Chapter 2: Steam Generator

2.1 Steam generator

It is the engineering device which generates steam at constant pressure. It is a closed vessel, generally made of steel in which vaporization of water takes place. Heat required for vaporization may be provided by the combustion of fuel in furnace, nuclear reactor, hot exhaust gases, solar radiations etc. Figure (2.1) explain the boiler diagrammatically.

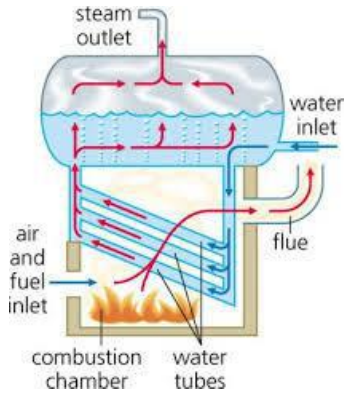


Figure (2.1) Boiler

2.2 Important Terms for Steam Boiler

The boiler consists from:

1. **Boiler Shell**: It is cylinder made from steel plates. Its volume must be sufficient to contain water and steam.
2. **Combustion Chamber**: It's a space below the boiler shell used for fuel burning.
3. **Grate**: It is a platform in the combustion chamber, in which the fuel (coal or wood) was burning. It's made from iron bars.
4. **Furnace**: it is the space above the grate and below the boiler, in which the fuel is actually burnt. It also called **fire box**.
5. **Heating Surface**: it is the part of the boiler exposed to fire or hot gases.
6. **Mountings**: these are the fittings which are mounted on the boiler like; pressure gauge, water level indicator, safety valve …etc.
7. **Accessories**: these are the devises which form an integral part of the boiler, but not mounted on it. They are economizer, super heater, feed pump …etc.

2.3 Boiler types

If f the boilers classified according to flow of water and hot gases, there are two major types;

1. **Fire tube boiler**: the hot gases follow through the boiler pipes and water surrounds them. It's used for low and medium capacity boilers see figure (2.2).
2. **Water tube boiler**: water and its vapor follow through the boiler pipes and hot gases surround them. It's used for high capacity boilers, see figure

(2.1). Table (2.1) explains the characteristics of fire tube and water tube boilers.

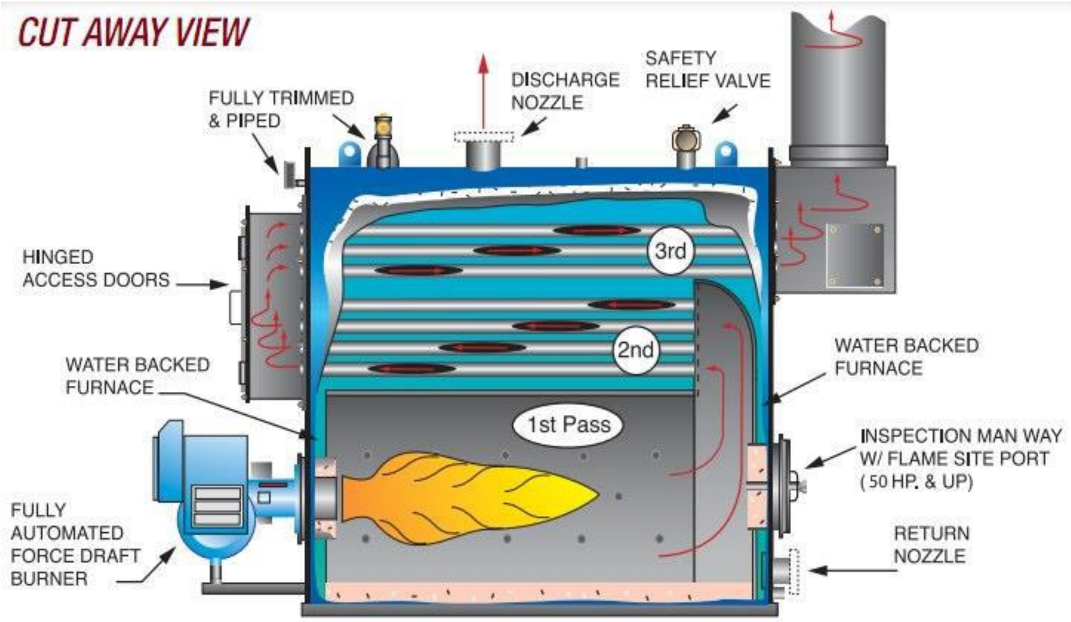


Figure (2.2) fire tube boiler.

Table (2.1) Features of fire tube and water tube boiler.

	Fire tube boiler	Water tube boiler
1	Hot gases from furnace flow through tubes which are surrounded by water.	Water circulated inside tubes which are surrounded by hot gasses.
2	Used for low and medium pressure up to 25 bar.	Used for high pressure up to 165 bar.
3	Used for low rate of steam generation up to 9 ton/hr.	Useful for high rate of steam generation 450 ton/hr.
4	The required floor area is low 5 m^2 for every 1 ton/hr.	The required floor area is high 8 m^2 for every 1 ton/hr.
5	Overall efficiency up to 75%	Overall efficiency up to 90%
6	It can be transported.	The transportation is difficult.
7	Operating coast is low.	Operating coast is high.
8	Not suitable for power plants.	Suitable for large power plants.
9	Explosion chance is low.	Explosion of the internal tubes is high.

2.4 Requirements for Good Boiler.

The good boiler must have the following features:

1. The boiler should generate steam at required pressure and quality and quantity with minimum fuel consumption. It should be economic.

2. The initial coast, installation coast, maintenance coast should be as low as possible.
3. All parts of the boiler should be easily reachable for cleaning and inspection.
4. The occupied area and weight of the boiler must be as low as possible.
5. The number of joint points in the boiler must be as low as possible to avoid leakage may occur through working.
6. The pressure drop across the boiler should be as low as possible.
7. The heat transfer rate through the boiler should be as high as possible.
8. Avoid deposition of mud and foreign materials on the inside surfaces and soot on the outer surface of the heat transferring parts.

2.5 Boiler Accessories

These are the devices which are used as integral parts of a boiler, and help in running efficiency. Though there are many types of boiler accessories, see figure (2.3), yet the following are important from the subject point of view:

1. Superheater
2. Economizer
3. Air preheater
4. Feed pump

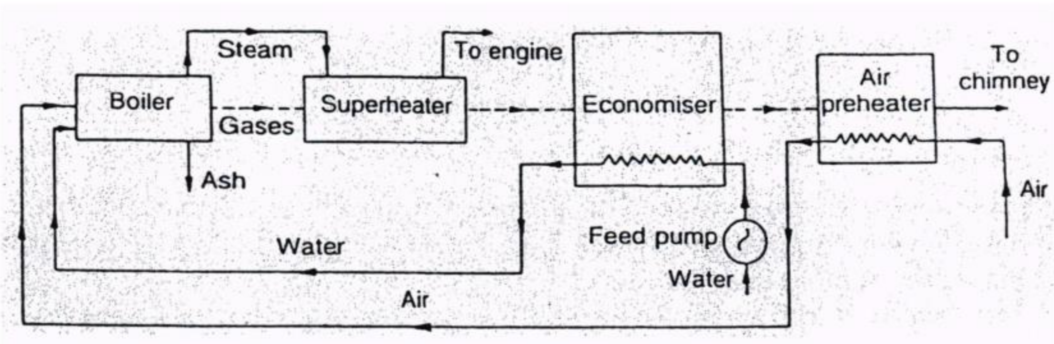


Figure (2.3) Boiler accessories.

Superheater: it is a device of steam generator unit. It is used to increase the temperature of saturated steam without raising its pressure. It is an integral part of a boiler.

Economizer: It is heat recovery device in which feed water is heated from heat available with exhaust gases. Thus hot feed water from economizer lowers the fuel requirement in combustion.

Air preheater: It is used for recovering the heat of exhaust gases by the air before being sent to furnace.

Feed pump: it is used for sending water into boiler at the pressure at which steam generation takes place. It is generally of two types: centrifugal pump and, reciprocating pump. The feed pump capacity should be greater than 15-20% of maximum continuous rating, to coverage excessive steam demand or blown out of the boiler to remove depositions and salts.

2.6. Boiler Calculations

Performance of the boiler was measured by evaporation capacity. To compare the evaporation capacity of the boilers, the inlet conditions must be identical. These conditions are: feed water temperature, working pressure, type of fuel, and the final conditions. The nominal feed water temperature is 100°C and nominal pressure is 1.013 bar. The quantity of heat required to converting saturated liquid water at 100°C and 1.013 bar to dry steam at the same temperature and pressure is called latent heat of evaporation.

To convert a 1 kg of distillated water at 100°C and 1.013 bar from saturated liquid to dry vapor, the quantity of energy consumed was 2257 kj/kg. So that:

E: Equivalent evaporation

$$E = \frac{Total\ heat\ required\ to\ evaporate\ 1\ kg\ of\ feed\ water}{2257}$$

$$E = \frac{m_e(h_2 - h_1)}{2257} \qquad \text{but,} \quad m_e = \frac{m_s}{m_f}$$

Where: E: equivalent evaporation in (kg/kg of fuel).
m_e: mass of water actually evaporated in kg/kg of fuel.
m_s: mass of water evaporated into a steam in kg.
m_f: mass of fuel in kg.
h_1: enthalpy or sensible heat of feed water entering boiler in kj/kg corresponding to T_1 °C (from steam tables).
h_2: enthalpy or total heat of steam leaving boiler in kj/kg corresponding to working pressure (from steam tables).
Note:

- if the steam leaving the boiler as wet steam $(h_2 = h_f + x h_{fg})$.
- if the steam leaving the boiler as dry steam $(h_2 = h_g)$.

- if the steam leaving the boiler as superheated steam $(h_2 = h)$ from superheated tables, or $\left[h_2 = h_g + C_p\left(T_{superheated} - T_{saturated}\right)\right]$.

Where : C_p: specific heat for the superheated steam $(2.1\ kj/kg.K)$.

$T_{superheated}$: degree of superheat of the steam in (°C).

$T_{saturated}$: saturated temperature of the steam at working pressure in (°C).

***F*$_e$:Factor of Evaporation**:

$$F_e = \frac{h_2 - h_1}{2257}$$

$F_e > 1$ for actual boilers.

η: Boiler Efficiency

It is defined as the ratio of the heat used in producing the staem to the heat liberated in the furnace. Sometimes is defined as the thermal efficiency of the boiler.

$$\eta = \frac{heat\ actully\ used\ in\ producing\ steam}{heat\ liberated\ in\ furnace} = \frac{m_s(h_2 - h_1)}{m_f \times C} = \frac{m_e(h_2 - h_1)}{C}$$

Where: C: calorific value of fuel in kj/kg of fuel.

Percentage of Energy Utilized through Steam Generator Part

The steam generator mainly divides into three main parts. These parts are; **economizer**, **boiler**, and **super heater**. Sometimes steam generator can be referred as a "Boiler". These three parts consumed the energy fuel combustion in the furnace. The percentage of energy utilized through every part of steam generator can be calculated as follows:

$$\text{percentage of energy utilized} = \frac{\text{energy utilized } through\ a\ part}{energy\ of\ combustion}$$

$$\text{percentage of energy utilized} = \frac{m_e(\Delta h)}{C} \times 100\%$$

Example (2.1): Boiler evaporates **3.6 kg** of water per kg of coal into dry saturated steam at **10 bar**. The temperature of feed water is **32 °C**. Find the equivalent evaporation from and 100 °C, and the evaporation factor.

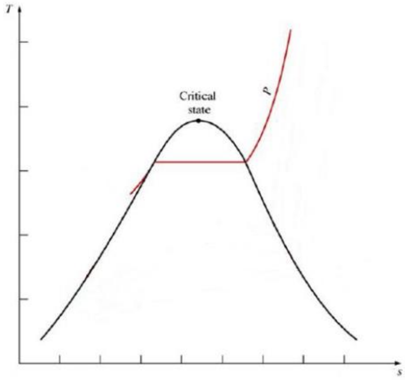
Solution: given $m_e = 3.6\ kg/kg\ of\ fuel; p = 10\ bar;\ T_1 = 32$ °C

From saturated steam tables, at 32 °C $h_{f1} = h_f = 134\ kj/kg$

From saturated steam tables, at 10 bar $h = h_g = 2776.2\ kj/kg$

$E = \frac{m_e(h_2-h_1)}{2257} = \frac{3.6(2776.2-134)}{2257} = 4.2\ kg/kg\ of\ coal$

$F_e = \frac{h_2-h_1}{2257} = \frac{2776.2-134}{2257} = 1.17$



Example (2.2): The following observations were made in a boiler trial: coal used is **250 kg**, the calorific value is **29800 kj/kg**, water evaporated is **2000 kg**, steam pressure is **11.5 bar**, dryness fraction of steam is **0.95**, and feed water temperature is **34 ºC**.

Calculate the equivalent evaporation per kg of fuel, and boiler efficiency.

Solution:

given; $m_f = 250\ kg; C = 29800\ kj/kg;\ m_s = 2000\ kg; p = 11.5\ bar;$

$x = 0.95;\ T_1 = 34°C$

From saturated steam tables, at 34 ºC $h_{f1} = h_f = 142.4\ kj/kg$

From saturated steam tables, at 11.5 bar

$h_f = 790\ kj/kg\ ; h_{fg} = 1991.4\ kj/kg$

For wet steam $h = h_f + xh_{fg} = 790 + 0.95 \times 1991.4 = 2681.8\ kj/kg$

$m_e = \frac{m_s}{m_f} = \frac{2000}{250} = 8\ kg/kg\ of\ fuel$

$E = \frac{m_e(h_2-h_1)}{2257} = \frac{8(2681.8-142.4)}{2257} = 8.8\ kg/kg\ of\ coal$

$\eta = \frac{m_e(h_2-h_1)}{C} = \frac{8(2681.8-142.4)}{29800} = 0.682 = 68.2\ \%$

Example (2.3): Boiler generates **2400 kg** of dry steam per hour at a pressure of **11 bar**. The grate area of the coal is **3 m^2** and **90 kg** of coal is burnt per m^2 of grate area per hour. The calorific value of the coal is **33180 kj/kg**, and the temperature of feed water is **17.5 ºC**. Determine (1) actual evaporation per kg of coal. (2) equivalent evaporation. (3) efficiency of the boiler.

Solution:

given: $m_s = 2400\ kg/h\ ; p = 11\ bar; grate\ area = 3\ m^3$

$coal\ burnt = 90\ kg/m^2 per\ hour;\ C = 33180\ kj/kg;\ T_1 = 17.5\ °C$

(1) actual evaporation per kg of coal;

The mass of coal burnt per hour is; $m_f = 90 \times 3 = 270\ kg/h$

$m_e = \frac{m_s}{m_f} = \frac{2400}{270} = 8.89\ kg/h$

(2) equivalent evaporation; from saturated steam tables

$@T_1 = 17.5\ °C \qquad h_{f1} = h_f = 73.4\ kj/kg$

$@p = 11\ bar\ h = h_g = 2779.7\ kj/kg$

$E = \frac{m_e(h_2 - h_1)}{2257} = \frac{8.89 \times (2779.7 - 73.4)}{2257} = 10.66\ kg/kg\ of\ fuel$

(3) efficiency of the boiler;

$\eta = \frac{m_e(h_2 - h_1)}{C} = \frac{8.89(2779.7 - 73.4)}{33180} = 0.725 = 72.5\ \%$

Example (2.4): Coal fired boiler plant consumes **400 kg** of coal per hour. The boiler evaporates **3200 kg** of water at **44.5ºC** into superheated steam at a pressure of **12 bar** and **274.5 ºC**. If the colorific value of fuel is **32760 kj/kg** of coal, determine; (1) equivalent evaporation from and at 100 ºC. (2) thermal efficiency of the boiler.

Solution: given

$m_f = 400\ kg/h;\ m_s = 32300\ kg;\ T_1 = 44.5\ °C; p = 12\ bar;$

$T_{super} = 275.5°C; C = 32760\ kj/kg\ of\ coal; take\ C_p = 2.12\ kj/kg.K$

(1) equivalent evaporation;

$m_e = \frac{m_s}{m_f} = \frac{3200}{400} = 8\ kg$

from saturated steam tables

$@T_1 = 44.5\ °C \qquad h_{f1} = h_f = 186.3\ kj/kg$

For the enthalpy of superheated steam leaving the boiler was;

$@p = 12\ bar \quad and\ T_2 = 274.5\ °C \quad \rightarrow\ h_2 = 2964.4\ kj/kg$

$E = \frac{m_e(h_2 - h_1)}{2257} = \frac{8 \times (2965.4 - 186.3)}{2257} = 9.85\ kg/kg\ of\ coal$

(2) thermal efficiency of the boiler.

$\eta = \frac{m_e(h_2 - h_1)}{C} = \frac{8 \times (2964.4 - 186.3)}{32760} = 0.678 = 67.8\ \%$

Example (2.5): the following observation were made on a boiler plant during one-hour test: steam pressure=**20 bar**, steam temperature=**260ºC**, steam generated=**37500 kg**, temperature of water entering the economizer=**15ºC**, temperature of water leaving the economizer=**90ºC**, fuel used=**4400 kg**, energy of combustion of fuel=**30000 kj/kg**.

Calculate; (1) the equivalent evaporation per kg of fuel, (2) the thermal efficiency of the plant, and (3) the percentage heat energy of the fuel utilized by economizer.

Solution: given

$p = 20\ bar;\ T_3 = T_{superheated} = 260℃;\ m_s = 37500\ kg/h$

$T_1 = 15℃;\ T_2 = 90℃; m_f = 4400\ kg/h\ ; C = 30000\ kj/kg$

(1) The equivalent evaporation per kg of fuel;

$m_e = \frac{m_s}{m_f} = \frac{37500}{4400} = 8.52\ kg/kg\ of\ fuel$

from saturated steam tables

$@T_1 = 15\ ℃ \qquad h_1 = h_f = 62.9\ kj/kg$

$@p = 20\ bar \quad and\ T_3 = 260\ ℃ \quad and\ h_3 = 2897\ kj/kg$

$E = \frac{m_e(h_3 - h_1)}{2257} = \frac{8.52 \times (2897 - 62.9)}{2257} = 10.7\ kg/kg\ of\ coal$

(2) thermal efficiency of the plant.

$\eta = \frac{m_e(h_3 - h_1)}{C} = \frac{8.52 \times (2897 - 62.9)}{30000} = 0.805 = 80.5\ \%$

(3) The percentage heat energy of the fuel utilized by economizer:

From saturated steam tables

$@T_2 = 90\ ℃ \qquad h_{f2} = h_f = 376.9\ kj/kg$

The heat utilized by the economizer per kg of fuel

$Economizer\ Energy = m_e(h_2 - h_1) = 8.52 \times (376.9 - 62.9) = 2675\ kj$

percentage energy utilized by economizer $= \frac{2675}{30000} = 0.089 = 8.9\ \%$

Example (2.6) the following particulars refer to a steam plant consisting of economizer, boiler, and superheater:

Steam pressure=**14 bar**; mass of steam generated=**5000 kg/h**; mass of coal used=**675 kg/h**; calorific value of coal=**29800 kj/kg** of coal; temperature of feed water entering the economizer=**30°C**; temperature of feed water leaving the economizer=**130°C**; dryness fraction=**0.97**; temperature of steam leaving the superheater=**320°C**.

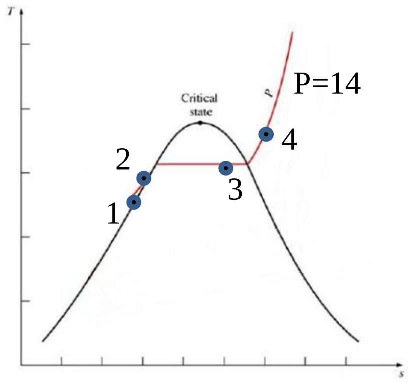
Determine (1) overall efficiency of the plant, and (2) the percentage of the available heat utilized in the boiler, economizer, and superheater respectively.

Solution:

given $p = 14\ bar;\ m_s = 5000\ kg/h\ ;\ m_f = 675\ kg/h\ ; C = 29800\ kj/kg$

$T_1 = 30℃;\ T_2 = 130℃;\ x = 0.97;\ T_3 = T_{superheat} = 320℃;$

$take\ for\ steam\ C_p = 2.1\ kj/kg.K\ ;for\ water\ C_p = 4.2\ kj/kg.K$



(1) Overall efficiency of plant

Mass of water actually evaporated per kg of fuel,

$m_e = \frac{m_s}{m_f} = \frac{5000}{675} = 7.41\ kg/kg\ of\ fuel$

from saturated steam tables

$@T_1 = 30℃\ \ h_1 = h_f = 125.77\ kj/kg$

$@T_2 = 130℃\ \ h_2 = h_f = 546.3\ kj/kg$

$@p = 14\ bar\ \ h_f = 830.1\ kj/kg\ ;\ h_{fg} = 1957.7\ kj/kg$

$h_3 = h_x = (830.1 + 0.97 \times 1957.7) = 2729\ kj/kg$

For the enthalpy of superheated steam leaving the boiler was;

$@p = 14\ bar\ \ \ and\ \ T_4 = 320\ ℃;\ h_4 = 3084\ kj/kg$

Or it can be obtained with the aid of superheated steam tables.

The overall efficiency

Or $\eta = \frac{m_e(h_4 - h_1)}{C} = \frac{7.41\times(3084-125.77)}{29800} = 0.735 = 73.5$ %

(2) percentage of available heat utilized

For Economizer: the enthalpy difference is;

$\Delta h_{economizer} = m_e \times (h_2 - h_1) = 7.41 \times (546.3 - 125.77)$

$\Delta h_{economizer} = 3116.1\ kj/kg$

For Boiler: the enthalpy difference is;

$\Delta h_{boiler} = m_e \times (h_x - h_2)$

But, $h_3 = h_x = \left(h_f + xh_{fg}\right)$

from saturated steam tables

Thus, $\Delta h_{boiler} = m_e \times (h_2 - h_1)$

$\Delta h_{boiler} = 7.41 \times (2729 - 546.3) = 16040\ kj/kg$

For Superheater: the enthalpy difference is;

$\Delta h_{superheater} = m_e \times (h_4 - h_3)$

$\Delta h_{superheater} = 7.41 \times (3084 - 2729) = 2631\ \ kj/kg$

percentage energy utilized by economizer $= \frac{3116.1}{29800} = 0.1045 = 10.45$ %

$\text{percentage energy utilized by boiler} = \frac{16174}{29800} = 0.538 = 53.8\ \%$

$\text{percentage energy utilized by superheater} = \frac{2397}{29800} = 0.08 = 8\ \%$

note: the overall efficiency of plant can be calculated as:

$\eta = 10.45\% + 53.8\% + 8\% = 72.25\%$

Example (2.7) Determine the actual evaporation per kg of coal and the equivalent evaporation if during boiler trial of one-hour duration following observations is made: Feed water supply temperature is **27ºC**, mean steam generation pressure is **10 bar**, dryness fraction of steam generated is **0.95**, feed water supplied is **2500 kg/hr**, and coal burnt: **275 kg/hr**. Moreover, mass of water in boiler after trial was **300 kg** less than that at commencement of trial.

Solution:

given $T_1 = 27°\text{C}; p = 10\ bar; x = 0.95; m_{s1} = 2500\ kg/h;\ m_f = 275\ kg/h$

$m_{s2} = 300\ kg/h$

From saturated steam tables

$@T_1 = 27°\text{C}\ \ h_1 = h_f = 113.2\ \ kj/kg$

$@p = 10\ bar \quad h_f = 762.79\ \ kj/kg;\ \ h_{fg} = 2015.3\ kj/kg$

$h_2 = h_f + x.h_{fg} = 762.79 + 0.95 \times 2015.3 = 2677.3\ \ kj/kg$

mass of evaporated water per hour

$m_s = m_{s1} + m_{s2} = 2500 + 300 = 2800\ kg/h$

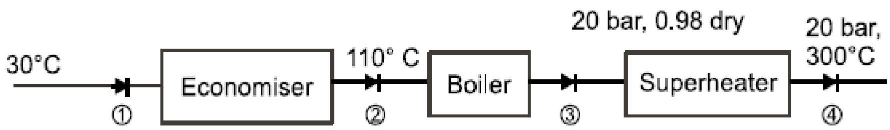
Actual evaporation of water per one kg of fuel

$m_e = \frac{m_s}{m_f} = \frac{2800}{275} = 10.18\ \ kg/kg\ of\ coal$

Equivalent Evaporation

$$E = \frac{m_e(h_2 - h_1)}{2257} = \frac{10.18 \times (2677.3 - 113.2)}{2257} = 11.56\ \ kg/kg\ of\ coal$$

Example (2.8) In a boiler installation feed water enters at **30°C** and leaves economizer section at **110°C** for being fed into boiler. Steam generated in boiler at **20 bar**, **0.98** dry and fed to super heater where its' temperature is raised up to **300°C**. For the coal with calorific value of **30,500 kJ/kg** and steam generation rate of **10kg/kg** of coal burnt determine the energy received per kg of water and steam in economizer, boiler and superheater section as fraction of energy supplied by coal. Take C_{PW} = **4.18 kJ/kg·K**, C_{PS}= **2.093 kJ/kg·K**.



Solution:

For feed water, $@\ T_1 = 30°C \quad h_1 = h_f = 125.79\ kJ/kg$

For feed water, @ $T_2 = 110°C \quad h_2 = h_f = 462.8\ kJ/kg$

From saturated steam tables

$@p = 20\ bar \quad h_f = 908.79\ kJ/kg\ \ and\ \ h_{fg} = 1890.7\ kJ/kg$

$h_3 = 908.79 + (0.98 \times 1890.7) = 2761.7\ kJ/kg$

From superheated steam tables

$@p = 20\ bar \quad T_4 = 300°C \ \rightarrow h_4 = 3023.5\ kJ/kg$

$Total\ heat\ supplied = h_4 - h_1 = 3023.5 - 125.79 = 2897.71\ kJ/kg$

$Heat\ consumed\ in\ economizer = h_2 - h_1 = 462.8 - 125.79$

$= 334.4\ kJ/kg\ steam$

$(h_2 - h_1) \times m_e = 334.4 \times 8 = 2678.4\ kJ/kg\ coal$

$Heat\ consumed\ in\ boiler = h_3 - h_2 = 2761.7 - 462.8$

$= 2299\ kJ/kg\ steam$

$(h_3 - h_2) \times m_e = 2299 \times 8 = 18392\ kJ/kg\ coal$

$Heat\ consumed\ in\ super\ heater = h_4 - h_3 = 3023.5 - 2761.7$

$= 261.8\ kJ/kg\ steam$

$(h_4 - h_3) \times m_e = 261.8 \times 8 = 2094.4\ kJ/kg\ coal$

$Heat\ provided\ by\ burning\ of\ coal = 30{,}500\ kJ/kg\ coal$

$Fraction\ of\ energy\ consumed\ in\ economizer = \frac{2678.4}{30500}$

$= 0.0878 = 8.78\ \%$

$Fraction\ of\ energy\ consumed\ in\ boiler = \frac{18415.2}{30500} = 0.6038 = 60.38\ \%$

$Fracton\ of\ energy\ consumed\ in\ superheater = \frac{2094.4}{30500}$

$= 0.0687 = 6.78\ \%$

Exercises

Problem (2.1) Boiler produces 4 kg of steam per kg of coal from feed water at 45°C. The steam pressure is 10.5 bar. If the dryness fraction of steam is 0.98, determine the equivalent evaporation from and at 100°C. **[Ans. 4.52kg]**

Problem (2.2) Boiler raises 3.7 kg of water per kg of coal from feed water at 54.5°C, to steam at the pressure of 34 bar and temperature of 370°C. Calculate the equivalent evaporation per kg of coal.

Problem (2.3) In a boiler trial, the following observations were recorded:
Boiler pressure=10 bar; dryness fraction of steam=0.95; coal consumption=500 kg/h; calorific value of coal=30500 kj/kg; feed water temperature=50°C; feed water supplied=4 ton/h.
Find the evaporation factor and equivalent evaporation from and at 100°Cin kg per kg of fuel. **[Ans. 1.09; 8.7 kg/kg of fuel]**

Problem (2.4) Boiler produces 9000 kg of steam while 1 ton of coal is burnt. The steam is produced at 10 bar from water at 15°C. The dryness fraction is 0.9. Determine the efficiency of the boiler when the calorific value of coal is 32000 kj/kg. **[Ans. 70.65 %]**

Problem (2.5) A boiler delivers steam at 100 bar and 500°C. The feed water inlet temperature is 160°C. The steam is produced at a rate of 100 ton/h and the boiler efficiency is 88%. Estimate the fuel burning rate in kg/h, if the calorific value of fuel is 21 Mj/kg. **[Ans. 14.6 ton/h]**

Problem (2.6) A steam power plant consisting of boiler, economizer, and superheater. It has the following particulars: steam pressure=12.6 bar; temperature of steam leaving the superheater=245°C; Fuel used per hour=1000 kg; feed water per hour=9000 kg; temperature of feed water entering the economizer=40°C; temperature of feed water leaving the economizer =115°C; dryness fraction of steam leaving the boiler=0.9; calorific value of fuel used=30240 kj/kg.

Calculate: (1) Overall efficiency of the plant, and (2) Percentage of heat in fuel used in the boiler, economizer, and, superheater.

[Ans. 81.3%; 62.6%; 9.37%; 9.33%]

Problem (2.7) During a boiler trial for 24 hour the following is observed; Steam generated = 160000 kg; Mean steam pressure = 12 bar; State of steam generated = 0.85; Feed water temperature = 30°C; Coal burnt = 16000 kg; C.V. of coal =

33400 kJ/kg; Determine equivalent evaporation from and at 100^oC and efficiency of boiler.

[Ans.10.45 kg/kg of coal, 70.65%]