1. ENERGY PERFORMANCE ASSESSMENT OF BOILERS

1.1 Introduction

Performance of the boiler, like efficiency and evaporation ratio reduces with time, due to poor combustion, heat transfer fouling and poor operation and maintenance. Deterioration of fuel quality and water quality also leads to poor performance of boiler. Efficiency testing helps us to find out how far the boiler efficiency drifts away from the best efficiency. Any observed abnormal deviations could therefore be investigated to pinpoint the problem area for necessary corrective action. Hence it is necessary to find out the current level of efficiency for performance evaluation, which is a pre requisite for energy conservation action in industry.

1.2 Purpose of the Performance Test

- To find out the efficiency of the boiler
- To find out the Evaporation ratio

The purpose of the performance test is to determine actual performance and efficiency of the boiler and compare it with design values or norms. It is an indicator for tracking day-to-day and season-to-season variations in boiler efficiency and energy efficiency improvements

1.3 Performance Terms and Definitions

1. Boiler Efficiency, $\eta = \dfrac{\text{Heat output}}{\text{Heat Input}} \times 100$

$$= \frac{\text{Heat in steam output (kCals)}}{\text{Heat in Fuel Input (kCals)}} \times 100$$

2. Evaporation Ratio $= \dfrac{\text{Quantity of Steam Generation}}{\text{Quantity of fuel Consumption}}$

1.4 Scope

The procedure describes routine test for both oil fired and solid fuel fired boilers using coal, agro residues etc. Only those observations and measurements need to be made which can be readily applied and is necessary to attain the purpose of the test.

1.5 Reference Standards

British standards, BS845: 1987

The British Standard BS845: 1987 describes the methods and conditions under which a boiler should be tested to determine its efficiency. For the testing to be done, the boiler should be operated under steady load conditions (generally full load) for a period of one hour after which readings would be taken during the next hour of steady operation to enable the efficiency to be calculated.

The efficiency of a boiler is quoted as the % of useful heat available, expressed as a percentage of the total energy potentially available by burning the fuel. **This is expressed on the basis of gross calorific value (GCV).**

This deals with the complete heat balance and it has two parts:

- Part One deals with standard boilers, where the indirect method is specified
- Part Two deals with complex plant where there are many channels of heat flow. In this case, both the direct and indirect methods are applicable, in whole or in part.

ASME Standard: PTC-4-1 Power Test Code for Steam Generating Units

This consists of

- Part One: Direct method (also called as Input -output method)
- Part Two: Indirect method (also called as Heat loss method)

IS 8753: Indian Standard for Boiler Efficiency Testing

Most standards for computation of boiler efficiency, including IS 8753 and BS845 are designed for spot measurement of boiler efficiency. **Invariably, all these standards do not include blow down as a loss in the efficiency determination process.**

Basically Boiler efficiency can be tested by the following methods:

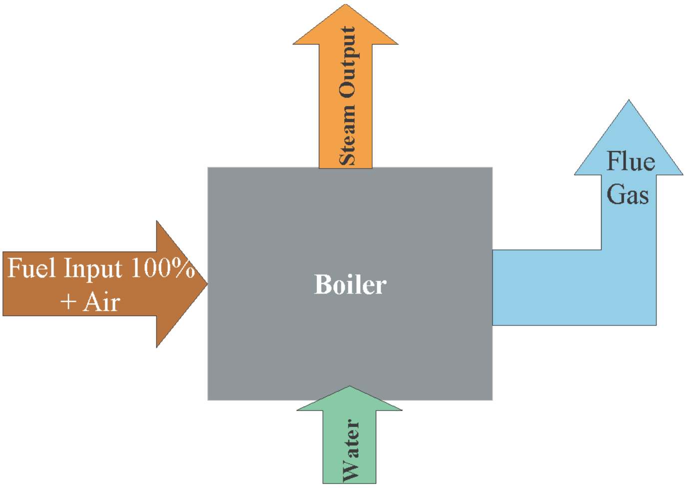
1) **The Direct Method:** Where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.
2) **The Indirect Method:** Where the efficiency is the difference between the losses and the energy input.

1.6 The Direct Method Testing

1.6.1 Description

This is also known as 'input-output method' due to the fact that it needs only the useful output (steam) and the heat input (i.e. fuel) for evaluating the efficiency. This efficiency can be evaluated using the formula:

$$Boiler\ Efficiency = \frac{Heat\ Output}{Heat\ Input} \text{ x } 100$$



$$\text{Efficiency} = \frac{\text{Heat addition to Steam x 100}}{\text{Gross Heat in Fuel}}$$

$$\textit{Boiler Efficiency} = \frac{\text{Steam flow rate x (steam enthalpy} - \text{feed water enthalpy)}}{\text{Fuel firing rate x Gross calorific value}} \; x\,100$$

1.6.2 Measurements Required for Direct Method Testing

Heat input

Both heat input and heat output must be measured. The measurement of heat input requires knowledge of the calorific value of the fuel and its flow rate in terms of mass or volume, according to the nature of the fuel.

For gaseous fuel: A gas meter of the approved type can be used and the measured volume should be corrected for temperature and pressure. A sample of gas can be collected for calorific value determination, but it is usually acceptable to use the calorific value declared by the gas suppliers.

For liquid fuel: Heavy fuel oil is very viscous, and this property varies sharply with temperature. The meter, which is usually installed on the combustion appliance, should be regarded as a rough indicator only and, for test purposes, a meter calibrated for the particular oil is to be used and over a realistic range of temperature should be installed. Even better is the use of an accurately calibrated day tank.

For solid fuel: The accurate measurement of the flow of coal or other solid fuel is very difficult. The measurement must be based on mass, which means that bulky apparatus must be set up on the boiler-house floor. Samples must be taken and bagged throughout the test, the bags sealed and sent to a laboratory for analysis and calorific value determination. In some more recent boiler houses, the problem has been alleviated by mounting the hoppers over the boilers on calibrated load cells, but these are yet uncommon.

Heat output

There are several methods, which can be used for measuring heat output. With steam boilers, an installed steam meter can be used to measure flow rate, but this must be corrected for temperature and pressure. In earlier years, this approach was not favoured due to the change in accuracy of orifice or venturi meters with flow rate. It is now more viable with modern flow meters of the variable-orifice or vortex-shedding types.

The alternative with small boilers is to measure feed water, and this can be done by previously calibrating the feed tank and noting down the levels of water during the beginning and end of the trial. Care should be taken not to pump water during this period. Heat addition for conversion of feed water at inlet temperature to steam, is considered for heat output.

In case of boilers with intermittent blowdown, blowdown should be avoided during the trial period. In case of boilers with continuous blowdown, the heat loss due to blowdown should be calculated and added to the heat in steam.

1.6.3 Boiler Efficiency by Direct Method: Calculation and Example

Test Data and Calculation

Water consumption and coal consumption were measured in a coal-fired boiler at hourly intervals. Weighed quantities of coal were fed to the boiler during the trial period. Simultaneously water level difference was noted to calculate steam generation during the trial period. Blow down was avoided during the test. The measured data is given below.

Type of boiler: Coal fired Boiler

Heat output data

Quantity of steam generated (output)	:	8 TPH
Steam pressure / temperature	:	10 kg/cm^2(g)/ 180°C
Enthalpy of steam(dry & Saturated) at 10 kg/cm^2(g) pressure	:	665 kCal/kg
Feed water temperature	:	85°C
Enthalpy of feed water	:	85 kCal/kg

Heat input data

Quantity of coal consumed (Input)	:	1.6 TPH
GCV of coal	:	4000 kCal/kg

Calculation

Boiler efficiency (η):

$$= \frac{Q \times (H - h) \times 100}{(q \times GCV)}$$

Where **Q** = Quantity of steam generated per hour (kg/hr)
q = Quantity of fuel used per hour (kg/hr)
GCV = Gross calorific value of the fuel (kCal/kg)
H = Enthalpy of steam (kCal/kg)
h = Enthalpy of feed water (kCal/kg)

Boiler efficiency (η)

$$= \frac{8\text{ TPH} \times 1000\text{kg/T} \times (665 - 85) \times 100}{1.6\text{ TPH} \times 1000\text{kg/T} \times 4000\text{ kCal/kg}}$$

= 72.5%

Evaporation Ratio = 8 Tonne of steam / 1.6 Tonne of coal
= 5

1.6.4 Merits and Demerits of Direct Method

Merits

- Plant people can evaluate quickly the efficiency of boilers
- Requires few parameters for computation
- Needs few instruments for monitoring

Demerits

- Does not give clues to the operator as to why efficiency of system is lower
- Does not calculate various losses accountable for various efficiency levels
- Evaporation ratio and efficiency may mislead, if the steam is highly wet due to water carryover

1.7 The Indirect Method Testing

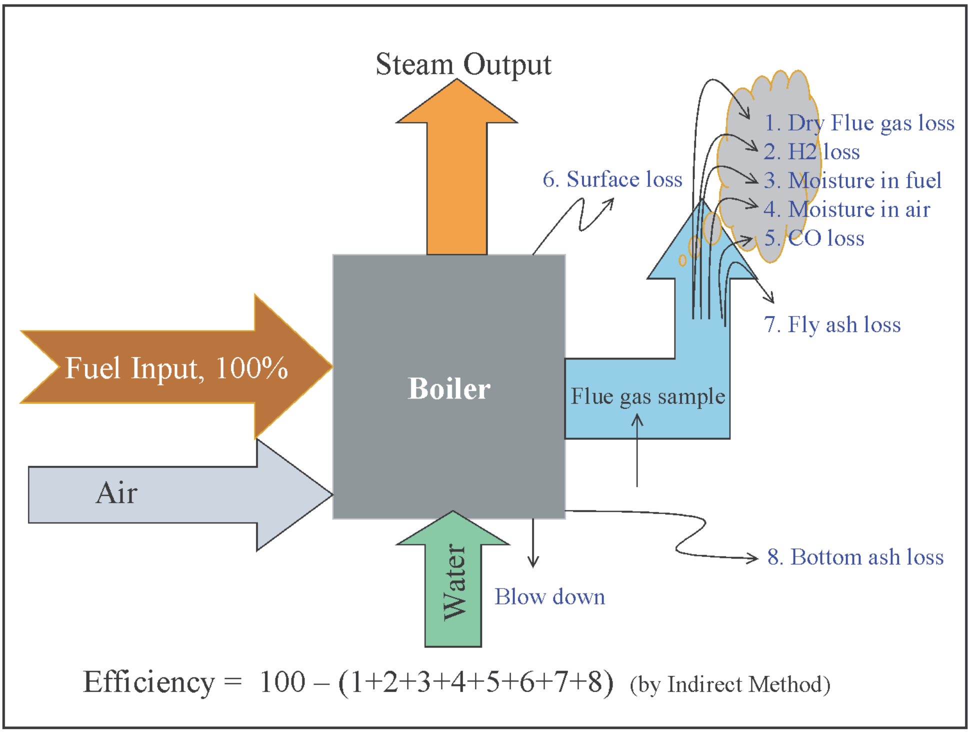
1.7.1 Description

The efficiency can be measured easily by measuring all the losses occurring in the boilers using the principles to be described. The disadvantages of the direct method can be overcome by this method, which calculates the various heat losses associated with boiler. The efficiency can be arrived at, by subtracting the heat loss fractions from 100.An important advantage of this method is that the errors in measurement do not make significant change in efficiency.

Thus if boiler efficiency is 90% , an error of 1% in direct method will result in significant change in efficiency. i.e. 90 ± 0.9 = 89.1 to 90.9. In indirect method, 1% error in measurement of losses will result in

Efficiency = 100 – (10 ± 0.1) = 90 ± 0.1 = 89.9 to 90.1

The various heat losses occurring in the boiler are:



The following losses are applicable to liquid, gas and solid fired boiler

L1– Loss due to dry flue gas (sensible heat)
L2– Loss due to hydrogen in fuel (H_2)
L3– Loss due to moisture in fuel (H_2O)
L4– Loss due to moisture in air (H_2O)
L5– Loss due to carbon monoxide (CO)
L6– Loss due to surface radiation, convection and other unaccounted*.

*Losses which are insignificant and are difficult to measure.
The following losses are applicable to solid fuel fired boiler in addition to above

L7– Unburnt losses in fly ash (Carbon)
L8– Unburnt losses in bottom ash (Carbon)

Boiler Efficiency by indirect method = 100 – (L1 + L2 + L3 + L4 + L5 + L6 + L7 + L8)

1.7.2 Measurements Required for Performance Assessment Testing

The following parameters need to be measured, as applicable for the computation of boiler efficiency and performance.

a) Flue gas analysis
   1. Percentage of CO_2 or O_2 in flue gas
   2. Percentage of CO in flue gas
   3. Temperature of flue gas

b) Flow meter measurements for
   1. Fuel
   2. Steam
   3. Feed water
   4. Condensate water
   5. Combustion air

c) Temperature measurements for
   1. Flue gas
   2. Steam
   3. Makeup water
   4. Condensate return
   5. Combustion air
   6. Fuel
   7. Boiler feed water

d) Pressure measurements for
   1. Steam
   2. Fuel
   3. Combustion air, both primary and secondary
   4. Draft

e) Water condition
1. Total dissolved solids (TDS)
2. pH
3. Blow down rate and quantity

The various parameters that were discussed above can be measured with the instruments that are given in Table 1.1.

TABLE 1.1 TYPICAL INSTRUMENTS USED FOR BOILER PERFORMANCE ASSESSMENT.

Instrument	Type	Measurements
Flue gas analyzer	Portable or fixed	% CO_2 , O_2 and CO
Temperature indicator	Thermocouple, liquid in glass	Fuel temperature, flue gas temperature, combustion air temperature, boiler surface temperature, steam temperature
Draft gauge	Manometer, differential pressure	Amount of draft used or available
TDS meter	Conductivity	Boiler water TDS, feed water TDS, make-up water TDS.
Flow meter	As applicable	Steam flow, water flow, fuel flow, air flow

1.7.3 Test Conditions and Precautions for Indirect Method Testing

A) The efficiency test does not account for:

- ***Standby losses.*** Efficiency test is to be carried out, when the boiler is operating under a steady load. Therefore, the combustion efficiency test does not reveal standby losses, which occur between firing intervals
- ***Blow down loss.*** The amount of energy wasted by blow down varies over a wide range.
- ***Soot blower steam.*** The amount of steam used by soot blowers is variable that depends on the type of fuel.
- ***Auxiliary equipment energy consumption.*** The combustion efficiency test does not account for the energy usage by auxiliary equipments, such as burners, fans, and pumps.

B) Preparations and pre conditions for testing

- Burn the specified fuel(s) at the required rate.
- Do the tests while the boiler is under steady load. Avoid testing during warming up of boilers from a cold condition
- Obtain the charts /tables for the additional data.
- Determination of general method of operation
- Sampling and analysis of fuel and ash.
- Ensure the accuracy of fuel and ash analysis in the laboratory.
- Check the type of blow down and method of measurement
- Ensure proper operation of all instruments.
- Check for any air infiltration in the combustion zone.

C) Flue gas sampling location

It is suggested that the exit duct of the boiler be probed and traversed to find the location of the zone of maximum temperature. This is likely to coincide with the zone of maximum gas flow and is therefore a good sampling point for both temperature and gas analysis.

D) Options of flue gas analysis

Check the Oxygen Test with the Carbon Dioxide Test

If continuous-reading oxygen test equipment is installed in boiler plant, use oxygen reading. Occasionally use portable test equipment that checks for both oxygen and carbon dioxide. If the carbon dioxide test does not give the same results as the oxygen test, something is wrong. One (or both) of the tests could be erroneous, perhaps because of stale chemicals or drifting instrument calibration. Another possibility is that outside air is being picked up along with the flue gas. This occurs if the combustion gas area operates under negative pressure and there are leaks in the boiler casing.

Carbon Monoxide Test

The carbon monoxide content of flue gas is a good indicator of incomplete combustion with all types of fuels, as long as they contain carbon. Carbon monoxide in the flue gas is minimal with ordinary amounts of excess air, but it rises abruptly as soon as fuel combustion starts to be incomplete.

E) Planning for the testing

- The testing is to be conducted for a duration of 4 to 8 hours in a normal production day.
- Advanced planning is essential for the resource arrangement of manpower, fuel, water and instrument check etc and the same to be communicated to the boiler Supervisor and Production Department.
- Sufficient quantity of fuel stock and water storage required for the test duration should be arranged so that a test is not disrupted due to non-availability of fuel and water.
- Necessary sampling point and instruments are to be made available with working condition.
- Lab Analysis should be carried out for fuel, flue gas and water in coordination with lab personnel.
- The steam table, psychometric chart, calculator are to be arranged for computation of boiler efficiency.

1.7.4 Boiler Efficiency by Indirect Method: Calculation Procedure and Formula

In order to calculate the boiler efficiency by indirect method, all the losses that occur in the boiler must be established. These losses are conveniently related to the amount of fuel burnt. In this way it is easy to compare the performance of various boilers with different ratings.

Conversion formula for proximate analysis to ultimate analysis

$$\%C = 0.97C + 0.7\ (VM + 0.1A) - M(0.6 - 0.01M)$$

$$\%H_2 = 0.036C + 0.086\ (VM - 0.1xA) - 0.0035M^2\ (1 - 0.02M)$$

$$\%N_2 = 2.10 - 0.020\ VM$$

where C = % of fixed carbon
A = % of ash
VM = % of volatile matter
M = % of moisture

However it is suggested to get a ultimate analysis of the fuel fired periodically from a reputed laboratory.

Theoretical (stoichiometric) air fuel ratio and excess air supplied are to be determined first for computing the boiler losses. The formula is given below for the same.

a) Theoretical air required for combustion	=	$[(11.6 x C) + \{34.8 x (H_2 - O_2/8)\} + (4.35 x S)]/100$ kg/kg of fuel. [from fuel analysis]
		Where C, H_2, O_2 and S are the percentage of carbon, hydrogen, oxygen and sulphur present in the fuel.
b) % Excess Air supplied (EA)	=	$\frac{O_2\%}{21 - O_{2\%}} x100$ [from flue gas analysis]
		Normally O_2 measurement is recommended. If O_2 measurement is not available, use CO_2 measurement
		$\frac{7900 x [(CO_2\%)_t - (CO_2\%)_a]}{(CO_2)_a\% \; x \; [100 - (CO_2\%)_t]}$ [from flue gas analysis]
Where, $(CO_2\%)_t$	=	Theoretical CO_2
$(CO_2\%)_a$	=	Actual CO_2% measured in flue gas
$(CO_2)_t$	=	$\frac{Moles\ of\ C}{Moles\ of\ N_2 + Moles\ of\ C}$
Moles of N_2	=	$\frac{Wt\ of\ N_2\ in\ theoritical\ air}{Mol.wt\ of\ N_2} + \frac{Wt\ of\ N_2\ in\ fuel}{Mol.Wt\ of\ N_2}$
Moles of C	=	$\frac{Wt\ of\ C\ in\ fuel}{Molecular\ Wt\ of\ C}$
c) Actual mass of air supplied/ kg of fuel (AAS)	=	{1 + EA/100} x theoretical air

The various losses associated with the operation of a boiler are discussed below with required formula.

1. Heat loss due to dry flue gas

This is the greatest boiler loss and can be calculated with the following formula:

$$L1 = \frac{m \; x \; C_p \; x \; (Tf - Ta)}{GCV \; of \; fuel} x \; 100$$

Where,

L_1 = % Heat loss due to dry flue gas

m = Mass of dry flue gas in kg/kg of fuel

= Combustion products from fuel: CO_2 + SO_2 + Nitrogen in fuel + Nitrogen in the actual mass of air supplied + O_2 in flue gas. (H_2O/Water vapour in the flue gas should not be considered)

C_p	=	Specific heat of flue gas in kCal/kg°C
T_f	=	Flue gas temperature in °C
T_a	=	Ambient temperature in °C

Note–1:

For Quick and simple calculation of boiler efficiency use the following.

A: Simple method can be used for determining the dry flue gas loss as given below.

a) Percentage heat loss due to dry flue gas = $$\frac{m \times C_p \times (T_f - T_a) \times 100}{\text{GCV of fuel}}$$

Total mass of flue gas (m)/kg of fuel = mass of actual air supplied/kg of fuel + 1 kg of fuel

Note-2: Water vapour is produced from Hydrogen in fuel, moisture present in fuel and air during the combustion. The losses due to these components have not been included in the dry flue gas loss since they are separately calculated as a wet flue gas loss.

2. Heat loss due to evaporation of water formed due to H_2 in fuel (%)

The combustion of hydrogen causes a heat loss because the product of combustion is water. This water is converted to steam and this carries away heat in the form of its latent heat.

$$L_2 = \frac{9 \times H_2 \times \{584 + C_p (T_f - T_a)\}}{\text{GCV of fuel}} \times 100$$

Where

H_2	=	kg of hydrogen present in fuel on 1 kg basis
C_p	=	Specific heat of superheated steam in kCal/kg°C
T_f	=	Flue gas temperature in °C
T_a	=	Ambient temperature in °C
584	=	Latent heat corresponding to partial pressure of water vapour

3. Heat loss due to moisture present in fuel

Moisture entering the boiler with the fuel leaves as a superheated vapour. This moisture loss is made up of the sensible heat to bring the moisture to boiling point, the latent heat of evaporation of the moisture, and the superheat required to bring this steam to the temperature of the exhaust gas. This loss can be calculated with the following formula

$$L_3 = \frac{M \times \{584 + C_p (T_f - T_a)\}}{\text{GCV of fuel}} \times 100$$

where

M	=	kg moisture in fuel on 1 kg basis
C_p	=	Specific heat of superheated steam in kCal/kg°C
T_f	=	Flue gas temperature in °C
T_a	=	Ambient temperature in °C
584	=	Latent heat corresponding to partial pressure of water vapour

4. Heat loss due to moisture present in air

Vapour in the form of humidity in the incoming air, is superheated as it passes through the boiler. Since this heat passes up the stack, it must be included as a boiler loss.

To relate this loss to the mass of coal burned, the moisture content of the combustion air and the amount of air supplied per unit mass of coal burned must be known.

The mass of vapour that air contains can be obtained from psychrometric charts and typical values are included below:

Dry-Bulb	Wet Bulb	Relative Humidity	Kilogram water per Kilogram dry air (Humidity Factor)
Temp °C	Temp °C	(%)	
20	20	100	0.016
20	14	50	0.008
30	22	50	0.014
40	30	50	0.024

$$L_4 = \frac{\text{AAS x humidity factor x } C_p \text{ x } (T_f - T_a) \text{ x } 100}{\text{GCV of fuel}}$$

where

AAS	=	Actual mass of air supplied per kg of fuel
Humidity factor	=	kg of water/kg of dry air
C_p	=	Specific heat of superheated steam in kCal/kg°C
T_f	=	Flue gas temperature in °C
T_a	=	Ambient temperature in °C (dry bulb)

5. Heat loss due to incomplete combustion:

Products formed by incomplete combustion could be mixed with oxygen and burned again with a further release of energy. Such products include CO, H_2, and various hydrocarbons and are generally found in the flue gas of the boilers. Carbon monoxide is the only gas whose concentration can be determined conveniently in a boiler plant test.

$$L_5 = \frac{\%CO \times C}{\%\,CO + \%\,CO_2} \times \frac{5744}{GCV\ of\ fuel} \times 100$$

L_5 = % Heat loss due to partial conversion of C to CO
CO = Volume of CO in flue gas leaving economizer (%)
CO_2 = Actual Volume of CO_2 in flue gas (%)
C = Carbon content kg / kg of fuel

or

When CO is obtained in ppm during the flue gas analysis
CO formation (M_{co}) = CO (in ppm) x 10^{-6} x M_f x 28
M_f = Fuel consumption in kg/hr
L_5 = M_{co} x 5744*
* Heat loss due to partial combustion of carbon.

6. Heat loss due to radiation and convection:

The other heat losses from a boiler consist of the loss of heat by radiation and convection from the boiler casting into the surrounding boiler house.

Normally surface loss and other unaccounted losses is assumed based on the type and size of the boiler as given below

For industrial fire tube / packaged boiler = 1.5 to 2.5%

For industrial watertube boiler = 2 to 3%

For power station boiler = 0.4 to 1%

However it can be calculated if the surface area of boiler and its surface temperature are known as given below :

$$L_6 = 0.548 \times [\,(T_s / 55.55)^4 - (T_a / 55.55)^4] + 1.957 \times (T_s - T_a)^{1.25} \times \text{sq.rt of } [(196.85\,V_m + 68.9) / 68.9]$$

where

L_6 = Radiation loss in W/m^2
V_m = Wind velocity in m/s
T_s = Surface temperature (K)
T_a = Ambient temperature (K)

Heat loss due to unburned carbon in fly ash and bottom ash:

Small amounts of carbon will be left in the ash and this constitutes a loss of potential heat in the fuel. To assess these heat losses, samples of ash must be analyzed for carbon content. The quantity of ash produced per unit of fuel must also be known.

7. Heat loss due to unburnt in fly ash (%).

$$L_7 = \frac{\text{Total ash collected / kg of fuel burnt x G.C.V of fly ash x 100}}{\text{GCV of fuel}}$$

8. Heat loss due to unburnt in bottom ash (%)

$$L_8 = \frac{\text{Total ash collected per kg of fuel burnt x G.C.V of bottom ash x 100}}{\text{GCV of fuel}}$$

Heat Balance:

Having established the magnitude of all the losses mentioned above, a simple heat balance would give the efficiency of the boiler. The efficiency is the difference between the energy input to the boiler and the heat losses calculated.

Boiler Heat Balance:

Input/Output Parameter		**kCal / kg of fuel**	**%**
Heat Input in fuel	=		100
Various Heat losses in boiler			
1. Dry flue gas loss	=		
2. Loss due to hydrogen in fuel			
3. Loss due to moisture in fuel	=		
4. Loss due to moisture in air	=		
5. Partial combustion of C to CO	=		
6. Surface heat losses	=		
7. Loss due to Unburnt in fly ash	=		
8. Loss due to Unburnt in bottom ash	=		
Total Losses	=		
Boiler efficiency = 100 – (1+2+3+4+5+6+7+8)			

1.8 Example: Boiler Efficiency Calculation

1.8.1 For Coal fired Boiler

The following are the data collected for a boiler using coal as the fuel. Find out the boiler efficiency by indirect method.

Fuel firing rate	=	5599.17 kg/hr
Steam generation rate	=	21937.5 kg/hr
Steam pressure	=	43 kg/cm^2(g)
Steam temperature	=	377 °C
Feed water temperature	=	96 °C
%CO_2 in Flue gas	=	14
%CO in flue gas	=	0.55
Average flue gas temperature	=	190 °C
Ambient temperature	=	31 °C
Humidity in ambient air	=	0.0204 kg / kg dry air
Surface temperature of boiler	=	70 °C
Wind velocity around the boiler	=	3.5 m/s
Total surface area of boiler	=	90 m^2
GCV of Bottom ash	=	800 kCal/kg
GCV of fly ash	=	452.5 kCal/kg
Ratio of bottom ash to fly ash	=	90:10
Fuel Analysis (in %)		
Ash content in fuel	=	8.63
Moisture in coal	=	31.6
Carbon content	=	41.65
Hydrogen content	=	2.0413
Nitrogen content	=	1.6
Oxygen content	=	14.48
GCV of Coal	=	3501 kCal/kg

Boiler efficiency by indirect method

Step – 1 Find theoretical air requirement

Theoretical air required for complete combustion = $[(11.6 \times C) + \{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)] / 100$ kg/kg of coal

= $[(11.6 \times 41.65) + \{34.8 \times (2.0413 - 14.48/8)\} + (4.35 \times 0)] / 100$

= **4.91 kg / kg of coal**

Step – 2 Find theoretical CO_2 %

% CO_2 at theoretical condition $(CO_2)_t$ = $\dfrac{Moles\ of\ C}{Moles\ of\ N_2 + Moles\ of\ C}$

Where,

Moles of N_2 = $\dfrac{Wt\ of\ N_2\ in\ theoritical\ air}{Mol.wt\ of\ N_2} + \dfrac{Wt\ of\ N_2\ in\ fuel}{Mol.Wt\ of\ N_2}$

Moles of N_2 = $\dfrac{4.91 x 77/100}{28} + \dfrac{0.016}{28} = 0.1356$

Where moles of C = 0.4165/12 = 0.0347

$(CO_2)_t$ = $\dfrac{0.0347}{0.1332 + 0.0347}$

$(CO_2)_t$ = 20.37%

Step – 3 To find Excess air supplied

Actual CO_2 measured in flue gas = 14.0%

% Excess air supplied (EA) = $\dfrac{7900 \text{ x } [(CO_2\%)_t - (CO_2\%)_a]}{(CO_2\%)_a \text{ x } [100 - (CO_2\%)_t]}$

= $\dfrac{7900 \text{ x } [20.37 - 14]}{14_a \text{ x } [100 - 20.37]}$

= **45.17 %**

Step – 4 to find actual mass of air supplied

Actual mass of air supplied = {1 + EA/100} x theoretical air

= {1 + 45.17/100} x 4.91

= **7.13 kg/kg of coal**

Step – 5 to find actual mass of dry flue gas

Mass of dry flue gas = Mass of CO_2 + Mass of N_2 content in the fuel + Mass of N_2 in the combustion air supplied + Mass of oxygen in flue gas

$$\text{Mass of dry flue gas} = \frac{0.4165 \times 44}{12} + 0.016 + \frac{7.13 \times 77}{100} + \frac{(7.13-4.91) \times 23}{100}$$

= **7.54 kg / kg of coal**

Step – 6 to find all losses

$$1.\ \%\ \text{Heat loss in dry flue gas}\ (L_1) = \frac{m \times C_p \times (T_f - T_a)}{\text{GCV of fuel}} \times 100$$

$$= \frac{7.54 \times 0.23 \times (190 - 31)}{3501} \times 100$$

L_1 = **7.88 %**

$$2.\ \%\ \text{Heat loss due to formation of water from}\ H_2\ \text{in fuel}\ (L_2) = \frac{9 \times H_2 \times \{584 + C_p (T_f - T_a)\}}{\text{GCV of fuel}} \times 100$$

$$= \frac{9 \times .02041 \times \{584 + 0.45(190 - 31)\}}{3501} \times 100$$

L_2 = **3.44 %**

3. % Heat loss due to moisture in fuel (L_3)

$$= \frac{M \text{ x } \{584 + C_p (T_f - T_a)\}}{\text{GCV of fuel}} \text{ X } 100$$

$$= \frac{0.316 \text{ x } \{584 + 0.45 (190 - 31) \}}{3501} \text{ x } 100$$

L_3 = **5.91 %**

4. % Heat loss due to moisture in air (L_4)

$$= \frac{\text{AAS x humidity x } C_p \text{ x } (T_f - T_a) \text{ x } 100}{\text{GCV of fuel}}$$

$$= \frac{7.13 \text{ x } 0.0204 \text{ x } 0.45 \text{ x } (190 - 31) \text{ x } 100}{3501}$$

L_4 = **0.29 %**

5. % Heat loss due to partial conversion of C to CO (L_5)

$$= \frac{\%CO \text{ x } C}{\% \; CO + (\% \; CO_2)_a} \text{ x } \frac{5744}{\text{GCV of fuel}} \text{ x } 100$$

$$= \frac{0.55 \text{ x } 0.4165}{0.55 + 14} \text{ x } \frac{5744}{3501} \text{ x } 100$$

L_5 = **2.58 %**

6. Heat loss due to radiation and convection (L_6)

= $0.548 \text{ x } [(343/55.55)^4 - (304/55.55)^4] + 1.957 \text{ x } (343 - 304)^{1.25} \text{ x sq.rt of } [(196.85 \text{ x } 3.5 + 68.9) / 68.9]$

= 633.3 w/m^2

= 633.3 x 0.86

= 544.64 kCal / m^2

Total radiation and convection loss per hour	=	544.64 x 90
	=	49017.6 kCal
% radiation and convection loss	=	$\frac{49017.6 \times 100}{3501 \times 5599.17}$
L_6	=	**0.25 %**

7. % Heat loss due to unburnt in fly ash

% Ash in coal	=	8.63
Ratio of bottom ash to fly ash	=	90:10
GCV of fly ash	=	452.5 kCal/kg
Amount of fly ash in 1 kg of coal	=	0.1 x 0.0863
	=	0.00863 kg
Heat loss in fly ash	=	0.00863 x 452.5
	=	3.905 kCal / kg of coal
% heat loss in fly ash	=	3.905 x 100 / 3501
L_7	=	**0.11 %**

8. % Heat loss due to unburnt in bottom ash

GCV of bottom ash	=	800 kCal/kg
Amount of bottom ash in 1 kg of coal	=	0.9 x 0.0863
	=	0.077 kg
Heat loss in bottom ash	=	0.077 x 800
	=	62.136 kCal/kg of coal
% Heat loss in bottom ash	=	62.136 x 100 / 3501
L_8	=	**1.77 %**

Boiler efficiency by indirect method	=	$100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8)$
	=	100 – (7.88 + 3.44 + 5.91 + 0.29 + 2.58 + 0.25 + 0.11 + 1.77)
	=	100 – 22.23
	=	**77.77 %**

SUMMARY OF HEAT BALANCE FOR COAL FIRED BOILER			
Input/Output Parameter		**kCal / kg of coal**	**% loss**
Heat Input	=	3501	100
Losses in boiler			
1. Dry flue gas, L_1	=	275.88	7.88
2. Loss due to hydrogen in fuel, L_2	=	120.43	3.44
3. Loss due to moisture in fuel, L_3	=	206.91	5.91
4. Loss due to moisture in air, L_4	=	10.15	0.29
5. Partial combustion of C to CO, L_5	=	90.32	2.58
6. Surface heat losses, L_6	=	8.75	0.25
7. Loss due to Unburnt in fly ash, L_7	=	3.85	0.11
8. Loss due to Unburnt in bottom ash, L_8	=	61.97	1.77
Boiler Efficiency = 100 – ($L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8$) = 77.77 %			

1.8.2 Efficiency for an oil fired boiler

The following are the data collected for a boiler using furnace oil as the fuel. Find out the boiler efficiency by indirect method.

Ultimate analysis (%)

Carbon	=	84
Hydrogen	=	12
Nitrogen	=	0.5
Oxygen	=	1.5
Sulphur	=	1.5
Moisture	=	0.5
GCV of fuel	=	10000 kCal/kg
Fuel firing rate	=	2648.125 kg/hr
Surface Temperature of boiler	=	80 °C
Surface area of boiler	=	90 m^2
Humidity	=	0.025 kg/kg of dry air
Wind speed	=	3.8 m/s

Flue gas analysis (%)

Flue gas temperature	=	190°C
Ambient temperature	=	30°C
Co_2% in flue gas by volume	=	10.8
O_2% in flue gas by volume	=	7.4

a) Theoretical air required	=	$[(11.6 \times C) + [\{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)] / 100$ kg/kg of fuel. [from fuel analysis]
	=	$[(11.6 \times 84) + [\{34.8 \times (12 - 1.5/8)\} + (4.35 \times 1.5)] / 100$
	=	**13.92 kg/kg of oil**
b) Excess Air supplied (EA)	=	$(O_2 \times 100) / (21 - O_2)$
	=	$(7.4 \times 100) / (21 - 7.4)$
	=	**54.4 %**
c) Actual mass of air supplied/ kg of fuel (AAS)	=	$\{1 + EA/100\} \times$ theoretical air
	=	$\{1 + 54.4/100\} \times 13.92$
	=	21.49 kg / kg of fuel
Mass of dry flue gas	=	Mass of $(CO_2 + SO_2 + N_2 + O_2)$ in flue gas + N_2 in air we are supplying
	=	$\frac{0.84 \times 44}{12} + \frac{0.015 \times 64}{32} + 0.005 + \frac{7.4 \times 23}{100} + \frac{21.49 \times 77}{100}$
	=	**21.36 kg / kg of oil**

$$\% \text{ Heat loss in dry flue gas} = \frac{m \times C_p \times (T_f - T_a)}{\text{GCV of fuel}} \times 100$$

$$= \frac{21.36 \times 0.23 \times (190 - 30)}{10000} \times 100$$

$$L_1 = \mathbf{7.86\ \%}$$

$$\text{Heat loss due to evaporation of water due to } H_2 \text{ in fuel } (\%) = \frac{9 \times H_2 \times \{584 + C_p (T_f - T_a)\}}{\text{GCV of fuel}} \times 100$$

$$= \frac{9 \times 0.12 \times \{584 + 0.45\,(190 - 30)\}}{10000} \times 100$$

$$L_2 = \mathbf{7.08\ \%}$$

% Heat loss due to moisture in fuel $= \dfrac{M \times \{584 + C_p (T_f - T_a)\}}{\text{GCV of fuel}} \times 100$

$= \dfrac{0.005 \times \{584 + 0.45 (190 - 30)\}}{10000} \times 100$

L_3 = **0.033%**

% Heat loss due to moisture in air $= \dfrac{\text{AAS} \times \text{humidity} \times C_p \times (T_f - T_a) \times 100}{\text{GCV of fuel}}$

$= \dfrac{21.36 \times 0.025 \times 0.45 \times (190 - 30) \times 100}{10000}$

L_4 = **0.38 %**

Radiation and convection loss (L_6) $= 0.548 \times [(T_s / 55.55)^4 - (T_a / 55.55)^4] + 1.957 \times (T_s - T_a)^{1.25} \times$ sq.rt of $[(196.85\, V_m + 68.9) / 68.9]$

$= 0.548 \times [(353 / 55.55)^4 - (303 / 55.55)^4] + 1.957 \times (353 - 303)^{1.25} \times$ sq.rt of $[(196.85 \times 3.8 + 68.9)/ 68.9]$

= 1303 W/m^2

= 1303 x 0.86

= 1120.58 kCal / m^2

Total radiation and convection loss per hour = 1120 .58 x 90 m^2
= 100852.2 kCal

% Radiation and convection loss $= \dfrac{100852.2 \times 100}{10000 \times 2648.125}$

L_6 = **0.38 %**
Normally it is assumed as 0.5 to 1 % for simplicity

Boiler efficiency by indirect method = 100 – ($L_1 + L_2 + L_3 + L_4 + L_6$)
= 100 – (7.86 + 7.08 + 0.033 + 0.38 + 0.38)
= 100 – 15.73
= **84.27 %**

Summary of Heat Balance for the Boiler Using Furnace Oil

Input/Output Parameter		kCal / kg of furnace oil	%Loss
Heat Input	=	10000	100
Losses in boiler :			
1. Dry flue gas, L_1	=	786	7.86
2. Loss due to hydrogen in fuel, L_2	=	708	7.08
3. Loss due to Moisture in fuel, L_3	=	3.3	0.033
4. Loss due to Moisture in air, L_4	=	38	0.38
5. Partial combustion of C to CO, L_5	=	0	0
6. Surface heat losses, L_6	=	38	0.38
Boiler Efficiency = 100 – (L_1 + L_2 + L_3 + L_4 + L_6) = 84.27 %			

Note:

For quick and simple calculation of boiler efficiency use the following.

A: Simple method can be used for determining the dry flue gas loss as given below.

a) Percentage heat loss due to dry flue gas = $\dfrac{m \times C_p \times (T_f - T_a) \times 100}{\text{GCV of fuel}}$

Total mass of flue gas (m) = mass of actual air supplied (ASS)+ mass of fuel supplied
= 21.49 + 1=22.49

$$\%\text{Dry flue gas loss} = \frac{22.49 \times 0.23 \times (190-30)}{10000} \times 100 = 8.27\%$$

1.9 Factors Affecting Boiler Performance

The various factors affecting the boiler performance are listed below:

- Periodical cleaning of boilers
- Periodical soot blowing
- Proper water treatment programme and blow down control
- Draft control
- Excess air control
- Percentage loading of boiler
- Steam generation pressure and temperature
- Boiler insulation
- Quality of fuel

All these factors individually/combined, contribute to the performance of the boiler and reflected either in boiler efficiency or evaporation ratio. Based on the results obtained from the testing further improvements have to be carried out for maximizing the performance. The test can be repeated after modification or rectification of the problems and compared with standard norms. Energy auditor should carry out this test as a routine manner once in six months and report to the management for necessary action.

1.10 Data Collection Format for Boiler Performance Assessment

Sheet 1 – Technical specification of boiler	
1	Boiler ID code and Make
2	Year of Make
3	Boiler capacity rating
4	Type of Boiler
5	Type of fuel used
6	Maximum fuel flow rate
7	Efficiency by GCV
8	Steam generation pressure &superheat temperature
9	Heat transfer area in m^2
10	Is there any waste heat recovery device installed
11	Type of draft
12	Chimney height in metre

Sheet 2 – Fuel analysis details

Fuel Fired
GCV of fuel
Specific gravity of fuel (Liquid)
Bulk density of fuel (Solid)

Proximate Analysis		**Date of Test:**
1	Fixed carbon	%
2	Volatile matter	%
3	Ash	%
4	Moisture	%

Ultimate Analysis		**Date of Test:**
1	Carbon	%
2	Hydrogen	%
3	Sulphur	%

4	Nitrogen	%
5	Ash	%
6	Moisture	%
7	Oxygen	%
Water Analysis	**Date of Test:**	
1	Feed water TDS	ppm
2	Blow down TDS	ppm
3	PH of feed water	
4	PH of blow down	
Flue gas Analysis	**Date of Test:**	
1	CO_2	%
2	O_2	%
3	CO	%
4	Flue gas temperature	°C

1.11 Boiler Terminology

MCR: Steam boilers rated output is also usually defined as MCR (Maximum Continuous Rating). This is the maximum evaporation rate that can be sustained for 24 hours and may be less than a shorter duration maximum rating

Boiler Rating

Conventionally, boilers are specified by their capacity to hold water and the steam generation rate. Often, the capacity to generate steam is specified in terms of equivalent evaporation (kg of steam / hour at 100°C). Equivalent evaporation- "from and at" 100°C. The equivalent of the evaporation of 1 kg of water at 100°C to steam at 100°C.

Efficiency : In the boiler industry there are four common definitions of efficiency:

a. Combustion efficiency

Combustion efficiency is the effectiveness of the burner only and relates to its ability to completely burn the fuel. The boiler has little bearing on combustion efficiency. A well-designed burner will operate with as little as 15 to 20% excess air, while converting all combustibles in the fuel to useful energy.

b. Thermal efficiency

Thermal efficiency is the effectiveness of the heat transfer in a boiler. It does not take into account boiler radiation and convection losses - for example from the boiler shell water column piping etc.

c. Boiler efficiency

The term boiler efficiency is often substituted for combustion or thermal efficiency. True boiler efficiency is the measure of fuel to steam efficiency.

Sheet 3 – Format sheet for boiler efficiency testing

Date: …………………   Boiler Code No. …………………

S.No	Time	Ambient air		Fuel		Feed water		Steam			Flue gas analysis				Surface Temp of boiler, °C
		Dry bulb Temp, °C	Wet Bulb Temp, °C	Flow Rate, kg/hr	Temp °C	Flow rate, m^3/hr	Temp °C	Flow rate, m^3/hr	Pressure kg/cm^2g	Temp °C	O_2 %	CO_2 %	CO %	Temp °C	
1.															
2.															
3.															
4.															
5.															
6.															
7.															
8.															

Boiler Supervisor   Energy Manager   Energy Auditor

d. Fuel to steam efficiency

Fuel to steam efficiency is calculated using either of the two methods as prescribed by the ASME (American Society for Mechanical Engineers) power test code, PTC 4.1. The first method is input output method. The second method is heat loss method.

Boiler turndown

Boiler turndown is the ratio between full boiler output and the boiler output when operating at low fire. Typical boiler turndown is 4:1. The ability of the boiler to turndown reduces frequent on and off cycling. Fully modulating burners are typically designed to operate down to 25% of rated capacity. At a load that is 20% of the load capacity, the boiler will turn off and cycle frequently.

A boiler operating at low load conditions can cycle as frequently as 12 times per hour or 288 times per day. With each cycle, pre and post purge airflow removes heat from the boiler and sends it out the stack. Keeping the boiler on at low firing rates can eliminate the energy loss. Every time the boiler cycles off, it must go through a specific start-up sequence for safety assurance. It requires about a minute or two to place the boiler back on line. And if there is a sudden load demand the start up sequence cannot be accelerated. Keeping the boiler on line assures the quickest response to load changes. Frequent cycling also accelerates wear of boiler components. Maintenance increases and more importantly, the chance of component failure increases.

Boiler(s) capacity requirement is determined by many different type of load variations in the system. Boiler over sizing occurs when future expansion and safety factors are added to assure that the boiler is large enough for the application. If the boiler is oversized the ability of the boiler to handle minimum loads without cycling is reduced. Therefore capacity and turndown should be considered together for proper boiler selection to meet overall system load requirements.

Primary air: That part of the air supply to a combustion system which the fuel first encounters.

Secondary air: The second stage of admission of air to a combustion system, generally to complete combustion initiated by the primary air. It can be injected into the furnace of a boiler under relatively high pressure when firing solid fuels in order to create turbulence above the burning fuel to ensure good mixing with the gases produced in the combustion process and thereby complete combustion

Tertiary air: A third stage of admission of air to a combustion system, the reactions of which have largely been completed by secondary air. Tertiary air is rarely needed.

Stoichiometric: In combustion technology, stoichiometric air is that quantity of air, and no more, which is theoretically needed to burn completely a unit quantity of fuel. 'Sub-stoichiometric' refers to the partial combustion of fuel in a deficiency of air

Balanced draught: The condition achieved when the pressure of the gas in a furnace is the same as or slightly below that of the atmosphere in the enclosure or building housing it.

Gross calorific value (GCV): The amount of heat liberated by the complete combustion, under specified conditions, by a unit volume of a gas or of a unit mass of a solid or liquid fuel, in the determination of which the water produced by combustion of the fuel is assumed to be completely condensed and its latent and sensible heat made available.

Net calorific value (NCV): The amount of heat generated by the complete combustion, under specified conditions, by a unit volume of a gas or of a unit mass of a solid or liquid fuel, in the determination of which the water produced by the combustion of the fuel is assumed to remain as vapour.

Absolute pressure The sum of the gauge and the atmospheric pressure. For instance, if the steam gauge on the boiler shows 9 kg/cm^2g the absolute pressure of the steam is 10 $kg/cm^2(a)$.

Atmospheric pressure The pressure due to the weight of the atmosphere. It is expressed in pounds per sq. in. or inches of mercury column or kg/cm^2. Atmospheric pressure at sea level is 14.7 lbs./ sq. inch. or 30 inch mercury column or 760mm of mercury (mm Hg) or 101.325 kilo Pascal (kPa).

Carbon monoxide (CO): Produced from any source that burns fuel with incomplete combustion, causes chest pain in heart patients, headaches and reduced mental alertness.

Blow down: The removal of some quantity of water from the boiler in order to achieve an acceptable concentration of dissolved and suspended solids in the boiler water.

Complete combustion: The complete oxidation of the fuel, regardless of whether it is accomplished with an excess amount of oxygen or air, or just the theoretical amount required for perfect combustion.

Perfect combustion: The complete oxidation of the fuel, with the exact theoretical (stoichiometric) amount of oxygen (air) required.

Saturated steam: It is the steam, whose temperature is equal to the boiling point corresponding to that pressure.

Wet Steam Saturated steam which contains moisture

Dry Steam Either saturated or superheated steam containing no moisture.

Superheated Steam Steam heated to a temperature above the boiling point or saturation temperature corresponding to its pressure

Oxygen trim sensor measures flue gas oxygen and a closed loop controller compares the actual oxygen level to the desired oxygen level. The air (or fuel) flow is trimmed by the controller until the oxygen level is corrected. The desired oxygen level for each firing rate must be entered into a characterized set point curve generator. Oxygen Trim maintains the lowest possible burner excess air level from low to high fire. Burners that don't have Oxygen Trim must run with Extra Excess Air to allow safe operation during variations in weather, fuel, and linkage.

Heat transfer mediums

There are different types of heat transfer medium e.g. steam, hot water and thermal oil. Steam and Hot water are most common and it will be valuable to briefly examine these common heat transfer mediums and associated properties.

Thermic Fluid

Thermic Fluid is used as a heat transfer mechanism in some industrial process and heating applications. Thermic Fluid may be a vegetable or mineral based oil and the oil may be raised to a high temperature without the need for any pressurization. The relatively high flow and return temperatures may limit the potential for flue gas heat recovery unless some other system can absorb this heat usefully. Careful design and selection is required to achieve best energy efficiency.

Hot water

Water is a fluid with medium density, high specific heat capacity, low viscosity and relatively low thermal conductivity. At relatively low temperature e.g. 70°C – 90°C, hot water is useful for smaller heating installations.

Steam

When water is heated its temperature will rise. The heat added is called sensible heat and the heat content of the water is termed its *enthalpy*. The usual datum point used to calculate enthalpy is 0°C.

When the water reaches its boiling point, any further heat input will result in some proportion of the water changing from the liquid to the vapour state, i.e. changing to steam. The heat required for this change of state is termed the 'latent heat of evaporation' and is expressed in terms of a fixed mass of water. Where no change in temperature occurs during the change of state, the steam will exist in equilibrium with the water. This equilibrium state is termed 'saturation conditions'. Saturation conditions can occur at any pressure, although at each pressure there is only one discrete temperature at which saturation can occur.

If further heat is applied to the saturated steam the temperature will rise and the steam will become 'superheated'. Any increase in temperature above saturated conditions will be accompanied by a further rise in enthalpy.

Steam is useful heat transfer medium because, as a gas, it is compressible. At high pressure and consequently density, steam can carry large quantities of heat with relatively small volume.

QUESTIONS	
1)	Define boiler efficiency.
2)	Why boiler efficiency by indirect method is more useful than direct method?
3)	What instruments are required for indirect efficiency testing?
4)	What is the difference between dry flue gas loss and wet flue gas loss?
5)	Which is the best location for sampling flue gas analysis?
6)	Find out the efficiency by direct method from the data given below. An oil fired package boiler was tested for 2 hours duration at steady state condition. The fuel and water consumption were 250 litres and 3500 litres respectively. The specific gravity of oil is 0.92. The saturated steam generation pressure is 7 kg/cm^2(g). The boiler feed water temperature is 30°C. Determine the boiler efficiency and evaporation ratio.
7)	What is excess air? How to determine excess air if oxygen / carbon dioxide percentage is measured in the flue gas?
8)	As a means of performance evaluation, explain the difference between efficiency and evaporation ratio.
9)	Testing coal-fired boiler is more difficult than oil-fired boiler. Give reasons.
10)	What is controllable and uncontrollable losses in a boiler?

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