms the evaporator unit in the boiler.

3.6.3 Driving force of natural circulation

The driving force of the natural circulation is based on the density difference between water/steam mixture in riser and downcomer tubes, of which the riser tubes represent the lower density mixture and downcomer tubes the higher density mixture as show in figure 3.6 .

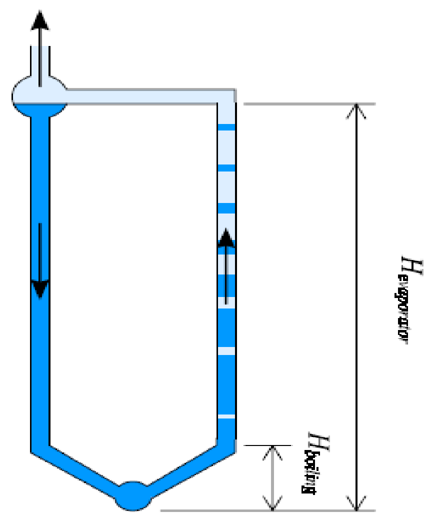


Figure 3.6: driving force in Natural circulation principle

The driving pressure can be defined as following:

$$\Delta p_d = g \cdot (H_{evaporator} - H_{boiling}) \cdot (\rho_{dc} - \rho_r)$$

Where:-

g : is the gravitational acceleration (9,81 m/s2).

H : the heights are according to Figure 3.6 [m].

$(\rho_{dc} - \rho_r)$: the difference in the average density between the downcomers (dc) and raiser (r) tubes [kg/m3].

The boiling height, i.e. the height where water has high enough temperature to boil, can be calculated using the circulation ratio and water/steam enthalpies:

$$H_{boiling} = \frac{h'' - h'}{\Delta h \cdot U} \cdot H_{evaporator}$$

Where:-

h'': is the enthalpy [kJ/kg] of saturated steam,

h' : enthalpy of saturated water (at the pressure of the steam drum),

U: is the circulation ratio, and

Δh: is the enthalpy change caused by the rise in evaporation pressure because of the subcooling of water in downcomer tubes).

3.7 Assisted or forced circulation boilers

3.7.1 General

In contrast to natural circulation boilers, forced circulation is based on pump-assisted internal water/steam circulation. The circulation pump is the main difference between natural and forced circulation boilers. In the most common forced circulation boiler type, the principles of forced circulation are basically the same as for natural circulation, except for the circulation pump. The operation pressure level of forced circulation boiler can be slightly higher than a natural circulation boiler, but since the steam/water separation in the steam drum is based on the density difference between steam and water, these boilers are not either suitable for supercritical pressures (>221 bar). Practically the maximum operation pressure for a forced circulation boiler is 190 bar and the pressure drop in the boiler is about 2-3 bar.

3.7.2 Principle of forced circulation

The water/steam circulation begins from the feed water tank, from where feed water is pumped. The feedwater pump raises the pressure of the feedwater to the wanted boiler pressure. In practice, the final steam pressure is below 190 bar, in order to keep the steam steadily in the subcritical region. The feed water is then preheated in the economizer almost up to the boiling point of the water at the current pressure.

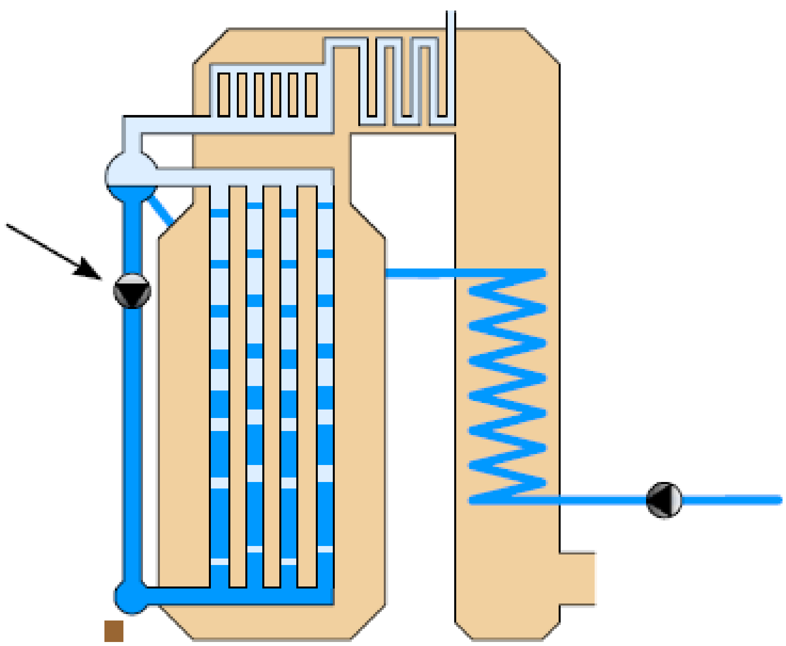


Figure 3.8 : Principle of forced/assisted circulation.

In a forced/assisted circulation boiler, the circulation pump Figure 3.8 provides the driving force for the steam/water circulation. Since the pump forces the circulation, the evaporator tubes can be built in almost any position. Greater pressure losses can be tolerated and therefore the evaporator tubes in a forced circulation boiler are cheaper and have a smaller diameter (compared to natural circulation evaporator tubes). This type of circulation is called forced circulation, due to the existence of a water circulation pump in the circuit. The steam/water circulation is forced by the pump and does not rely on density differences as in natural circulation.

3.8 Circulation ratio

The circulation ratio is one important variable when designing new boiler. It is defined as the mass rate of water fed to the steam-generating tubes (raisers) divided by the mass rate of generated steam. Thus, it is meaningful to define the circulation ratio only for water tube boilers:

$$U = \frac{\dot{m}_{raisers}}{\dot{m}_{feedwater}}$$

The variations in circulation ratio result from the pressure level of the boiler, therefore high pressure boilers have low ratios and low- construction of the recovery boiler using natural circulation drum.

For certain natural circulation applications dimensioning the circulation ratio is very difficult. The circulation ratio varies between 5 and 100 for natural circulation boilers. The circulation ratio of forced circulation boilers is normally between 3 and 10. Once through boilers generate the same mass rate of steam as has been fed to boiler, thus their circulation ratio is 1.

3.9 BOILER ACCESSORIES

The boiler accessories are fitted for efficient operation of the boiler. A modern boiler has the following accessories associated with it.

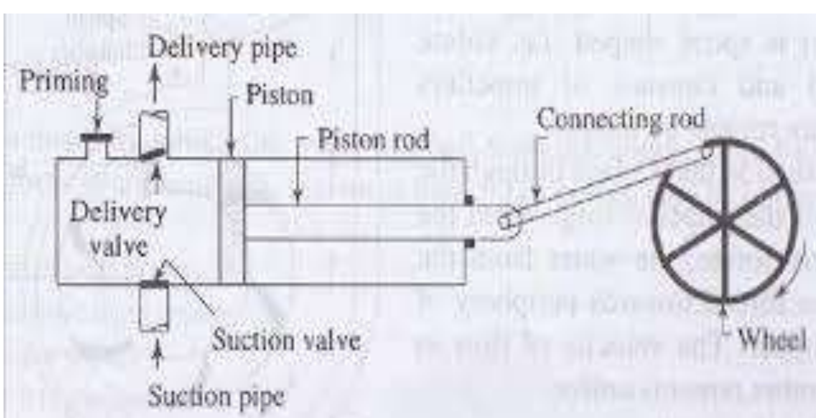
1. Feed pump.
2. Economizer.
3. Air preheater.
4. Superheater.
5. Steam drum (steam separator).
6. Injector.

3.9.1 Feed Pump

Feed pump is used to force the water into the boiler. Since the inside pressure of the boiler is high, the water should be pumped to a considerable pressure above that of boiler.

Basically two types of pumps are in use as show in figure 3.9 :

1. Reciprocating feed pump: consists of a cylinder and a piston. The piston displaces water as it reciprocates inside the cylinder.
2. Rotary feed pump: are of centrifugal type and are commonly run either by a small steam turbine or by electric motor.



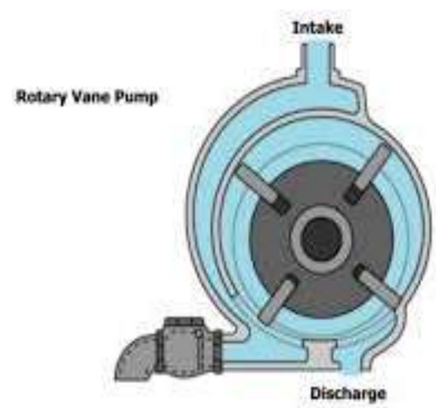


Figure 3.9: Water Feed Pump

3.9.2 Economizer

It is also known as **'Feed water heater'**. It is used to heat the feed-water by utilizing the heat of the waste flue gases before they are discharged to the atmosphere through chimney. Figure 3.10 show types of economizers.

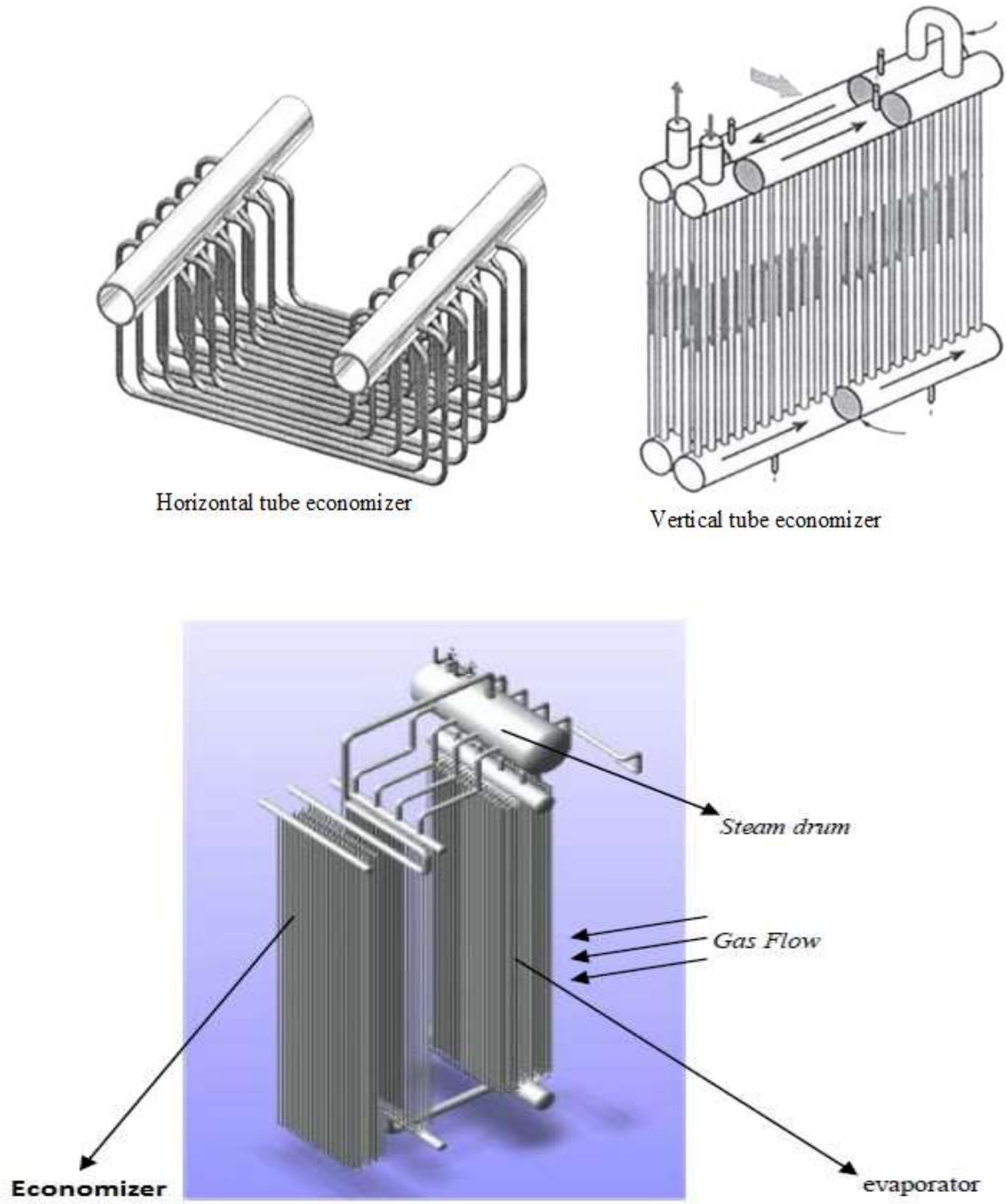


Figure 3.10: Types of Economizer

3.9.2.1 The economizer has many advantages

1. The temperature range between various parts of the boiler is reduced which results in reduction of stress on the inner wall of boiler drum due to uneven thermal expansion.
2. Evaporate capacity of the boiler is increased.
3. Overall efficiency of the plant is increased.

3.9.3 Air Pre-Heaters

Air preheater is an auxiliary system that increases the temperature of air before it enters the furnace as show in figure 3.11 . It is generally placed after the economizer - i.e in between economizer and chimney.

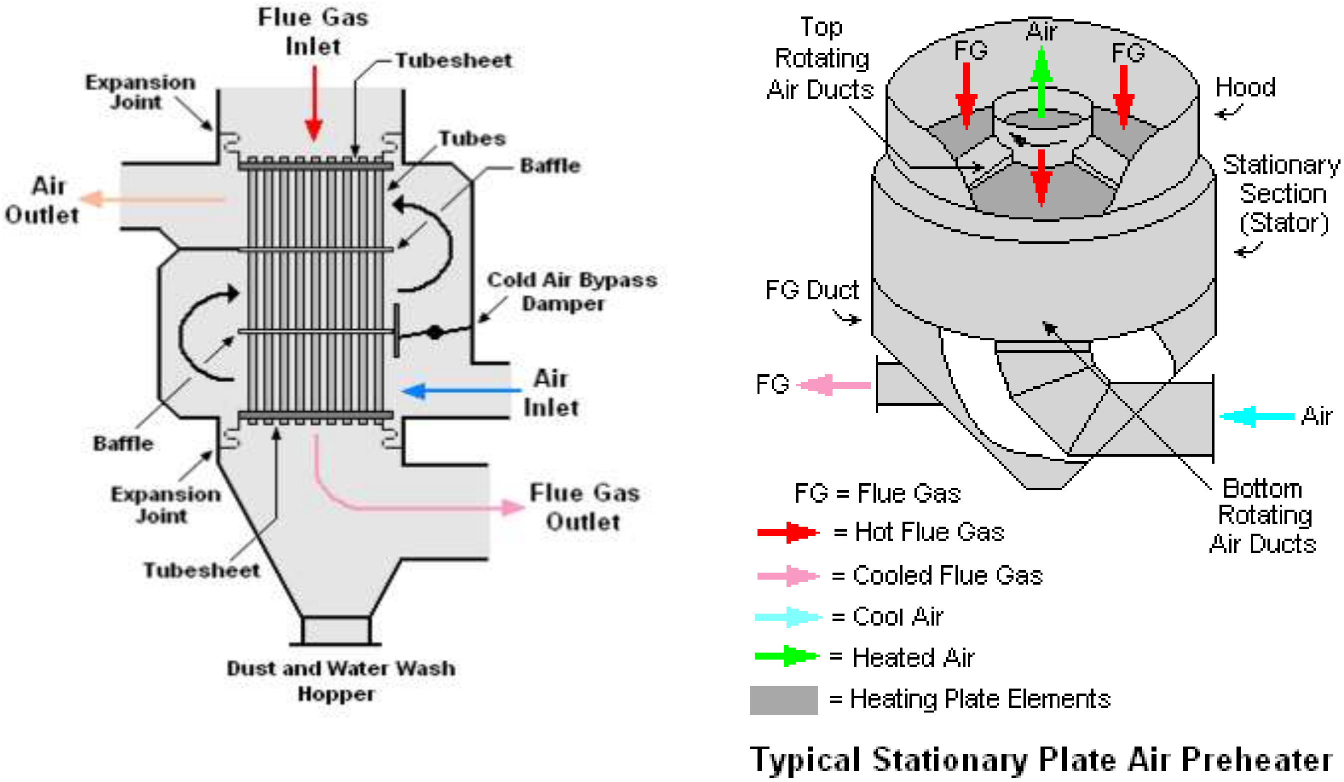


Figure 3.11: Air Preheater.

3.9.4 Super Heaters

They are located in the path of the hot furnace gases. The superheater in the form of coils of the tube and are used to heat up the steam above the saturation temperature. Figure 3.12 shows the steam superheater.

Super heater steam has the following advantages.

1. Steam consumption by the turbine is reduced.
2. Loss due to condensation is reduced.
3. Erosion of turbine blade is eliminated.
4. Efficiency of the plant is increased.

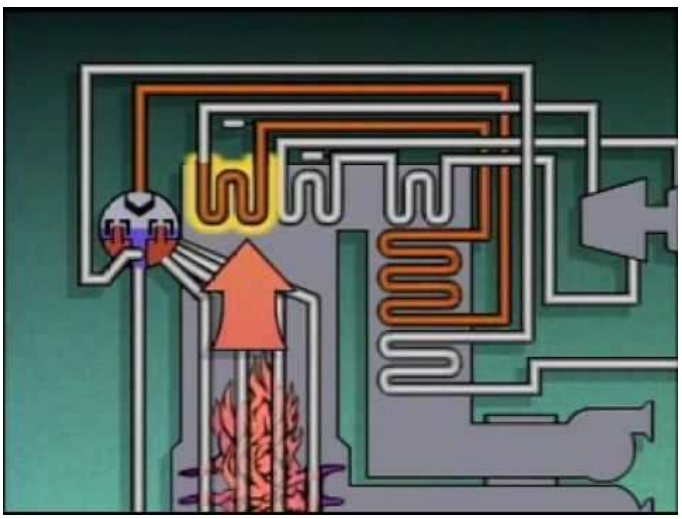


Figure 3.12: Steam Superheater.

3.9.5 Steam Drum (Steam separator)

The steam generated may be either wet steam (or) dry steam (or) superheated steam. The wet steam must be separated from the dry steam before letting it enter the main steam line figure 3.13. This separation is done by steam separator. It prevents the wet steam from entering the main steam line, thus prevents the turbine blades from corrosion.

Figure 3.13: Steam Drum

For the smallest drops (less than 10 microns) fiber mist eliminators are used. As the particles become larger, impingement devices like screens are adopted. As they get still larger, chevrons are used. Finally, for the larger drops, cyclones are adopted. They can operate for the entire range of liquid-to-gas-phase flow rates.

A system which has different geometric constraints is illustrated in Figure 3.14. Head room is limited in a steam drum so the liquid and vapor from many heated tubes enter at the bottom; pass up into the periphery into a double row of cyclone separators. Almost dry steam leaves out of the top of the cyclone while the separated liquid leaves the bottom. The almost-dry steam proceeds to the scrubber section (usually chevrons) and then out of the drum to the superheater.

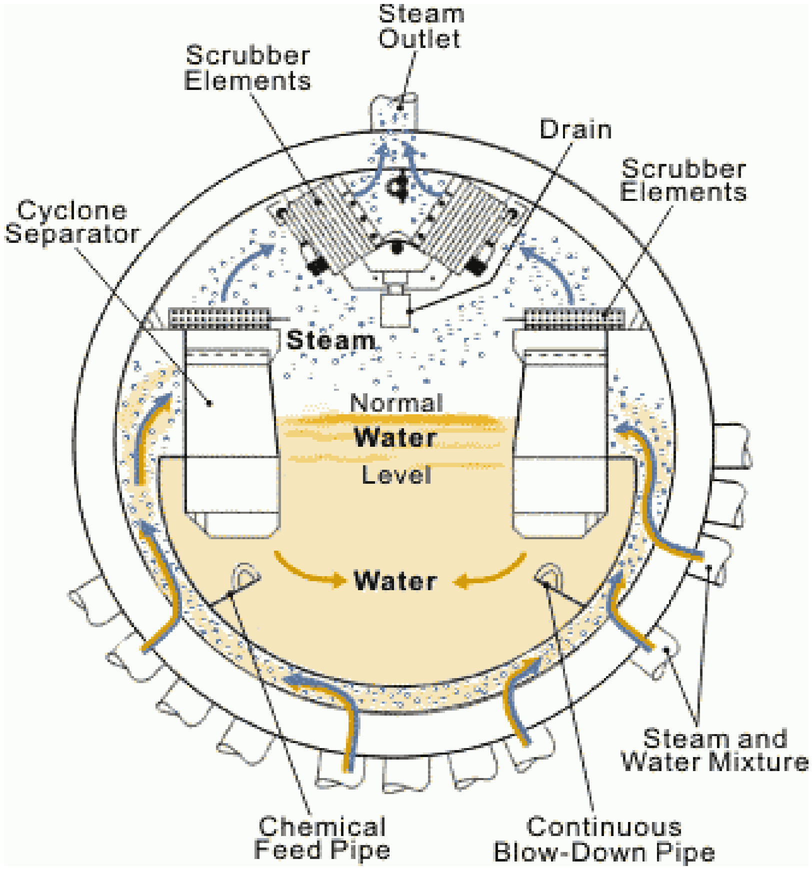


Figure 3.14: Steam Drum Separator Section Typical of Modern Drum.

The mass flow rate of drops less than 10 microns in diameter is quite small in typical steam generation installations so the mass fraction of liquid flowing out of the separator section for installation of this type is typically of the order of 0.1 percent.

Separation can be a problem when some vapor is entrained with liquid, such as when a jet or stream of liquid enters a pool. This is called carryunder. To prevent carryunder from being a problem, the liquid flow rate down in the pool must be kept well below the bubble rise velocity; that is, the velocity down for the liquid should be less than 0.2 m/s.

3.9.5.1 Types of Separators

3.9.5.1.1 Gravity Separators

The simplest separator is the gravity separator shows in figure 3.15. The superficial velocity of vapor at the free surface should be less than 0.3 m/s. When the velocity is greater than this the carryover increases rapidly. Often these separators are constructed as large-diameter inclined pipes in which the two-phase mixture enters at the bottom of the high end, and separated liquid is removed from the bottom of the low end. Vapor is removed from the top of the high end. In excess of 99 percent of the entrained liquid can be removed in gravity separators though some small drops are carried over for all flow rates. These separators can be horizontal or vertical cylinders or spheres.

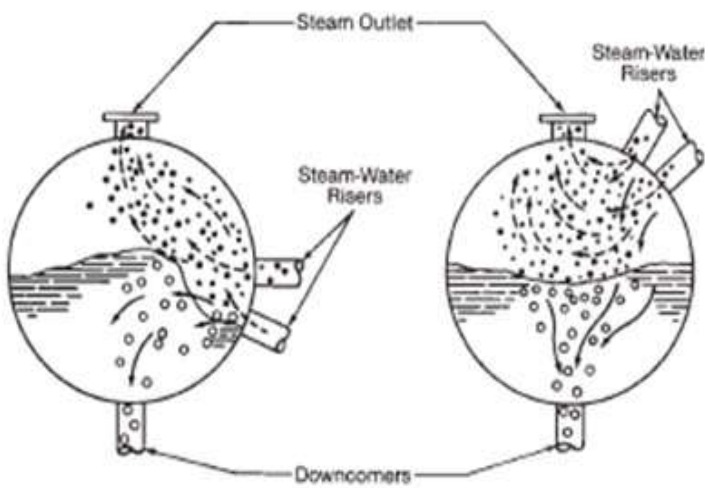


Figure 3.14: Steam Drum Separator Section Typical of Modern Drum.

3.9.5.1.2 Centrifugal Separators

Centrifugal separators have a higher characteristic throughout and have the unique characteristic in that they can be used to separate any proportions of liquid or vapor in the incoming stream. They are used within their design envelope; they effectively separate 99 percent of the liquid. Drops that are less than 10 microns in diameter are not usually separated. The pressure drop in these separators tends to be larger than in other kind because the characteristic velocity is larger. The swirl shown in the center of Figure 3.15 is typical of centrifugal separators.

When a cyclone separator is overloaded, the pressure in the swirl chamber drops so much below that of the pool into which the separated liquid drains that the liquid rises up the downcomer and floods the separator.

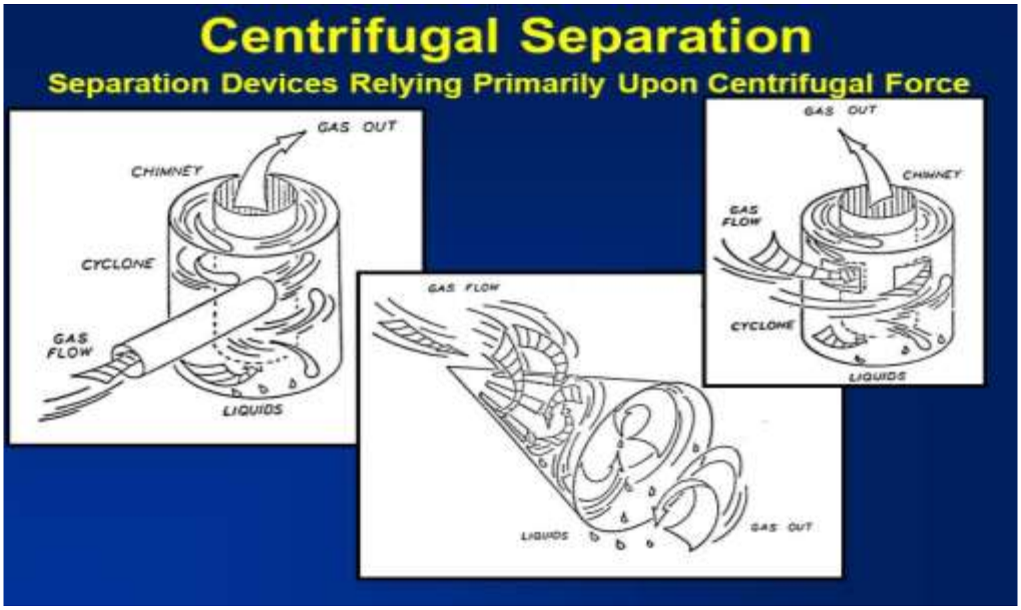


Figure 3.15 : Steam Drum Separator Section Typical of Modern Drum.

3.9.5.1.3 Chevrons and Screens

Chevrons and screens operate by intercepting drops which are unable to follow the vapor as it goes through a tortuous path through the device. These separators work on dispersed flows and are generally ineffective on drops less than 10 microns in diameter. Figure 3.16 shows how the chevrons are arranged. Vapor flow is in the horizontal plane while the separated liquid runs down due to gravity normal to the page.

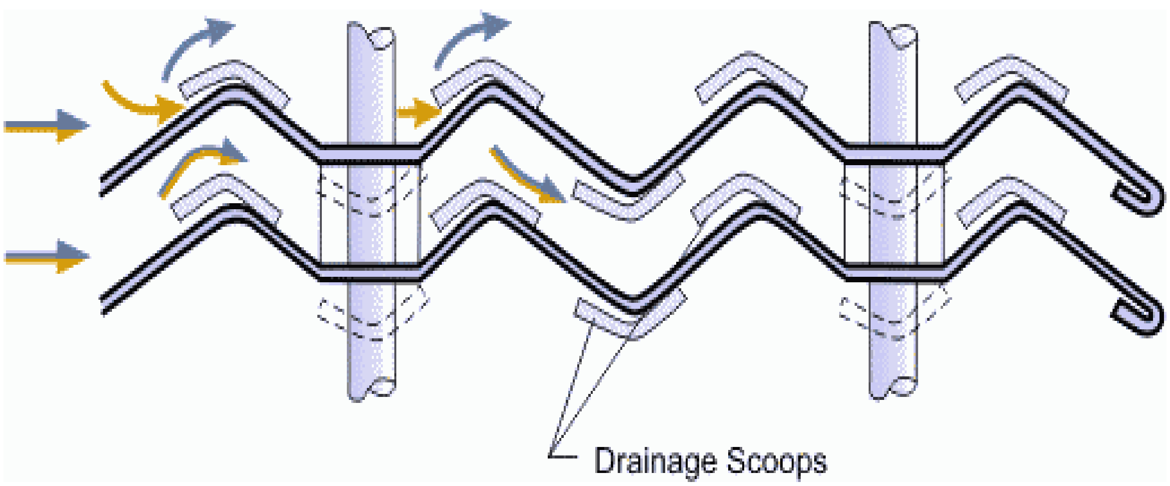


Figure 3.16 . Chevron Separator with Scoops Showing the Path of the Air or Vapor.

When a chevron separator is overloaded, the liquid is re-entrained before it can drain away. Knitted wire mesh separators perform much the way chevron separators do except that they have lower characteristic velocities in them but can trap smaller drops. They fail when overloaded in the same way that chevron separators do, the separated liquid is re-entrained before the liquid can drain away. Mist eliminators are particularly well adapted to the elimination of drops smaller than 10 microns. They consist of a mat or bundle of fibers arranged so that the separated liquid can drain away easily, and the gas can continue on through the filter material see Figure 3.17.

As the velocity through these separators increases, they also fail in the same way as the wire mesh or chevron separators; the liquid is re-entrained before it has a chance to drain away.

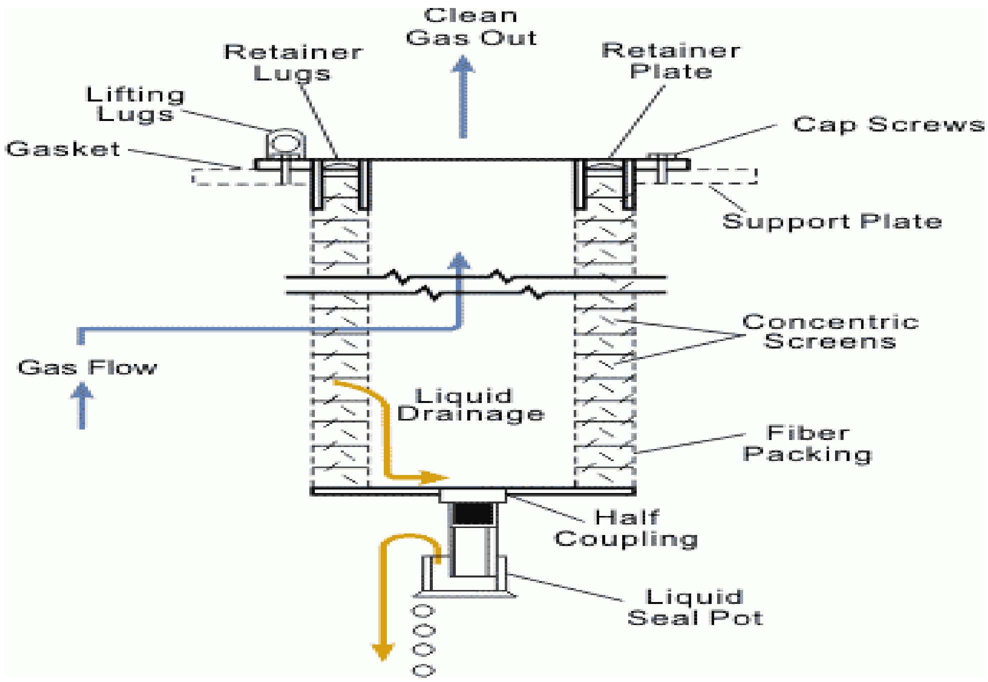


Figure 3.17. A high efficiency Brink mist eliminator element.

Pressure drop in separators is the penalty we must pay to separate the two phases. It is important to be able to estimate the pressure drops through the separator and select a separator type which is suitable for the application in question. Table 3.2 summarizes the performance of these kinds of separators in terms of the dimensional quantity given below.

$$F_s = v_g \sqrt{\rho_g}$$

Where :- F_s : is a dimensional constant in $m/s(kg/m^3)^{1/2}$.

v_g = Vapor-phase velocity in m/s .

p_g = Vapor density in kg/m^3.

in which the characteristic velocity is the velocity into the separator.

Table 3.2. Types of Separators and Their Characteristics

Type	Approximate size droplet size range (in microns)	Separation system flow regime	Typical F_S	Typical ΔP in CM of H_2O	Two phase flow regime
Gravity Separator	>10.0	Laminar or Turbulent	0.3–0.6	Negligible ~1 velocity head	Any quality but best for low quality slug or annular dispersed flow
Fiber Mist Eliminators	>0.1	Turbulent	3.0–6.0	About 1 velocity head	Highly dispersed
Knitted Wire Mesh	>3.0	Turbulent	1.0–2.0	.25–5	Highly dispersed droplet flow
Chevron or Impingement Separator	>6.0	Turbulent	1.0–4.5	2.5–5	Highly dispersed droplet flow
Cyclone Separator	10.0 and up	Turbulent	3.0–20.0	7.5–7.5	Any quality or flow regime

3.9.6 Injector

An injector is used to feed water into boiler using steam from the same boiler as show in figure 3.18 A&B.

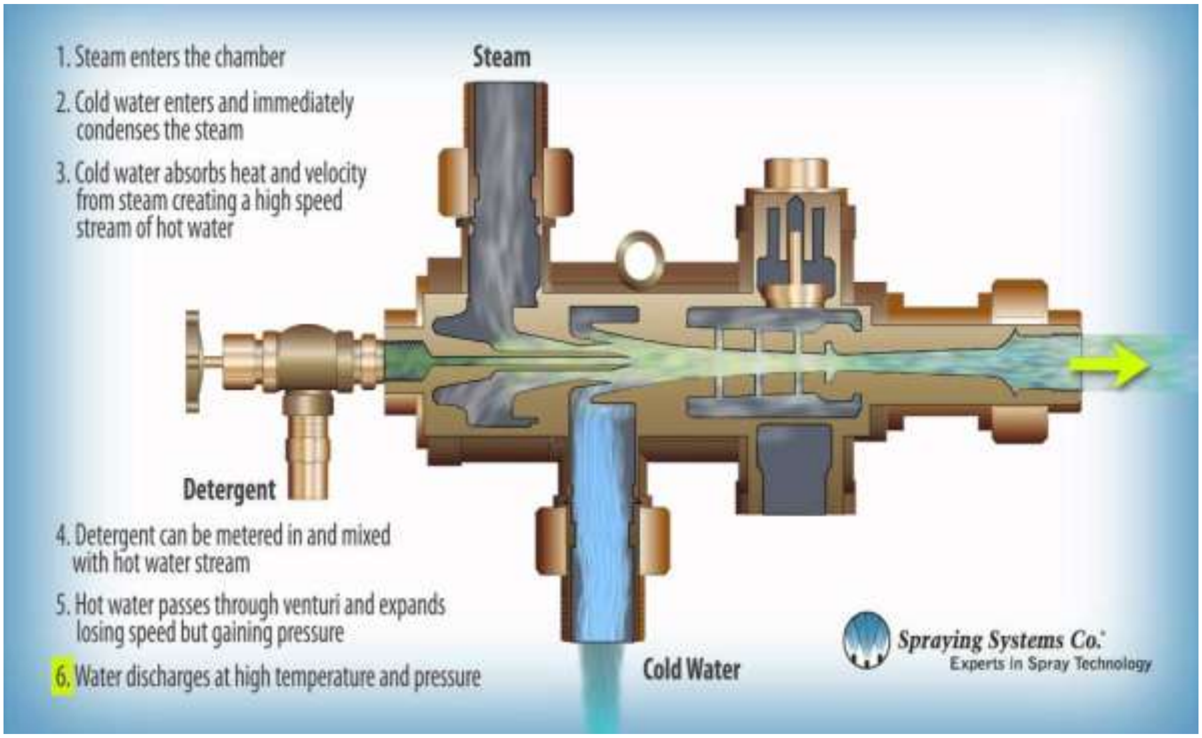


Figure 3.18: A Steam Injector.

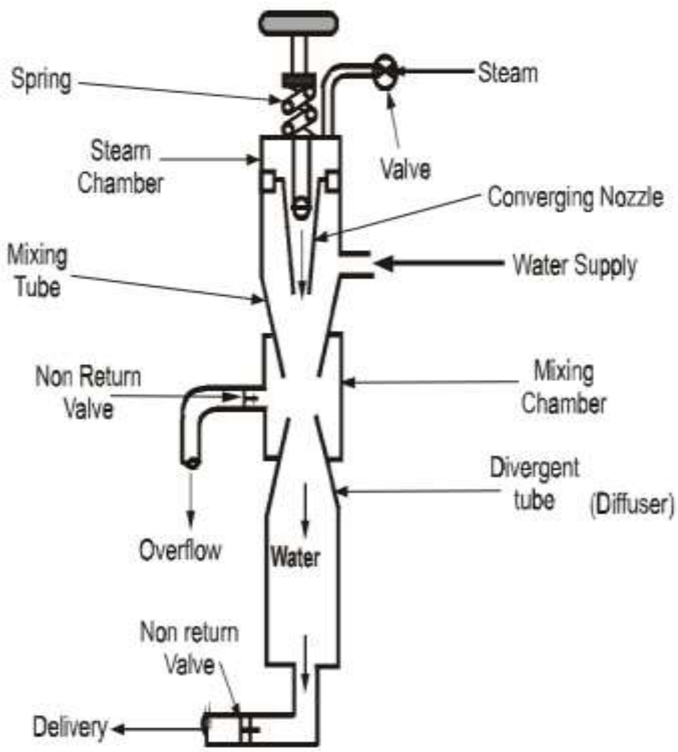


Figure 3.18: B Steam Injector.

Determination of steam/water parameters

Given parameters

Normally in a steam boiler design assignment the parameters describing the live (output) steam, e.g. mass flow, pressure and temperature are given. If the steam boiler to be designed has a reheat cycle, also reheat pressure and temperature are given. Reheat steam mass flow can be given as well. These parameters are used to determine the rest of the steam/water parameters.

Pressure losses

The pressure losses in the heat exchanger units of the boiler are estimated according to the following approximations:

- **Economizer**: the pressure loss is 5-10 % of the pressure of the feedwater entering the economizer.
- **Evaporator**:

1- ***Once through boilers***: in once-through boilers the pressure loss of the evaporator is between 5 and 30 %.

2- ***Forced and natural circulation boilers***: the pressure drop in the evaporator part of drum based boilers does not affect the pressure loss of the main steam/water flow through the boiler. This means that saturated steam leaving the steam drum has the same pressure as the feedwater entering the steam drum. The pressure loss of the evaporator has to be overcome using the driving force (natural circulation) or circulation pump (forced circulation).

- **Superheater**: the total pressure drop of all superheater packages is less than 10 % of the pressure of the superheated steam.

- **Reheater**: the pressure drop in the reheater is about 5 % of the pressure of reheated steam Pressure losses of connection tubes between different heat transfer surfaces (e.g. between evaporator and superheater) can be neglected in these calculations.

Procedure for determination of specific enthalpies and mass flow rates

1. The ***specific enthalpy of the superheated steam*** can be determined with an h-s diagram if both the temperature and the pressure of the steam are known. Thus, the specific enthalpies for live (superheated) steam and reheated steam can be calculated.

2. The ***total pressure loss of the superheater stages*** should be chosen. Thus, the pressure in steam drum (drum-type boilers) or pressure after evaporator (once-through boilers) can be calculated by adding the pressure loss over the superheater stages to the pressure of the superheated steam.

3. ***Specific enthalpy of saturated water and steam*** (in the steam drum) can be read from an h-s diagram or steam tables, as the pressure in the steam drum is known. In once-through boilers the determination of specific enthalpy after the evaporator is based on the temperature. The reason for this is the unclear state of supercritical steam after the evaporator in once-through circulation. The temperature after the evaporator in once-through boilers is typically between 400 and 450 °C.

4. For ***removal of minerals*** concentrated in the steam drum, a part of the water in steam drum is removed as blowdown water from the bottom of

the steam drum. Normally the mass flow rate of blowdown is 1-3 % of the mass flow rate of feedwater coming into steam drum.

5. In principle, the feedwater coming into steam drum should be saturated water. To prevent the feedwater from boiling in the transportation pipes, the temperature of the feedwater reaching the steam drum is 15-30 °C below saturation temperature. The feedwater is then called *subcooled* (in contrast to supercooled). When the temperature in the steam drum and the value of subcooling are known, the temperature after the economizer can be determined. Thewater pressure after the economizer can be assumed to be equal to the pressure in the steam drum and specific enthalpy after the economizer can then be read from a h-s diagram. In once through boilers the pressure after the economizer can be calculated by adding the pressure loss in the evaporator to the pressure after evaporator. The temperature after the evaporator is normally between 300 and 350 °C (can be chosen). Knowing the pressure and the temperature, the specific enthalpy after the evaporator can be defined.

6. The pressure before the economizer can be calculated by adding the pressure loss in the economizer to the feedwater pressure after economizer. The feedwater temperature might be stated in the boiler design assignment. If it is not given, it should be chosen from the range of 200-250 °C. The mass flow rate before the economizer is the blow down mass flow rate added to the mass flow rate from the steam drum to the superheaters.

Superheater and Reheater

Reheating takes usually place in two stages. The pressure before the reheater is the reheated steam pressure added on the pressure loss in the reheater. The steam goes through a high pressure turbine before it enters the reheater. In the high-pressure turbine, the specific enthalpy of steam decreases according to the isentropic efficiency of the turbine. Isentropic efficiency is normally between 0,8 and 0,9. A part of the low-pressure steam coming from high-pressure turbine continues to the high-pressure feedwater heater (closed-type feedwater heater). However, the mass flow rate of reheated steam is still 85-90 % of that of the live steam.

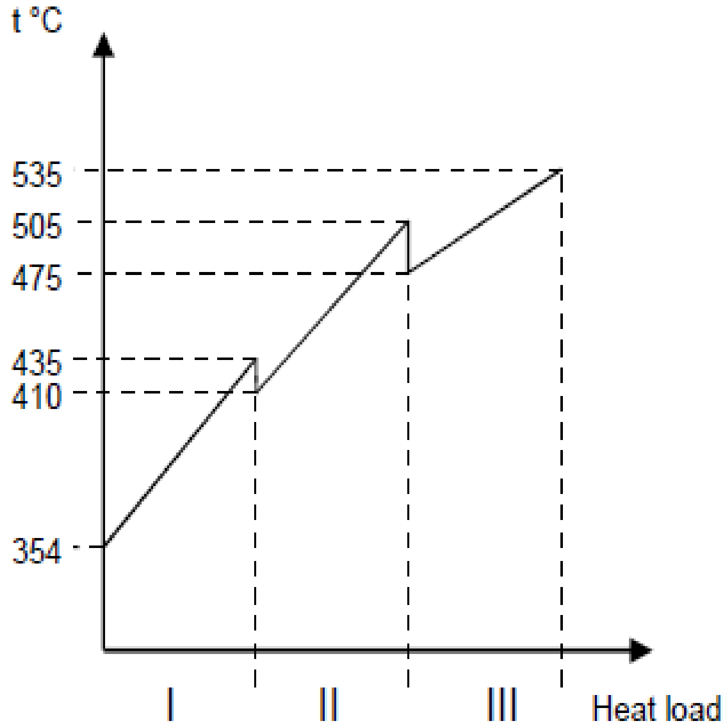


Figure 3.19: An example of the heat load share of superheater stages.

Superheating is often applied in three stages having spray water groups between each other to reduce steam temperature when necessary. Between reheaters, the steam temperature is controlled using other means. Spray water group dimensioning is usually based on a Heat load steam temperature decrease of 15-40 °C by water spraying. Spray water originates normally from the feedwater line before the economizer. Thus the pressure difference is the pressure loss of the heat transfer surfaces between the economizer inlet and the location of the spray water nozzle. An example of a possible heat load share between the superheater stages is shown in figure 3.19.

Pressure loss in superheaters can be divided into equal partial pressure losses corresponding to each superheater stage. Pressure loss of the spray nozzles can be neglected. Temperature rise over all superheaters can be divided into quite similar parts along the same principle.

Spray water group mass flow

Normally the mass flow rate of superheated steam (live steam) is known. Thus, mass flow rate calculations start usually by calculating the mass flow rate of spray water to the last spray water group (which is in this example between the second and third superheater stages). The mass flow rates can be solved with energy and mass balance equations. With the equations below (equation 1), the mass flow rate of steam after second superheater stage and mass flow rate of spray water to the last spray water group can be calculated. The mass flow rate of spray water to the first spray water group can be calculated along the same procedure:

$$\dot{m}_{SHII} + \dot{m}_{SPRAYII} = \dot{m}_{SHIII}$$
$$\dot{m}_{SHII} \cdot h_{SHII,2} + \dot{m}_{SPRAYII} \cdot h_{SPRAY} = \dot{m}_{SHIII} \cdot h_{SHIII,1} \qquad \ldots\ldots\ldots.. (1)$$

where $\dot{m}_{SHII}$ is the mass flow rate of steam after second superheater stage [kg/s], $\dot{m}_{SPRAYII}$ the mass flow rate of spray water to second spray water group, $\dot{m}_{SHIII}$ the mass flow rate of superheated steam (live steam), $h_{SHII,2}$ the specific enthalpy of steam after second superheater stage [kJ/kg], h_{SPRAY} the specific enthalpy of spray water (feedwater), and $h_{SHIII,1}$ the specific enthalpy of steam before third superheater stage. Figure shows a flow chart with the symbols visualized of the boiler arrangement used in this calculation model.

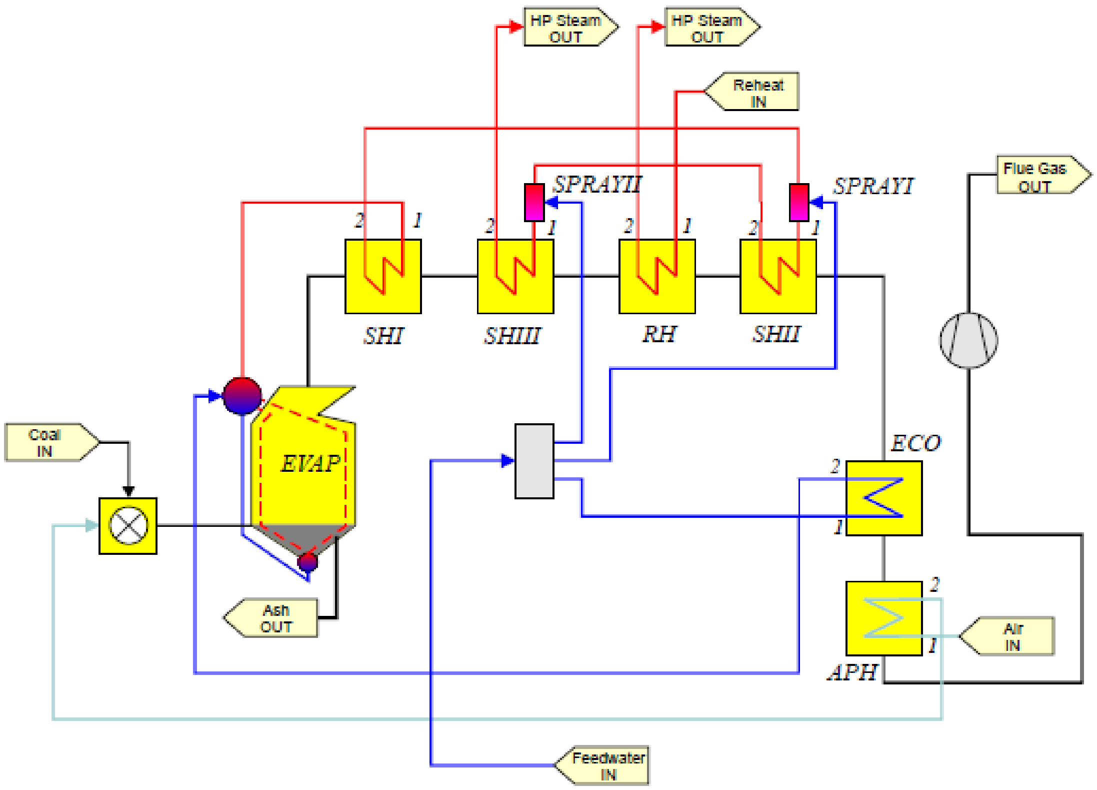


Figure 3.20: Flow chart of the PCF boiler arrangement used in this heat load calculation model.

Calculations of heat load

When the steam parameters and mass flows have been determined, the heat load of the heat exchanger units can be calculated. The heat load is the heat transferred by a heat exchanger (calculated in kW).

Evaporator

The heat load of the evaporator part of the boiler can be calculated as:

$$\phi_{EVAP} = \dot{m}_{SH}\left(h'' - h_{ECO2}\right) + \dot{m}_{BD}\left(h' - h_{ECO2}\right) \tag{2}$$

where $\dot{m}_{SH}$ is the mass flow of steam before superheater [kg/s], h'' the specific enthalpy of saturated steam at steam drum pressure [kJ/kg], h_{ECO2} the specific enthalpy after economizer $\dot{m}_{BD}$ the mass flow of blowdown water from steam drum, and h' the specific enthalpy of saturated water at steam drum pressure [kg/s]

Superheater

Normally superheating takes place in three or four stages in a big boiler. This calculation example is based on three stage superheating. The heat load of the first superheater stage is

$$\phi_{SHI} = \dot{m}_{SH}\left(h_{SHI,2} - h''\right) \tag{3}$$

where $h_{SHI,2}$ is the specific enthalpy of steam after the first superheater stage. In the second superheater stage the heat load added can be calculated as:

$$\phi_{SHII} = \dot{m}_{SHII}\left(h_{SHII,2} - h_{SHII,1}\right) \tag{4}$$

where $\dot{m}_{SHII}$ is the mass flow of steam before the second superheater [kg/s], $h_{SHII,2}$ the specific enthalpy of steam after the second superheater stage [kJ/kg], and $h_{SHII,1}$ the specific enthalpy of steam before the second superheater stage. Similarly, the heat load added in third superheater stage can be calculated as:

$$\phi_{SHIII} = \dot{m}_{SHIII}\left(h_{SHIII,2} - h_{SHIII,1}\right) \tag{5}$$

wher $\dot{m}_{SHIII}$ = Mass flow of steam before third superheater [kg/s], $h_{SHIII,2}$ the specific enthalpy of steam after third superheater stage [kJ/kg], and $h_{SHIII,1}$ the specific enthalpy of steam before third superheater stage [kJ/kg].

Reheater

The heat load of the reheater stage can be calculated as:

$$\phi_{RH} = \dot{m}_{RH}\left(h_{RH2} - h_{RH1}\right) \tag{6}$$

where $\dot{m}_{RH}$ is the mass flow rate of steam in the reheater [kg/s], h_{RH2} the specific enthalpy of steam after the reheater [kJ/kg] , and h_{RH1} the specific enthalpy of steam before the reheater.

Economizer

The heat load of the economizer can be calculated as:

$$\phi_{ECO} = \dot{m}_{ECO}\left(h_{ECO2} - h_{ECO1}\right) \tag{7}$$

where $\dot{m}_{ECO}$ is the mass flow rate of feedwater in the economizer [kg/s], h_{ECO2} the specific enthalpy of feedwater after the economizer [kJ/kg], and h_{ECO1} the specific enthalpy of feedwater before the economizer.

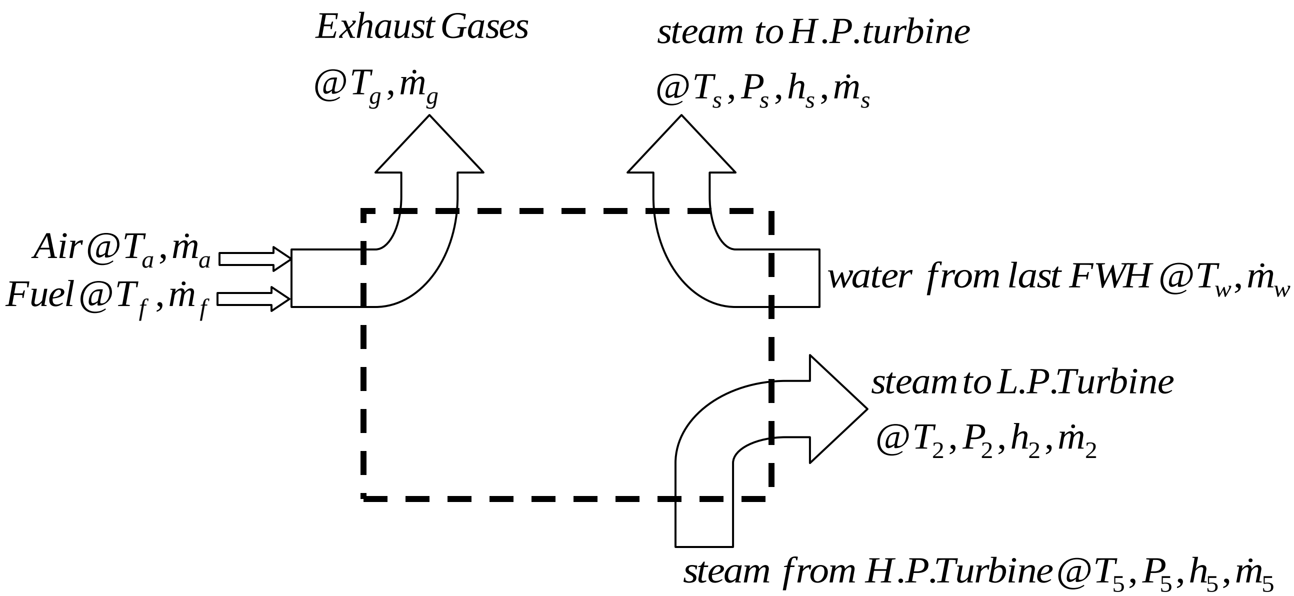
Air preheater

In order to calculate the heat load for the air preheater, we need to know the combustion air mass flow, the temperature of the flue gases and the incoming air. The combustion air fed into air preheater, is taken from upper part of the boiler room. The temperature of the combustion air before the air preheater is therefore between 25 and 40°C (in Finnish conditions). The flue gases exiting the boiler are usually kept above 130-150 °C in order to prevent corrosion. The enthalpies can be taken from tables:

$$\phi_{APH} = \dot{m}_{FUEL} \cdot \frac{\dot{m}_{AIR}}{\dot{m}_{FUEL}} \cdot \left(h_{APH2} - h_{APH1}\right) \tag{8}$$

where $\dot{m}_{FUEL}$ is the mass flow rate of fuel fed into the boiler [kg/s], $\frac{\dot{m}_{AIR}}{\dot{m}_{FUEL}}$ the mass flow rate of combustion air divided by the mass flow rate of fuel fed into the boiler, h_{APH1} the specific enthalpy of combustion air before the air preheater [kJ/kg], and h_{APH2} the specific enthalpy of combustion air after the air preheater.

3.10: Boiler Calculations and Performance:



3.10.1 Boiler efficiency: it is defined as the ratio between the total heat output (to convert water to steam and to reheat the steam) to the heat input as fuel. Each kg of fuel has a chemical energy known as "heating value" or calorific value".

$$\eta_b = \frac{\dot{m}_s(h_s - h_w) + \dot{m}_1(h_2 - h_1)}{\dot{m}_f.C.V}$$

Where C.V. is the calorific value in kJ/kg_f

By mass balance:

$$\dot{m}_w = \dot{m}_s$$
$$\dot{m}_5 = \dot{m}_6$$
$$\dot{m}_g = \dot{m}_a + \dot{m}_f$$

3.10.2 Equivalent Evaporation:

it can be defined as the flow rate ratio of steam to fuel that attained if the boiler receive saturated water at 100 ^oC and convert it to saturated steam at the same temperature.

$$E.E = \frac{(\dot{m}_s / \dot{m}_f)(h_s - h_w)}{2257}$$

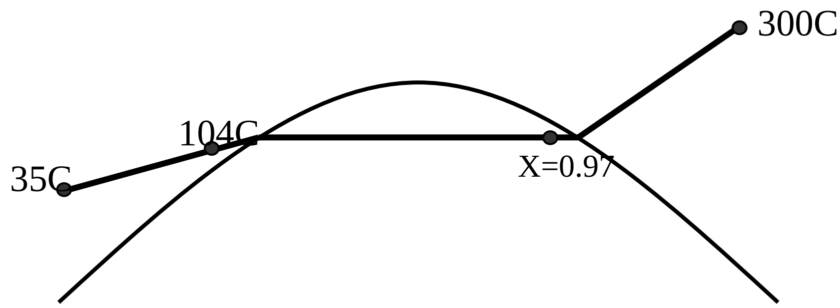
Where the value 2257 represent the latent heat of evaporation at 100^{o}C.

Example 1:

A steam generator works at 15 bar absolute pressure. The economizer receives the water at 35^oC and heats it to 104^oC while the super heater receives wet steam from steam drum at $x = 0.97$ and heats it to 300^oC. The coal used as a fuel has a heating value of $33.5MJ/kg$ and the steam produced per kg coal is $10kg_s/kg_f$. The air is drawn by the forced draft fan to the boiler at 20^oC and $20kg_a/kg_f$. The flue gases are discharged to the chimney at 150^oC. Assuming $Cp_g = 1.008kJ/kg..K$:

1. Determine the $\eta_b; E.E$
2. Draw the heat balance sheet.

Solution:



$$\eta_b = \frac{\dot{m}_{sf}(h_s - h_w)}{C.V} = \frac{10*(3039-147)}{33500} = 86.3\%$$

$$E.E = \frac{\dot{m}_{sf}(h_s - h_w)}{2257} = \frac{10*(3039-147)}{2257} = 12.8 kg_s / kg_f$$

$$Q_{economizer} = \dot{m}_{sf} * Cp_w * (T_2 - T_1) = 10*4.2*(104-35) = 2898 kJ/kg_f$$

$$Q_{evaporator} = \dot{m}_{sf} * (h_3 - h_2) = 10*(2731-437) = 22940 kJ/kg_f$$

where $h_3 = h_f + x.h_{fg} = 844.6 + 0.97*1945.2 = 2731\ kJ/kg$

and $h_2 = Cp_w.T_2 = 4.2*104 = 437\ kJ/kg$

$$Q_{superheater} = \dot{m}_{sf} * (h_4 - h_3) = 10*(3039-2731) = 3080 kJ/kg_f$$

$$Q_{chimney} = \dot{m}_{gf} * Cp_g * (T_g - T_a) = \frac{\dot{m}_a + \dot{m}_f}{\dot{m}_f}.Cp_g * (T_g - T_a) = (1 + \dot{m}_{af}) * Cp_g * (T_g - T_a)$$

$$= (1+20)*1.008*(150-20) = 2751.84 kJ/kg_f$$

Energy input KJ/Kg_f	Energy output KJ/Kg_f		
33500			%
	Economizer	2898	8.4
	Evaporator	22940	66.5
	Super heater	3080	8.8
	Chimney	2752	8
	Uncounted	1830	8.3

EXAMPLE 2

The following results were obtained from a boiler trail. Feed water temperature = 36° C, steam pressure = 14.8 bar, with dry saturated steam. Duration of trail = 10 hrs. Total Quantity of steam generated = 50,000 kg. Total coal burned = 6000 kg, C.V of coal = 30,000 kJ/kg. Total grate area = 3 m^2.

Calculate (i) Amount of coal burned per m2 grate area per hour, (ii) boiler efficiency, (iii) equivalent evaporation.

<u>SOLUTION</u>**:**

(i) Amount of coal burned per m^2 area per hour

$$= \frac{\text{Total coal burnt}}{\text{Grate area} \times \text{Duration of trail}}$$

$$= \frac{6000}{3 \times 10}$$

$$= \mathbf{200\ kg}$$

(ii) Equivalent Evaporation

$$m_e = \frac{m_a\,(h - h_f)}{h_{fg}}$$

$$(m_a) = \frac{m_s}{m_f}$$

$$m_a = \frac{50{,}000}{6000}$$

$$\boldsymbol{m_a} = \mathbf{8.33\ kg}$$

From steam tables, corresponding to steam pressure = 14.8 bar, dry saturated steam $h = hg = 2789.4$ kJ/kg

From steam tables , corresponding to feed water temperature = 36° C,

$\therefore\ hf = 150.7$ kJ/kg

From steam tables, corresponding to 100°C

$hfg = 2256.9$ kJ/kg

$$\therefore\ m_e = \frac{8.33 \times (2789.4 - 150.7)}{2256.9}$$

$$= \mathbf{9.739\ kg/kg\ of\ coal}$$

(iii) Boiler efficiency

Since boiler efficiency, $\eta_b = \dfrac{m_a\,(h - h_f)}{C.V}$

$$= \frac{8.33\ (2789.4 - 150.7)}{30000}$$

$$\eta_b = \mathbf{73.26\%}$$

Power Plant Engineering TUTORIAL SHEET - 3

Steam Generators

الجامعه المستنصريه ــ كليه الهندسه
قسم الهندسه الميكانيكيه

1- How much is used/kg of coal burnt in a boiler having chimney of 35 m height to create a draught of 20 mm of water, when the temperature of flue gas in the chimney is 370ºC and the boiler house temperature is 34ºC. Does this chimney satisfy the condition of maximum discharge?

Answers: 18.683 kg of air/kg of coal, $W' = 21.172$

2- Calculate the mass of flue gases flowing through the chimney when draught produced is equal to 1.9 cm of water. Temperature of flue gases is 290° C and the ambient temperature is 20° C. The flue gases formed per kg of fuel burnt are 23 kg. Neglect the losses and take the diameter of chimney as 1.8 m.

Answers: $H = 34.67$ m , $H1 = = 29.05$ m of air, $mg = 39.8$ kg/s

3- A boiler generates 2400 kg of dry steam per hour at a pressure of 11 bar the grate area is 3 m2, and 90 kg of coal is burnt per m2 of grate area per hour. The calorific value of coal is 33180 kJ/kg and the temperature of feed water is 17.5° C. Determine (i) Actual evaporation per kg of coal (ii) Equivalent evaporation from and at 100° C (iii) efficiency of the boiler.

Answers: 8.889 kg/kg of fuel, 10.659 kg/kg of coal, 86.93%

Problems

Q1//a 1**.173-MW** steam power plant of **overall efficiency of 32%** utilize a steam generator that produces steam at **40bar and 300 ^{o}C** at a rate of **1.128kg/s**. The temperature of the feed water is raised from **40 ^{o}C to 125 ^{o}C** in the **economizer** and the **ambient air** is drawn to the boiler at a rate of **2.72 kg/s at 16 ^{o}C**. The temperature of **flue gases** leaving the chimney is **150.4 ^{o}C** and its **specific heat is Cp=1.01 kJ/kg.K** and the **dryness fraction** of steam collected in the steam drum is **0.95**. The fuel used is of **33000kJ/kg heating value**.

1. Determine the **boiler efficiency** and the **equivalence evaporation**.
2. Determine the **thermal efficiency** if the **generator efficiency 0.95**.
3. Draw the **heat balance sheet**.

Q2/a steam power plant of a **25-MW** electric output power has a **medium water tube steam generator** of the following specifications

Steam production	31.6kg/s
Steam pressure	60bar
Steam temperature	500 ^{o}C
Dryness fraction of steam in the steam drum	0.96
Feed water temperature from F.W.Hs	100 ^{o}C
Water leaving economizer	250 ^{o}C
Fuel :natural gas of heating value	38700 kJ/m^3
Fuel consumption	2.85 m^3/s
Percent of unburned fuel	3%
Flue gas flow rate	12.8 kg/s
Flue gas temperature	150 ^{o}C
Flue gas specific heat	1.008 kJ/kg.K
Ambient temperature	30 ^{o}C

1. Determine the **boiler efficiency** and the **equivalent evaporation**.
2. Draw the **heat balance sheet** for the boiler.
3. Determine the **overall efficiency** for this plant.

Q3/a **3-MW** steam power plant have a water tubes boiler of the following specification:

Steam production	***9000 kg/h***
Steam pressure	***15 bar***
Steam temperature	***300*** *°C*
Dryness fraction of steam in the steam drum	***0.9***
Feed water temperature	***313K***
Water leaving economizer	***115*** *°C*
heating value of the fuel	***31 MJ/kg***
Fuel consumption	***1000 kg/h***
Flue gas temperature	***160*** *°C*
Flue gas density	***1.15 kg/m³***
Flue gas specific heat	***1.11 kJ/kg.K***
Boiler house temperature	***20*** *°C*
Chimney diameter	***1.24 m***
Velocity of flue gases leaving the chimney	***3 m/s***

1. Determine the overall efficiency, boiler efficiency, and equivalence evaporation.
2. Draw the heat balance sheet for the boiler.
3. State the requirements of good steam generator.