CHAPTER – 10
Boiler Performance & Efficiency

Introduction:

Boiler efficiency is defined as the heat added to the working fluid expressed as a percentage of the heat in the fuel being burnt. Boiler efficiency to the greater extent depends on the skill of designing but there is no fundamental reason for any difference in efficiency between a high pressure and low pressure boiler. Large boilers generally would be expected to be more efficient particularly due to design improvements. Here we are listing some of the design requirement of boilers:

a. Should be able to produce at required parameters over an appreciable range of loading.
b. Compatible with feed water conditions which change with the turbine load.
c. Capable of changes in demand for steam without excessive pressure swing.
d. Reliable.

Boiler performance:

The purpose of a steam boiler is to evaporate water by heat obtained by the combustion of fuel and the amount of water evaporated is therefore one of the quantities to be considered in dealing with the performance of a steam boiler.
The amount of steam generated by the boiler in kilograms per hour at the observed pressure and temperature, quality of steam and feed water temperature is called Total Evaporation. The Actual Evaporation (m_a) is expressed in terms of kilograms of steam generated per kilogram of fuel used.
i.e. Actual Evaporation, m_a = (total evaporation per hour) / (fuel used per hour)

But the amount of water evaporated by a boiler is not a sufficiently definite measure of its performance because under different conditions as to temperature of feed water, and temperature and dryness of steam produced, a given evaporation will represent different amounts of heat utilized by the boiler.
Therefore, to provide common basis for comparing the evaporative capacity of boilers working under different conditions, it is necessary that the water be supposed to be evaporated under some standard conditions. The standard conditions adopted are: feed water supplied to the boiler at 100^o C and converted in to dry saturated steam at 100^o C and the working pressure 1.01325 bar (atmospheric pressure at sea level). Under these conditions, the evaporation of 1 kg of water at 100^o C requires 2.257 kJ to be converted into dry saturated steam at 100^o C, which is the enthalpy of evaporations of steam at 100^o C.

Equivalent Evaporation From & At 100^oC:

Equivalent evaporation may be defined as the evaporation which would be obtained if the feed water were supplied at 100^o C and converted into dry saturated steam at 100^oC (1.01325 bar pressure).
Under actual working conditions of the boiler, suppose

m_a = actual mass of water evaporated in kg per kg of fuel,
H = Enthalpy of 1 kg of steam produced under actual working condition in kJ,
h = Enthalpy of 1 kg of feed water entering the boiler in kJ,
Ls = Enthalpy of evaporation of 1 kg of steam at 100^oC (2257 kJ), and
m_e = equivalent evaporation in kg of water from and at 100^oC per kg of fuel burnt.

Then, heat transferred to 1 kg of feed water in converting it to dry saturated steam or heat required to produce 1 kg of steam = (H-h) kJ and
Heat required to produce m_a kg of steam under actual working conditions
= m_a (H-h) kJ.
Equivalent evaporation in kg of water from and at 100^oC per kg of fuel burnt,

$m_e = m_a (H-h) / Ls = m_a (H-h) / 2257$

Factor of Equivalent Evaporation:

Factor of Equivalent Evaporation is the ratio of heat absorbed by 1 kg of feed water under actual working conditions to that absorbed by 1 kg of feed water evaporated from and at 100^oC (i.e. standard conditions)".

Factor of equivalent evaporation = (H – h) / Ls = (H – h) / 2257

The mass of water evaporated is also expressed in terms of "Evaporation per hour per square metre of heating surface of the boiler"

Evaporation per m^2 of heating surface
= m kg per hour / Total area of heating surface in m^2
Where, m is the actual mass of water evaporated in kg per

Boiler efficiency or thermal efficiency of the boiler:

Boiler efficiency determination

There are two basic ways of determining the efficiency of a boiler :
(a) The Direct Method;
(b) The indirect Losses Method.

The direct method

This was standard for a long time, but is little used now.
According to this method the boiler efficiency is defined as, the ratio of the heat utilized by feed water in converting it to steam, to the heat released by complete combustion of the fuel used in the same time, i.e., output divided by the input to the boiler.
The output or the heat transferred to feed water is based on the mass of steam produced under the actual working conditions. The input to a boiler or heat released by complete combustion of fuel may be based on the higher calorific value of the fuel.
Boiler efficiency = m_a (H-h) / C.V.

Where, $\mathbf{m_a}$ = actual evaporation in kg per kg of fuel burnt,
H = Enthalpy of 1 kg of steam produced under actual working condition in kJ,
h = Enthalpy of 1 kg of feed water entering the boiler in kJ and.
C.V. = calorific value of fuel in kJ/kg

If a boiler is provided with an economiser and a superheater, then each of these elements of a boiler will have its own efficiency. If the boiler, economiser & superheater are considered as a single unit, the efficiency in that case is known as the overall efficiency of the boiler plant or efficiency of the combined boiler plant.

Economiser efficiency:

Economiser is placed in between boiler and chimney to recover heat from the hot flue gases which are released in atmosphere through chimney.
The efficiency of the economiser is the ratio of the heat gained by the feed water passing through the tubes of economiser and the heat given away by the hot flue gases passing over the tubes of the economiser.

Economiser efficiency = $m_a C_{PW}(t_2 - t_1) / m_f C_{PG}(t_{f1} - t_{f2})$

Where,
m_a = mass of steam produced per kg of fuel burnt
m_f = mass of flue gases produced per kg of fuel burnt.
C_{PW} = specific heat of water
C_{PF} = specific heat of flue gases
t_1 = Feed water temperature entering economiser
t_2 = Feed water temperature leaving economiser
t_{f1}= Temperature of hot flue gases entering economiser
t_{f2} = Temperature of hot flue gases leaving economiser.

Superheater efficiency:

Superheater is normally placed directly after the furnace in the way of hot flue gases or in the furnace itself. The dry saturated steam is drawn from the boiler steam drum and passed through the superheater coil where, at constant pressure, maximum heat is observed by the steam & converted into superheated steam.
The efficiency of superheater may be stated as the ratio of the heat gained by the dry saturated steam passing through superheater coils & heat given away by the hot gases passing over the superheater coils.
If superheater is placed in the furnace, in front of burners, radiation heat is also absorbed.
Superheater efficiency = $m_a [H + C_{PS} (t_{sup} - t_{sat})] / m_f C_{PF}(tfi - t_{fo})$

Where,
m_a = weight of steam produced in kg per kg of fuel burnt
m_f = weight of hot flue gases generated in kg per kg of fuel burnt
H = Enthalpy of saturated steam in kJ/ kg

t_{sat} = Temperature of steam entering the superheater,
t_{sup} = Temperature of steam leaving the superheater,
t_{fi} = Temperature of hot gases entering the superheater.
t_{fo} = Temperature of hot gases leaving the superheater,
C_{PF} = specific heat of hot gases at constant pressure
C_{PS} = specific heat of steam at constant pressure.

The indirect losses method:

The efficiency of a boiler equals 100% minus the losses. Thus, if the losses are known the efficiency can be derived easily. This method has several advantages, one of which is that errors are not so significant: for example, if the losses total 10% then an error of 1.0% will affect the result by only 0.1%.
The losses method is now the usual one for boiler efficiency determination. In fact there is no provision on many modern boilers for fitting coal weighing equipment, in which case the direct method cannot be used. A typical pulverized fuel boiler heat balance is:

Gross CV Basis		Net CV Basis	
Loss due to :			
Dry flue gas	3.98%	Dry flue gas	4.3%
Wet flue gas	5.27%	Sensible heat in water vapour	0.75%
C in A	0.24%	C in A	0.25%
Radiation and unaccounted	0.44%	Radiation and unaccounted	0.45%
Total loss	9.93%	Total loss	5.75%
Boiler efficiency =	90.07%	Boiler efficiency =	94.25%

Another point to bear in mind is that if a boiler is tested and found to have an efficiency of, say 94%, it would be quite wrong to imagine that it is operated normally at that efficiency. During testing, particular care is taken to keep the steam pressure, temperature and so on, as steady as possible and there is neither blowdown nor sootblowing. Also the boiler is probable tested immediately after a soot blow. So there are many factors common to normal operation that are absent when testing. Thus the test efficiency is probable the best that can be attained and for normal operation the value will be less.

Heat losses in boiler plant

Heat Losses in boiler Plant is mainly divided in to four parts.

(a) Heat lost to chimney gases or flue gases (i.e. heat carried away by the products of combustion.
(b) Heat lost due to incomplete combustion
(c) Heat lost due to unburnt fuel.
(d) Heat lost to external radiation.

We will illustrate these losses one by one.

(a) Heat lost to chimney gases or flue gases

The flue gases going out of chimney are made up of

(i) Dry flue gases
(ii) Steam in flue gases formed from the combustion of hydrogen present in the fuel together with any moisture present in the fuel

(i) Heat lost to dry flue gases per kg of fuel burnt = $m_g \times Cp\ (t_1 - t_o)$

Where, m_g = weight of dry flue gases in kg per kg of fuel
Cp = specific heat of dry flue gases in kJ per kg K
$t_1 - t_o$ = rise in temperature of flue gases (difference between temperature of flue gases leaving the boiler t_1 and temp. of the boiler room t_o)

(ii) Heat lost to steam in flue gases per kg of fuel burnt:

Mass of steam formed per kg of fuel burnt = $9H_2$ + mass of moisture per kg of fuel (m)
Assuming that the steam in flue gasses exist as superheated steam at atmospheric pressure and at flue gas temperature,
Heat lost to steam in the flue gases per kg of fuel burnt.

$$= [9H2 + m] \times [Hsup - h]$$
$$= [9H2 + m] \times [2676.1 + Cp\ (t_1 - 100) - h]\ kJ$$

Where,
t_1 = the temperature of flue gases leaving the boiler
Hsup = enthalpy of 1 kg of superheated steam at atmospheric pressure (1.01325 bar) and at flue gas temperature in kJ
Cp = Specific heat of superheated steam in kJ per kg K
h = enthalpy of 1 kg of water at boiler house temperature in kJ
m = mass of moisture present in 1 kg of fuel and
H_2 = mass of hydrogen present in 1 kg of fuel.

(b) Heat lost due to incomplete combustion (burning of carbon to CO)

For complete combustion of any fuel, all the carbon should be converted to

CO_2 (carbon dioxide). Any CO present in flue gases is due to insufficient air supply. Incomplete combustion means burning of carbon (C) to CO (carbon monoxide),
1 kg of carbon burnt to CO_2 releases 33,830 kJ, while 1 kg of carbon burnt to CO releases only 10,130 kJ.
Thus, 33,830 – 10,130 = 23,700 kJ heat is lost due to incomplete combustion or in other wards, we can say that 23,700 kJ heat is available in CO per kg of carbon,

(c) Heat lost due to unburnt fuel

When solid fuels are used, some of the fuel falls through the grate bars and is lost with ash. The heat loss is calculated by multiplying mass of unburnt fuel lost through grate bars by the calorific value of the fuel.
In oil fired boilers, due to improper conditions of burners, sometimes, oil droplets falls inside the furnace which is not burnt and is considered as loss.

Heat Loss = $c\, m_a / 100 \times 33{,}830$ kJ/kg fuel,
Where c = % carbon in dry ash
m_a = mass of ash kg/kg fuel
33,830 = calorific value of carbon burnt to CO_2 in kJ/kg

(d) Heat lost to external radiation

Effective lagging of the surface of boiler exposed to atmosphere is necessary to reduce such loss to minimum. These losses range for 110/210 MW units from 0.93% to 1% on higher side. They can be calculated by graphical methods and alignment charts.

Operational Factors:

The losses over which the operator can exert a control are dry flue gas loss, carbon in ash loss and incomplete combustion (combustible in gas loss).

a. Dry flue gas loss - % excess air and gas temperature at air heater outlet
b. Carbon in ash loss - % excess air and p.f. fineness
c. Combustible in gas loss – excess air

The boiler operation should be aimed at reducing the sum of above losses. The final gas temperature should be above flue gas dew point. It is important to remember that dew point for water vapour is not 100ºC but lower than this, because of partial pressure. Most coal fired boilers have specified air heater gas outlet temperature of the order of 130ºC being the minimum practical temperature which is consistent with minimising air heater corrosion. A high air heater gas outlet temperature reduces boiler efficiency drastically. (A 22ºC rise in air heater gas outlet temperature reduces boiler efficiency by 1%).
Boiler operation should be aimed at minimising the causes of high gas exit temperature which could be due to

- Lack of soot blowing
- Deposits on boiler heat transfer surface
- High excess air

- Low final feed temperature
- Higher type of burner (+ve lift of burner angle) at low load
- Incorrect S/Air to P/Air ratio

Examples

Example 1: A boiler takes feed water at 105^o C. The steam pressure of generation is 18.5 kg/cm^2g and steam is saturated. The steam generated per kg of coal is 5.5 kg with coal quality of 4800 cal/gm GCV. Calculate the thermal efficiency of steam generation.

Solution: Here, Feed water temp = 105^o C

∴ Enthalpy of 1 kg of feed water, h = 4.187 × (105 – 0) = 439.64 kJ/ kg

GCV of coal = 4800 cal/gm = 4800 kcal/ kg × 4.187 = 20097.60 kJ/ kg,

Steam pressure = 18.5 kg/cm^2g= 18.5 × 0.981 + 1.013 (atm. Pr.) = 19.16 bar abs.

Weight of steam generated, m_a = 5.5 kg/kg of coal

From steam tables, at 19.16 bar, Hs= 2798.59 kJ/ kg (enthalpy of saturated steam)

Thermal efficiency of boiler = m_a (Hs - h) / C. V.

= 5.5 (2798.59 – 439.64) / 20097.60 = **0.6455 or 64.55%**

Example 2: A boiler generates 900 kg of dry saturated steam per hour at a pressure of 11 kg/cm2 ab. The feed water is heated by economiser before it is supplied to the boiler. If the feed water enters the economiser at 30 deg.C and leaves at 90 deg.C, find the percentage saving in heat by the use of economiser. If 2000 kg/hr of flue gases pass over the economiser at 320 deg.C and leave the economiser at 170 deg.C , calculate the effectiveness of the economiser. Take specific heat of the flue gases as 0.24.

Solution:

Dry saturated steam is produced at 11 kg/cm^2 ab. = 11 × 0.981 = 10.79 bar ab.

From steam tables,

Enthalpy of 1 kg of dry saturated steam at 10.79 bar ab. Hs = 2780.94 kJ/ kg.

Enthalpy of feed water at 30^oC = h_1 = 30 × 4.187 = 125.61 kJ/ kg

∴Net heat req. to produce 1 kg of above steam from feed water at 30^oC

= 2780.94 – 125.61 = 2655.33 kJ/ kg

and enthalpy of feed water (1 kg) at 90^oC = h_2 =90 × 4.187 = 376.83 kJ/ kg

Net heat req. to produce 1 kg of above steam from feed water at 90^oC

= 2780.94 – 376.83 = 2404.11 kJ/ kg

Net saving in heat by using feedwater at 90^oC instead of at 30^oC (i.e. by the use of economizer) = 2655.33 – 2404.11 = 251.22 kJ/ kg

∴Percentage saving in heat by the use of economiser = 251.22/ 2655.33 × 100

= **9.5%**

Now, Effectiveness of economiser or efficiency of economiser

= $m_a C_{PW} (t_2 - t_1)/ m_f \times C_{PF} (t_{f1}-t_{f2})$,

here, m_a = 900 kg/ hr, C_{PW} = 4.187 kJ/ kg, t_2 = 90°C, t_1 = 30°C, m_f = 2000 kg/ hr, C_{PF} = 0.24 × 4.187 = 1.005 kJ/ kg, t_{f1}= 320°C and t_{f2}= 170°C

= 900 × 4.187 × (90-30)/ 2000 × 1.005 × (320-170)

= 226098/ 301500 = 0.75 = **75%**

Example 3: A boiler receives feed water at 25 deg.C and generates 8 kg of steam per kg of coal at 14 ata having dryness 0.95. Calorific value of coal used is 7650 kcal/kg. Estimate the thermal efficiency of the boiler.

Solution: Here, feed water temp = 25° C

Enthalpy of 1 kg of feed water h = 25 × 4.187 = 104.68 kJ/ kg

C.V. of coal = 7650 × 4.187 = 32030.55 kJ/ kg

Steam generation rate (weight) (m_a) = 8 kg /kg of coal.

Pressure 14 ata = 14 × 0.981 = 13.73 bar ab. And steam is 0.95 dry

From steam tables at 13.73 bar pressure,

h_f = 826.14 kJ/ kg and h_{fg} = 1963.21 kJ/ kg

Enthalpy of 1 kg of wet steam 0.95 dry

Hwet = $h_f + xh_{fg}$ = 826.14 + 0.95 × 1963.21 = 2691.19 kJ/ kg

∴Thermal efficiency of the boiler = m_a (Hwet - h) / C.V.

= 8 (2691.19 – 104.68)/ 32030.55 = 0.6460 or **64.60%**

Example 4: A boiler is heated by a gas which has calorific value of 2400 kcal/m3. If the boiler is in the form of a vertical cylinder 120 cm in diameter and contains water to a height of 90 cm, How many cubic meter of gas would be required to heat water from 45 c and change half of it into steam of dryness fraction 0.95 at 12 kg/cm2ab. Efficiency of the boiler may be taken as 70%.

Solution: Here, η = 70%

C.V. of gas = 2400 kcal/m3 × 4.187 = 10048.80 kJ/ m^3

Total quantity of water inside the boiler = Volume of the cylinder

= $\pi/4\ d^2 \times h = \pi/4\ (1.2)^2 \times 0.90$

= 1.018 m^3 = 1.018 × 1000 = 1018 kg

Now, half of this quantity is converted into steam

∴ Mass of steam m_a = 1018/2 = 509 kg

From steam tables, at 12 kg/cm^2ab = 12 × 0.981 = 11.77 bar ab.

h_f = 794.69 kJ/ kg , h_{fg} = 1989.42 kJ/ kg and T_s = 187.13°C

Heat required by complete water up to saturated temp = 1018 × 4.187 × (187.13 - 45)

= 605810.08 kJ

and heat absorbed by saturated water of mass 509 kg to become wet steam of dryness fraction 0.95 is m × (x × h_{fg}) = 509 × 0.95 × 1989.42 = 961984.04 kJ

∴Total heat transferred from Gas to feed water steam

= 605810.08 + 961984.04 = 1567794.12 kJ

& Heat supplied by fuel = Volume of Gas × C. V.

Now η = Heat absorbed by feed water/ Heat supplied by fuel

Or, 0.70 = 1567794.12/ (V × 10048.80)

$\therefore$ Volume of Gas = 1567794.12/ (0.70 × 10048.80) = **222.88 m^3**

Example 5: The following data refer to an economiser attached to a boiler in a college laboratory. Temp of feed water in the feed tank = 22 deg.C, Temp. of water entering at the economiser = 55 deg.C, Temp. of water leaving the economiser = 95 deg.C, Temp. of flue gases entering the economiser is 300 deg.C and leaving is 150 deg.C. The air supplied per kg of coal is 16 kg. Determine the amount of steam generated in the boiler per kg of coal burnt, if the specific heat of flue gases is 0.24.

Solution: Heat absorbed by feedwater in economiser
= Heat given away by flue gases in economiser.
Mass of feed water × C_{PW} × Δt = mass of gases × C_{PF} × ΔT)
Here, Mass of feed water = m, C_{PW} = 4.187 kJ/ kg, Δt = 95 – 55 = 40°C, mass of gases
= 16 + 1 = 17 kg, C_{PF} = 0.24 × 4.187 = 1.005 kJ/ kg and ΔT = 300 – 150 = 150°C
$\therefore$ m × 4.187 × 40 = 17 × 1.005 × 150
or, m = amount of water heated in the economizer (and subsequently converted into steam)
= **15.30 kg/ kg of coal burnt**

Example 6: The following readings were obtained during a boiler trial of 6 hr duration.
Mean steam pressure = 12 bar
Mass of steam generated = 40000 kg
Mean dryness fraction = 0.85
Mean feed water temp. = 30 deg C
Coal used = 4000 kg
Calorific value of coal = 8000 kcal/kg
Calculate,
(1). the factor of equivalent evaporation
(2). the equivalent evaporation from & at 100 deg.C &
(3). the efficiency of the boiler

Solution: At 12 bar, from steam tables
h_f = 798.60 kJ/ kg & h_{fg} = 1986.20 kJ/ kg
Enthalpy of 1 kg of wet steam at 12 bar & 0.85 dry
Hwet = $h_f + xh_{fg}$ = 798.60 + 0.85 × 1986.20 = 2486.87 kJ/ kg
& Enthalpy of 1 kg of feedwater, h = 4.187 × (30-0) = 125.61 kJ/ kg
Factor of equivalent evaporation = (Hwet – h)/ 2257
= (2486.87 – 125.61)/ 2257 = **1.046**

Now, actual evaporation/steam generation per kg of coal burnt = 40000 / 4000
= 10 kg/kg of coal
Equivalent evaporation from & at 100 c
$m_e = m_a \times 1.046 = 10 \times 1.046 =$ **10.46**

C.V. of coal = 8000 kcal/kg = 8000 × 4.187 = 33496 kJ/ kg
Efficiency of the boiler = m_a (Hwet-h) / C.V. = 10 × (2486.87 – 125.61)/ 33496
= 0.705 or **70.50 %**

Example 7: The following data refer to a boiler plant consisting of an economiser, a boiler and a superheater.

1. Mass of water evaporated/ hr - 5940 kg
2. Mass of coal burnt/hr - 675 kg
3. Calorific value of coal - 7560 kcal/kg
4. Pressure of steam at boiler stop valve - 14 bar ab.
5. Temp. of FW entering economizer – 32 deg. C
6. Temp. of FW leaving economizer - 115 deg. C
7. Dryness fraction of steam leaving the boiler & entering the superheater - 0.96.
8. Temp. of steam leaving the superheater – 200 deg. C
9. Specific heat of superheated steam – 2.30 kJ/ kg K

Determine

(a) Percentage of heat in coal utilized in economizer, boiler and superheater
(b) Overall efficiency of boiler plant.

Solution: Here,
Mass of water evaporated per kg of coal m_a = 5940/ 675 = 8.8 kg/kg of coal
C.V. of coal = 7560 kcal/kg = 7560 × 4.187 = 31653.72 kJ/ kg
Steam pressure = 14 bar ab.
From steam tables, h_f = 830.30 & h_{fg} = 1959.70 and T_s = 195^{o}C
Enthalpy of 1 kg of wet steam at 14 bar & 0.96 dry
Hwet = $h_f + xh_{fg}$ = 830.30 + 0.96 × 1959.70 = 2711.61 kJ/ kg
Enthalpy of 1 kg of FW at 32 C = 4.187 × (32-0) = 133.98 kJ/ kg
& Enthalpy of 1 kg of FW at 115 C = 4.187 × (115-0) = 481.51 kJ/ kg
& Enthalpy of 1 kg of SH steam at 14 bar & 200 C
Hsup = $h_f + h_{fg}$ + Kp (tsup-ts) = 830.30 + 1959.70 + 2.30 × (200-195)
= 2801.20 kJ/ kg
∴Overall efficiency of boiler plant = m_a (Hsup - h) / C.V.
= 8.8 (2801.20 – 133.98)/ 31653.72
= 0.7415 or **74.15 %**
Now, Total heat gain by FW thru' economiser, boiler & Superheater = Hsup – h
= 2801.20 – 133.98 = 2667.22 kJ/ kg
Heat gain by FW in economiser to raise temperature from 32 C to 115 C
= 481.51 – 133.98 = 347.53 kJ/ kg
Percentage of heat utilized in Economiser = 100 × 347.53/ 2667.22 = **13.03%**
Heat gain by FW in converting into wet steam of 0.96 dry in boiler from 115^{o}C water

= 2711.61 – 481.51 = 2230.10 kJ/ kg
Percentage of heat utilized in Boiler = 100 × 2230.10/ 2667.22 = **83.61%**
& Heat gain by wet steam in converting into superheater steam of 200 C
2801.20 – 2711.61 = 89.59 kJ/ kg
Percentage of heat utilized in Boiler = 100 × 89.59/ 2667.22 = **3.36 %**

Example 8: A Cornish boiler of 26.89 m3 capacity generates steam at a pressure of 8 bar. Two third of volume is occupied by water & remaining one third by steam. Calculate the energy released due to explosion and the horse power developed if the period of explosion is 1 second.

Solution: Here,
Boiler capacity = 26.89 m^3
Pressure = 8 bar, period of explosion = 1sec.
Now, volume occupied by water = (2/ 3) × 26.89 = 17.93 m^3
Density of water at 8 bar, at a temp. of 170.40 C = 1/ 0.001115 = 896.86 kg/m^3
∴Weight of water in the boiler = 896.86 × 17.93 = 16080.70 kg
From steam table at 8 bar,
h_f = 721.10 kJ/ kg and h_g = 2769.10 kJ/ kg and V_g = 0.240 m^3/ kg
Weight of steam in the boiler = (1/3) × 26.89 × (1/ 0.240)
= 37.35 kg
Now, when the explosion of boiler occurs, the pressure will be equal to one atmosphere
= 1.0132 bar
From steam table at 1.0132 bar,
h_f = 419.10 kJ/ kg and h_g = 2676.00 kJ/ kg
∴Due to explosion, the heat energy release will be equal to
=16080.70 (721.10 – 419.10) + 37.35 (2769.10 – 2676.00)
= 4852894.11 kJ = **4852.89 MJ**
Since the energy is released in 1 second
The Power of the boiler = 4852.89/ 1 = **4852.89 MW =** 4852.89 × 10^6/ 735.75
= **6.60 × 10^6 HP**

Example 9: A boiler producing 1200 kgs steam/hr at 14 bar and with 65 degree C superheat and burns 160 kgs of coal/hr. If the calorific value of coal is 7200 kcal/kg, the temperature of water is 28 deg. C and specific heat of steam is 2.30. Calculate,

1. Boiler H.P
2. Equivalent evaporation from & at 100 C
3. Boiler plant efficiency

Solution: Here,
Steam production = 1200 kg/ hr &
Coal consumption = 160 kgs/hr
∴weight of steam produced per kg of coal m_a = 1200/ 160 = 7.5 kg/ kg of coal
C.V = 7200 kcal/ kg = 7200 × 4.187 = 30146.40 kg
From steam tables at 14 bar,

h_g = 2790 kJ/ kg and T_s = 195°C
Degree of superheat = 65°C
Enthalpy of 1 kg of superheated steam Hsup = h_g + kp (Tsup-Tsat)
= 2790 + 2.30 × 65 = 2939.50 kJ/ kg
Enthalpy of 1 kg of Feed water at 28°C = 4.187 × (28-0) = 117.24 kJ/ kg
Equivalent evaporation from & at 100 C
$m_e = m_a$ (Hsup-h)/ 2257 = 7.5 (2939.50 – 117.24)/ 2257 = **9.38**
∴Boiler Plant Efficiency

$\eta = m_a$ (Hsup-h) / C.V.
= 7.5 (2939.50 – 117.24)/ 30146.40 = 0.7021 = **70.21 %**

Now, total heat absorbed by FW of 28°C in converting into steam with 65°C superheat per hour = 1200 × (Hsup - h) = 1200 × (2939.50 – 117.24) = 3386712 kJ/ hour
∴Power of the boiler = heat energy absorbed per second = 3386712/ 3600 = 940.75 kW

∴Boiler H.P. = 940.75 × 10^3 / 735.75 = **1278.63 HP**

Example 10: In a boiler, the following observations were made.
Pressure of the steam = 10 bar
Steam produced = 540 kg/hr
Fuel used = 65 kg/hr
Moisture in the fuel = 2 percent by mass
Mass of dry flue gases = 9 kg/kg of fuel
Lower calorific value of fuel = 32000 kJ/kg
Temp. of the flue gases = 325 deg. C
Temp. of the boiler house = 28 deg. C
Feed water temp. = 50 deg. C
Mean specific heat of flue gases = 1 kJ/kg K
Dryness fraction of steam = 0.95
Draw up a heat balance sheet for the boiler

Solution: At 10 bar pressure, from steam tables
h_f = 762.8, h_{fg} =2015.3
Enthalpy of 1 kg of wet steam
Hwet = $h_f + xh_{fg}$ = 762.8 + 0.95 × 2015.3 = 2677.33 kJ/kg
Fuel used = 65 kg/hr & steam produced = 540 kg/hr
Weight of steam produced per kg of fuel = 540 / 65 = 8.31 kg / kg of fuel
T = 325 C, Ta = 28 C
Feed water temp.= 50 C
Enthalpy of 1 kg of FW at 50 C = 50 × 4.187 = 209.35 kJ/kg
CV = 32000 kJ/kg . Heat supplied by 1 kg of dry fuel = 0.98 × 32000 = 31360 kJ/ kg
(Wt. of moisture in fuel = 2% by weight)

For Heat balance sheet of the boiler……
Total heat liberated per kg of fuel = 31360 kJ -------- (1)
Heat utilized in raising steam per kg of fuel = 8.31 (2677.33 – 209.35)
= 20508.91 kJ/ kg----- (2)
Heat carried away by dry flue gases per kg of fuel = m_g × Cp × (t1-to) = 9 × 1 (325-28)
= 2673 kJ/kg of fuel -------------- (3)
Heat carried away by steam formed due to moisture present in fuel:
Now at 28°C, enthalpy of 1 kg of moisture in fuel h_o = 4.187 × 28 = 117.24 kJ
Again at atmospheric pressure, h_g = 2676 kJ/ kg
Degree of superheat of steam formed from moisture = 325 – 100 = 225°C
Moisture in 1 kg of fuel = 0.02 x 1 = 0.02 kg
Heat carried away by moisture = m_g (Hsup-ho) = 0.02 × {2676 + (2.1 × 225) – 117.24}
= 60.62 kJ ------------- (4)
[Cp = 2.1 kJ/ kg K]

Heat lost due to radiation (external) & accounted losses
= (1) - {(2) + (3) + (4) }
= 31360 - {20508.91 + 2673 + 60.62}= 8117.47 kJ
So, the heat balance sheet of the boiler may be prepared as under

Heat supplied	kJ	Heat expenditure	kJ	%
Heat supplied by 1 kg of coal	31360	1. Heat utilized in raising steam 2. Heat carried away by dry flue gas 3. Heat carried away by moisture in fuel 4. Heat lost by radiation etc.	20508.91 2673 60.62 8117.47	65.40 8.52 0.19 25.89
Total	31360	Total:	31360	100

Example 11: Compare the efficiencies of two boilers plant A & B with the following particulars.
Boiler - A: 7.9 kg of steam/kg of coal at 14 bar, dryness fraction 0.95 from feed water at 25 C, C.V. of fuel is 7200 kcal/kg.
Boiler - B: 9.5 kg of steam/kg of coal at 12 bar superheated steam of 250 C from feed water at 90 C, C.V. of fuel is 7500 kcal/kg.

Solution: For **Boiler- A**
Steam pressure = 14 bar & steam is wet
∴From steam tables, h_f =830.30 kJ/ kg and h_{fg} = 1959.70 kJ/ kg
∴Enthalpy of 1 kg of wet steam with 0.95 dry
Hwet = $h_f + xh_{fg}$ =830.30 + 0.95 × 1959.70 = 2692.02 kJ/ kg
m_a = 7.9 kg/kg of coal
CV = 7200 kcal/kg = 7200 × 4.187 = 30146.40 kJ/ kg
Feed water temp = 25 C

Enthalpy of 1 kg feed water at 25 C, h = 4.187 × 25 = 104.68 kJ/ kg

∴Efficiency of boiler - A

η = m_a (Hwet-h) / C.V. = 7.9 (2692.02 – 104.68)/ 30146.40 = 0.6780 or **67.80 %**

&

For boiler - B

steam pressure = 12 bar & steam is superheated.

From steam tables, h_g = 2784.80 kJ/ kg & T_s = 188°C

∴Enthalpy of 1 kg of S.H. steam with 250 C temp.,

Hsup = h_g + Cp (T_{sup} - T_{sat})

= 2784.80 + 2.01{250-188}= 2909.42 kJ/ kg

Here, feed water temp. = 90°C

Enthalpy of 1 kg of feed water at 90°C = h = 4.187 × 90 = 376.83 kJ/ kg

& CV = 7500 kcal /kg = 7500 × 4.187 = 31402.50 kJ/ kg,

m_a = 9.5 kg/ kg of coal

∴Efficiency of Boiler – B

η = m_a (Hsup-h) / C.V. = 9.5 (2909.42 – 376.83)/ 31402.50 = 0.7662 OR **76.62 %**

Therefore, Boiler-B is more efficient than Boiler -A

Example 12: Boiler which originally burned coal is converted so as to burn oil fuel. The following data are taken before and after conversion. The equivalent evaporation from & at 100 C = 8 kg when it is coal fuel & the equivalent evaporation from & at 100 C = 14.4 kg
when it burns oil fuel.
How many barrels of 200 liters capacity are equivalent in heat to one tone of coal? The specific gravity of oil fuel is 0.8. If the C.V. of oil fuel is 10000 kcal /kg, find the calorific value of coal. Determine the efficiency of boiler which is assumed to be same before & after conversion?

Solution:

In case of coal, Equivalent evaporation = 8 kg &

In case of oil fuel, Equivalent evaporation = 14.4 kg

The efficiency of the boiler is the same. Therefore the C.V. of the fuels are proportional to their equivalent evaporation. Now, C.V. of oil fuel = 10000 kcal/kg = 41870 kJ/ kg & the equivalent evaporation is 14.4 kg. & the equivalent evaporation for the boiler when coal is burnt is 8 kg.

∴Calorific value of coal = 41870 × 8/ 14.4 = 23261.11 kJ/ kg

Now, efficiency of the boiler = <u>Heat utilized for steam generation from one kg fuel</u>

Calorific value of fuel

Specific enthalpy of evaporation of steam at atmospheric pressure = 2256.9 kJ/ kg

∴Efficiency of the boiler = (14.4 × 2256.9)/ 41870 = 0.7762 or **77.62 %**

Heat value of one tone of coal = 1000 × 23261.11 = 23261110 kJ

Now, one kg of oil has heat value of 41870 kJ,

∴Heat of 1 tone of coal is equivalent to 23261110/ 41870 = 555.55 kg of oil
One barrel of oil weight 200 × 0.8 = 160 kg
One tone of coal = 555.55/ 160 = **3.47 barrel of fuel oil in heat value**

Example 13: The design heat release in combustion chamber of a water tube boiler is 3.5×10^6 kcal/hr and the dimensions of combustion chamber are 4.5 m × 3.0 m × 9.0 m. The pressure of steam generator is 40 bar and dryness fraction is 0.98. Feed water enters into the boiler at temp. of 115°C. Efficiency of boiler is 78% on the gross calorific value of fuel.
Determine (1) The fuel consumption in kg/hr where GCV of fuel is 6500 kcal/kg.
(2) Amount of steam generated in kg/h

Solution: Here,
Pressure of steam = 40 bar & steam is wet having X = 0.98
From steam tables,
Enthalpy of 1 kg of wet steam, Hwet = hf + Xhfg = 1087.30 + 0.98 × 1714.10
= 2767.12 kJ/ kg
Feed water temp. entering to boiler = 115 C
Enthalpy of 1 kg of this FW h = 4.187 × 115 = 481.51 kJ/ kg
Heat absorbed by steam in converting from water = 2767.12 – 481.51 = 2285.61 kJ/ kg

Now, efficiency of the boiler η = 78% = m_a (Hwet - h) / C.V.
CV of fuel = 6500 × 4.187 = 27215.50 kJ/ kg
0.78 = m_a × 2285.61/ 27215.50
∴ m_a = 9.29 kg/kg of fuel burnt
Now, design heat release in combustion chamber = $3.5 \times 10^6 \times 4.187 = 14.65 \times 10^6$ kJ/ kg
∴Fuel consumption = 14.65×10^6/ 27215.50 = **538.30 kg/hr**
& steam generated in kg per hour = 9.29 × 538.30 = **5000.81 kg/ hr**

Example 14: Water enters a boiler plant at temp. of 27 C & leaves it as steam at pressure of 11 ata and temp of 245. The superheater is opened out for repairs & plant works without SH and it supplies steam having dryness fraction of 0.95, to the steam engine, which works on cut off governing. Find out the increase in steam consumption due to stoppage of superheater. It could be assumed that the load remains the same in both the cases.

Solution: It is assumed that the steam engine works on cut off governing and the load remains the same during both the periods i.e. the quantity of steam supplied per stroke by volume remains the same. The density of steam, when superheated is less than the density of steam when it is wet, and hence for same volume the quantity of steam required by mass is more when the steam is wet and therefore the steam consumption increases.

Let quantity of steam required by engine/hr = V_1 m^3

If V_{sup} = specific volume of superheated steam in m^3/ kg

Then, superheated steam consumption per hour = V_1/ V_{sup} kg

& If V_{wet} = specific volume of wet steam in m^3/ kg

Then, wet steam consumption per hour = V_1/ V_{wet} kg

∴Ratio of two steam consumption = (V_1/ Vwet) / (V_1/ Vsup) = Vsup / Vwet

Now, from steam tables, at 11 ata = 11 × 0.981 = 10.80 bar ab,

Specific volume of saturated steam = 0.1812 m^3/kg

∴Specific volume of wet steam having a dryness fraction of 0.95 = 0.95 × 0.1812 = 0.1721 m^3/ kg

& sp. volume of superheated steam V_{sup} at 245°C = 0.213 m^3/kg (from steam tables by interpolation)

∴Ratio of two steam consumption = 0.213/ 0.1721 = 1.237

∴Increase in steam consumption by mass = (1.237 - 1) × 100 = **23.70 %**

Example for Practice:
(Work out in SI unit only)

Question 1: The following data refers to a boiler
Fire grate size - 1.96 m long × 2.0 m wide
Consumption of coal -140 $kg/m^2/hr$
Water evaporated - 6.0 kg/kg of coal
Feed water temp. - 20 C
Pressure of steam - 5.0 bar & Quality of steam - Dry and saturated
Find coal consumption in tones per day & water evaporated in m^3 per day.
Take Boiler efficiency as 50% & CV of coal as 32000 KJ/kg

Question 2: Steam leaving a boiler is dry & saturated a 13.0 bar
Temp. of feedwater entering economizer = 35 C
Temp. of feedwater leaving economizer = 120 C
Amount of feed water pumped to the boiler = 1500 ltrs / min
Efficiency of pump-moter set = 85 %
Calculate the percentage of heat saving by the use of economiser and power required for pumping.

Question 3: A steam generation plant supplies 8500 kgs of steam per hour at a pressure of 0.75 MN/m2. The steam is 0.95 dry. Feed water inlet temp = 41.5 deg.C, coal consumption = 900 kg/hr, C V of coal = 324.50 KJ/kg,
Determine,
(a) The boiler power developed
(b) The boiler efficiency
(c) The equivalent evaporation from & at 100 C
(d) The saving in fuel consumption by installing an economiser it is estimated that the feed water temp. could be raised to 100 C assuming that other conditions remained unchanged & the efficiency of boiler increases by 6%

Question 4: A boiler generates 750 kg of steam per hour at 11 kg/cm2 and with 40 C superheat and burns 100 kg of coal per hour. If the CV of coal is 7000 kcal/kg & FW temp is 45 C assuming specific heat of superheated steam as 0.05 calculate,
(a) The equivalent evaporation from & 100c per kg of coal
(b) The boiler efficiency

Question 5: Find the rise in temperature of air in a preheater if 16 kg of air is supplied per kg of fuel burnt & temp of flue gases drops in preheater is 139 C. The efficiency of preheater is 78% the specific heat of flue gases and air is 0.24

Question 6: Determine the % tuel saving by installing an economizer with a boiler if the steam leaves the Boiler at a pressure of 14 ata and temp of 316 deg C. The feed water enters the economiser at 60 C & leaves at 143.5 C

Question 7: Determine the percentage fuel saving by installing an economiser with a Lancashire boiler if the steam leaves the boiler dry & saturated at 13 ata. The feed water enters the economizer at 35 deg.C & leaves at 120 deg.C

Question 8: The following data refer to a steam boiler plant consists of an economiser, a boiler and a superheater.

1. Mass of water evaporated/h -------7800 kg
2. Calorific value of coal --------------8000 kcal/kg
3. Mass of coal burnt /h ---------------770 kg
4. Steam generation pressure -----------20 kg/cm^{2}ab
5. Temp. of feed water leaving the economizer-----100 deg.C
6. Temp. of feed water entering the economiser ----32 deg.C
7. Steam generation temperature ----------------------300 deg.C
8. Dryness fraction of steam leaving drum & entering to the sup. heater - 0.96
9. Specific heat of S.H. steam -------------------- 0.55

Determine,

a. Percentage of heat in coal utilized in economiser boiler & superheater.
b. Overall efficiency of boiler plant

Question 9: The following observations were made in a boiler trial:
Coal used = 250 kgs of CV 29800 kJ/kg
Water evaporated = 2000 kg
Steam pressure = 11.5 bar
Dryness fraction of steam = 0.95
Feed water temperature = 34 deg. C
Calculate: (1) the equivalent evaporation from and at 100 deg. C / kg of coal
(2) the efficiency of the boiler

Question 10: A boiler producing 1200 kgs of steam/hr at 14 ata and with 65^{o}C superheat & burns 170 kgs of coal/hr. If the calorific value of coal is 7000 kcal/kg. the temperature of water is 29 deg.C and specific heat of steam is 0.55. Calculate: (1) Boiler H.P. (2) Boiler plant efficiency (3) Equivalent evaporation from & at 100 deg. C.

Question 11: In a boiler trial, the following quantities were obtained.
Mean temp. of F.W = 15 C
Mean steam generation Pr = 14 ata
Mean dryness fraction = 0.95
Weight of coal burnt/hr = 250 kg
C.V. of coal = 7250 kcal/kg
Weight of water supplied to the boiler in 7 Hrs & 12 Minutes = 16500 kgs
Weight of water in the boiler at the end of trial was less than at commencement by 1000 kgs.
Calculate : (a) Actual evaporation/kg of coal
(b) Equivalent evaporation from & at 100 C
(c) Thermal efficiency of boiler
(d) Boiler H.P. developed

Question 12: The fire grate of boiler is 1.9 mtr long & 0.85 mtr wide & it burns 120 kg of coal per m^2/hr. If one kg of coal evaporates 5.0 kgs of water, find out the coal consumption /shift of eight hours and also the quantity of water evaporated in kgs/shift.

Question 13: Following results were obtained in a boiler trail.
Feed water per hour 2280 ltrs. At 30°C steam product is 0.95 dry at 8.5 ata.; coal per hour 300 kg of calorific value of 6500 Kcal/kg; ash and unburant coal from beneath fire bars 24 kg/hr. of calorific value 620 Kcal/kg.; weight of flue gas per kg of coal burnt 17.3 kg. Flue gas temp. = 330°C; ambient temp. = 19°C; specific heat of flue gas 0.24 Draw the heat balance sheet for the boiler.

Question 14: One boiler which originally burnt F. oil is converted so as to burn coal. The following data were taken before and after conversion.
The equivalent evaporation from and at 100oC = 14.4 kg, when it burns oil. The equivalent evaporation from and at 100oC = 8 kg, when it converted into coal firing. To calculate how much coal is equivalent in heat to 1000 kg of F. oil.
If the specific gravity of F. oil is 0.8 and cv of F. oil being used earlier is 42 MJ/ kg, find the cv of coal. Also determine the efficiency of boiler, which is same in both cases.

Question 15:
a) A steam boiler generate 7.5 ton of steam per ton of coal burned. Calculate the equivalent evaporation from and 100˚C per ton of coal from the following data.
Steam pressure – 10 bar
Dryness fraction – 0.95
Feed water temp - 50˚C

b) A boiler is working at 14 bar & evaporates 8.5 kg of coal fired from the boiler. Feed water entering at 39˚C. Determine the equivalent evaporation from at 100˚C if the steam is 0.97 at stop valve.

Question 16: A boiler generates 8200 kg of steam per hour at a pressure of 18 bar. Coal burnt 950 kg/hr and has CV of 28840 kj/kg. The feed water temperature is raised from 40˚C to 110˚C in the economizer. The steam leaves the boiler drum at 0.95 dryness and leaves the superheater at 200˚C. Find the equivalent evaporation, overall efficiency and % of heat received in economizer and supeheater.

Question 17: boiler is heated by a gas which has calorific value of 2400 Kcal / m^3. If the boiler is in the form of a vertical cylinder 120cm in diameter and contains water to a height of 90cm, How many cubic meter of gas would be required to heat water from 45°C and change half of it in to steam of dryness fraction 0.95 at 12Kg/cm^2 at efficiency of boiler may be taken as 70%.

Question 18: In a test one boiler plant at 10 hours duration following observation were made;

Coal burnt	:	5000kg
C. V. of coal	:	29.69 MJ/kg
Steam generated	:	45000kg
Pressure of steam	:	15 bar
Temp. of steam	:	250°C
Feed water temp	:	42°C
FW temp leasing economizer	:	-115°C

Calculate the efficiency of plant & % of heat saving by economizer.