STEAM BOILERS

Steam Generator

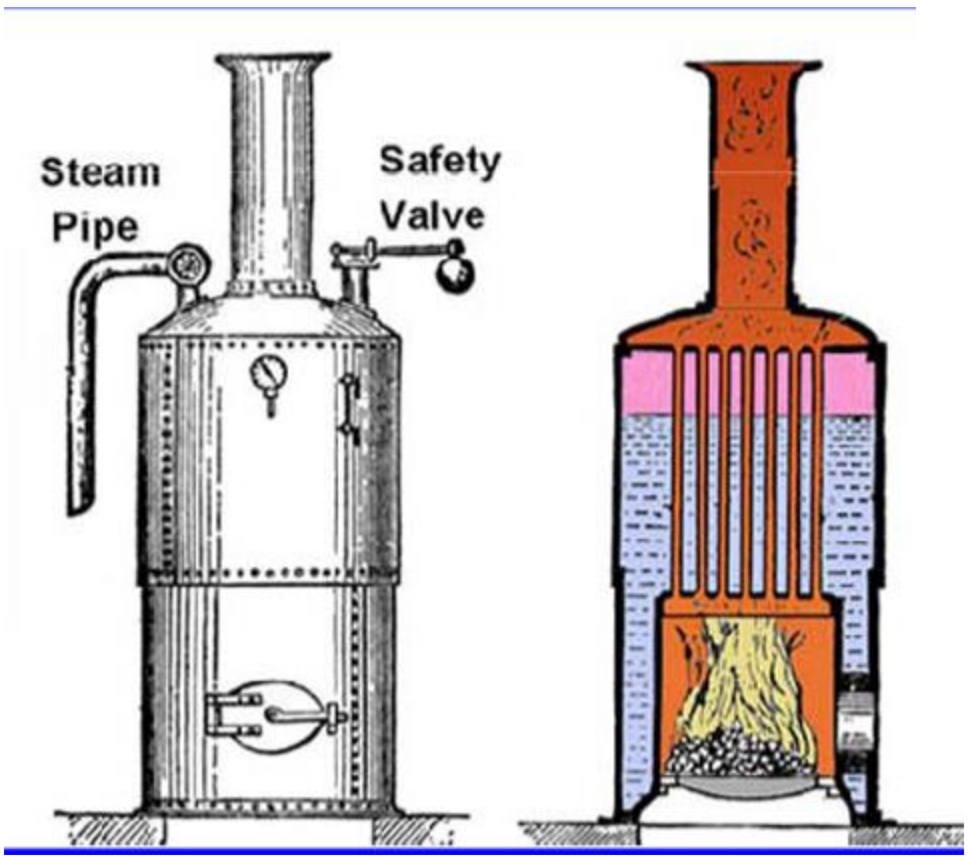
Steam Generators depends on :

- ***Types of Fuel (Solid, Liquid and Gases)***
- ***Circulation Systems (Natural, Forced, Once through)***
- ***Heat transfer Process (Radiation, Convection, Radiation)***
- ***End use***
- ***Capacity***

Boilers

Boiler is an apparatus to produce steam. Thermal energy released by combustion of fuel is used to make steam at the desired temperature and pressure.

Simple Boiler..



Purpose of boilers

- For generating power in steam engines or steam turbines
- In textile industries for sizing and bleaching
- For heating the buildings in cold weather and for producing hot water for hot water supply

Primary requirements of a boiler

- The water must be contained safely
- The steam must be safely delivered in desired condition (as regard its pressure, temperature, quality and required rate)

Boiler properties:

I. Safety. The boiler should be safe under operating conditions.
II. Accessibility. The various parts of the boiler should be accessible for repair and maintenance.
III. Capacity. Should be capable of supplying steam according to the requirements.

IV. Efficiency. Should be able to absorb a maximum amount of heat produced due to burning of fuel in the furnace.

V. It should be simple in construction .

VI. Its initial cost and maintenance cost should be low.

VII. The boiler should have no joints exposed to flames.

VIII. Should be capable of quick starting and loading.

Boiler terms

- **Shell**: Consists of one or more steel plates bent into a cylindrical form and riveted or welded together. The shell ends are closed with end plates
- **Setting**: The primary function of setting is to confine heat to the boiler and form a passage for gases. It is made of brick work and may form the wall of the furnace and combustion chamber

- **Grate**: it is a platform in the furnace upon which fuel is burnt

- **Furnace**: it is the chamber formed by the space above the grate and below the boiler shell, in which combustion takes place.

- **Water space and steam space**: the volume of the shell that is occupied by the water is termed as water space while the entire shell volume less the water and tubes is called steam space

- **Mountings**: The items which are used for **safety** of boiler and its ***control*** are called called mountings

- **Accessories**: The items which are used for **increasing the boiler efficiency** are called accessories

- **Water level**: The level at which water stands in the boiler is called water level

- **Refractory**: insulation material used for lining combustion chamber

- **Foaming**: Formation of steam bubbles on the surface of boiler water due to high surface tension of water

Boiler accessories

Feed pumps:

- Used to deliver feed water to the boiler.

➢ It is desirable that the quantity of water supplied should be at least equal to that evaporated and supplied to the engine

➢ Two types of which are commonly used as feed pumps are

1. reciprocating pump
2. rotary pump

Injector

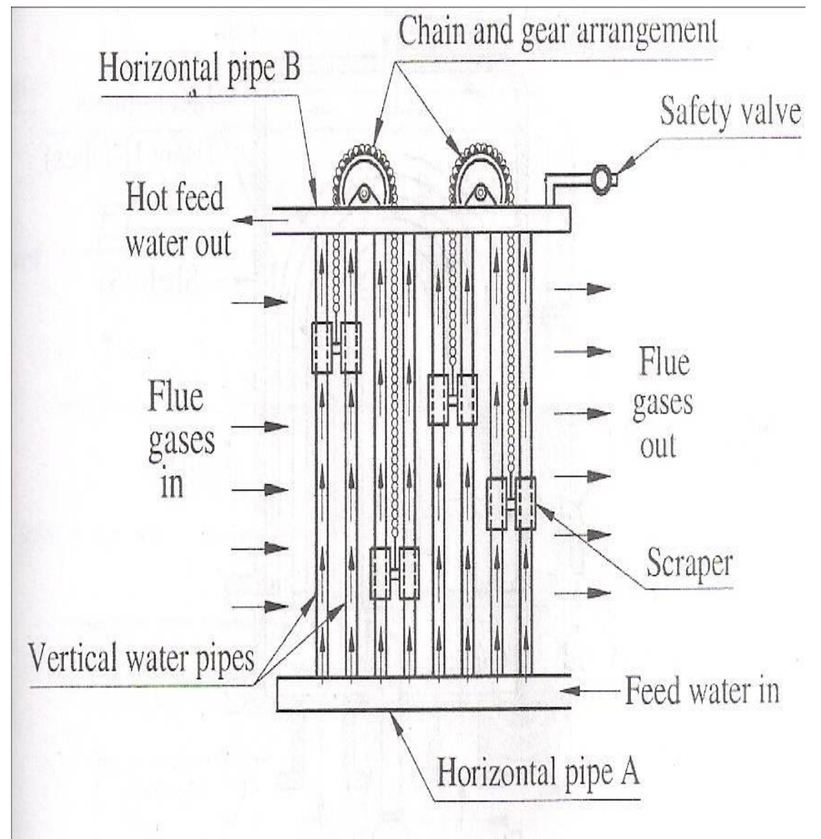
- Function of injector is to feed water into the boiler
- It is commonly employed for vertical and locomotive boilers and does not find its application in large capacity high pressure boilers
- Also used where the space is not available for the installation of feed pump

Economizer

- Is a device in which the waste heat of the flue gases is utilized for heating the feed water
- Economizers are of two types

  Independent type

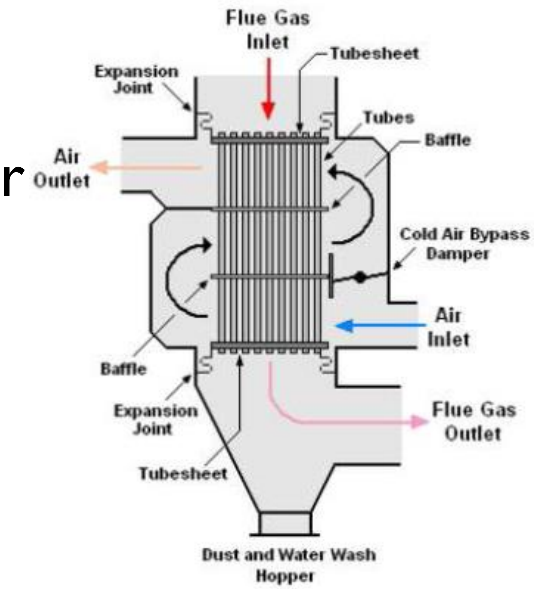
  Integral type



Air Pre-heater

- The function of the air pre-heater is to increase the temperature of air before it enters the furnace.
- It is placed after the economizer.
- Flue gases pass through the economizer

and then to the air preheater



- Degree of preheating depends on
  - Type of fuel
  - Type of fuel burning equipment, and
  - Rating at which the boiler and furnace are operated

Types of Air Preheaters

I. Tubular type

II. Plate type

III. Storage type

Super heater

- The function of a super heater is to increase the temperature of the steam above its saturation point

- The super heater is very important accessory of a boiler and can be used both on fire tube and water – tube boilers.

- **Advantages of super heated steam**

  - Steam consumption of the engine or turbine is reduced.

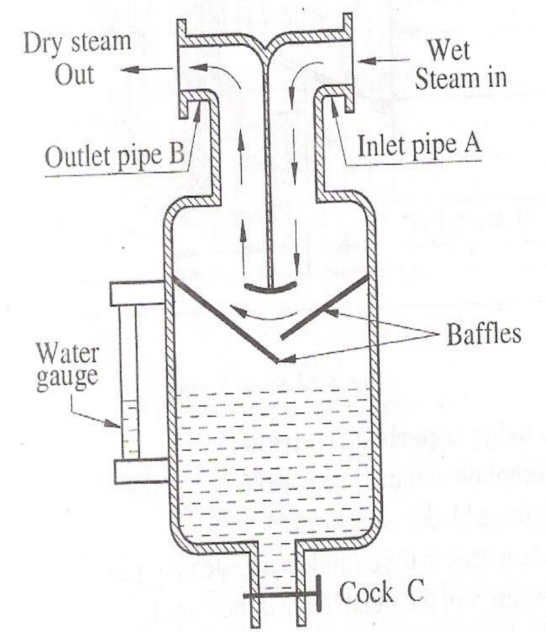
  - Erosion of turbine blade is eliminated.

  - Efficiency of the steam plant is increased.

  - Losses due to condensation in the cylinders and the steam pipes are reduced.

Steam separator

- The function of a steam separator is to remove the entrained water particles from the steam conveyed to the steam engine or turbine.
- It is installed as close to the steam engine as possible on the main steam pipe from the boiler.



STEAM TRAP

- Steam trap is used to collect and automatically drain away the water resulted from partial condensation of steam without steam to escape with this condensate through a valve.
- A **steam trap** is a device used to discharge condensates and non-condensable gases with a negligible consumption or loss of live **steam**.
- Most **steam traps** are nothing more than automatic valves.

- According to principle of operation the steam separators are classified as follows

  - Impact or baffle type

  - Reverse current type

  - Centrifugal type

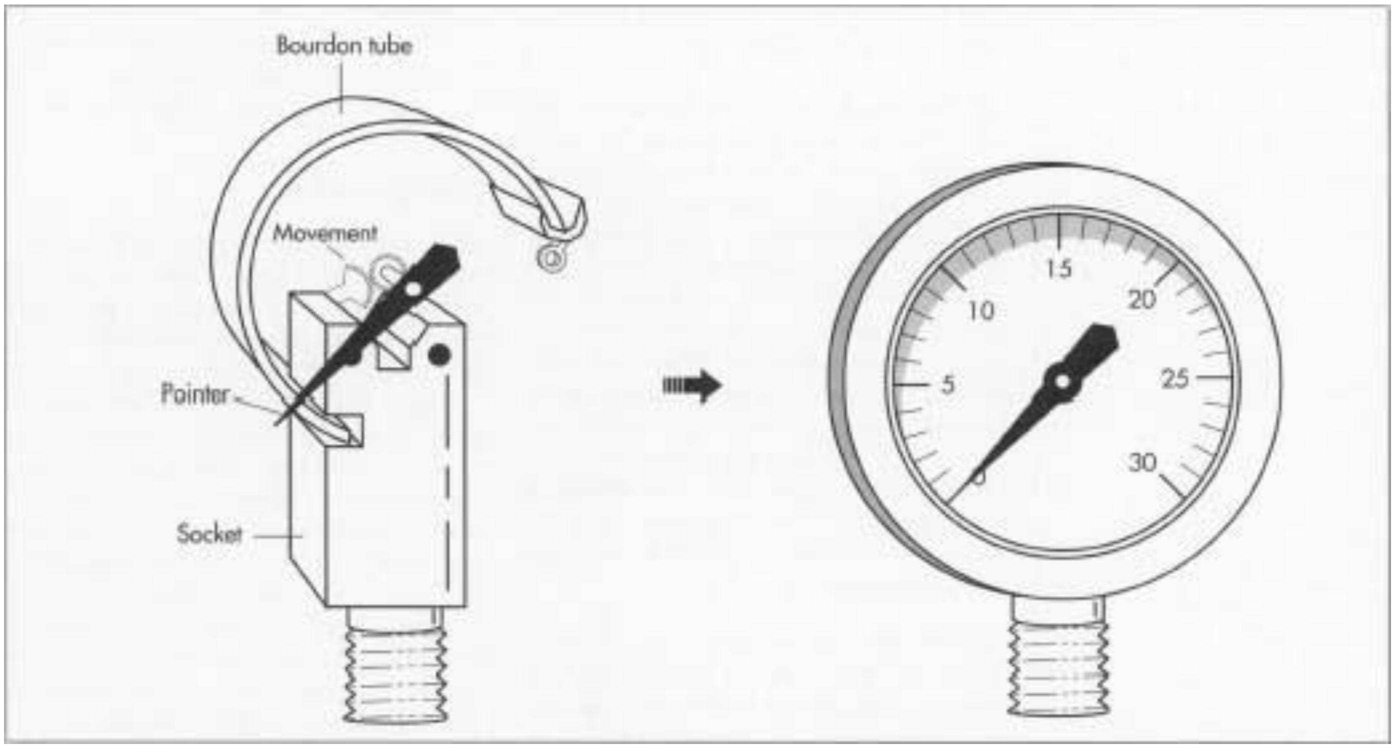
Boiler mountings

- Pressure gauge
- Fusible plug
- Steam stop valve
- Feed check valve
- Blow off cock
- Mud and man holes

Pressure gauge

- To record the steam pressure at which steam is generated in the boiler
- A bourdon pressure gauge in its simplest form consists of a simple elastic tube
- One end of the tube is fixed and connected to the steam space in the boiler
- Other end is connected to a sector through a link

Pressure gauge



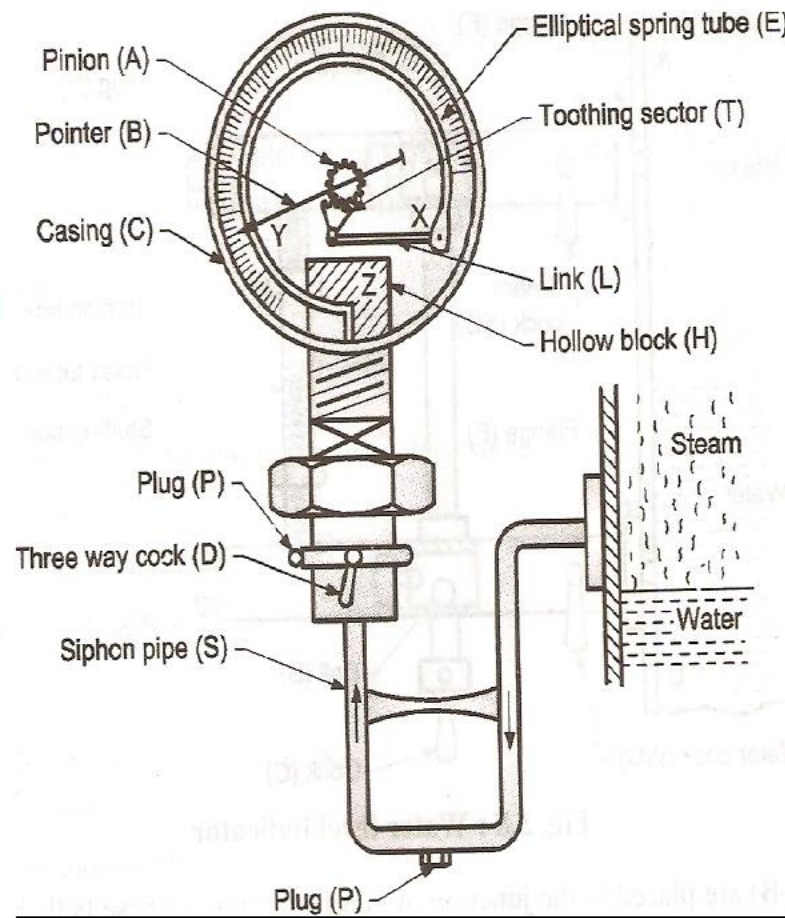
PRESSURE GAUGE
(*Bourdon's*)

a) Records gauge pressure

b) Elliptical spring tube is also called Bourdon tube and is made up of special quality Bronze.

c) Plug (P) is provided for cleaning the siphon tube.

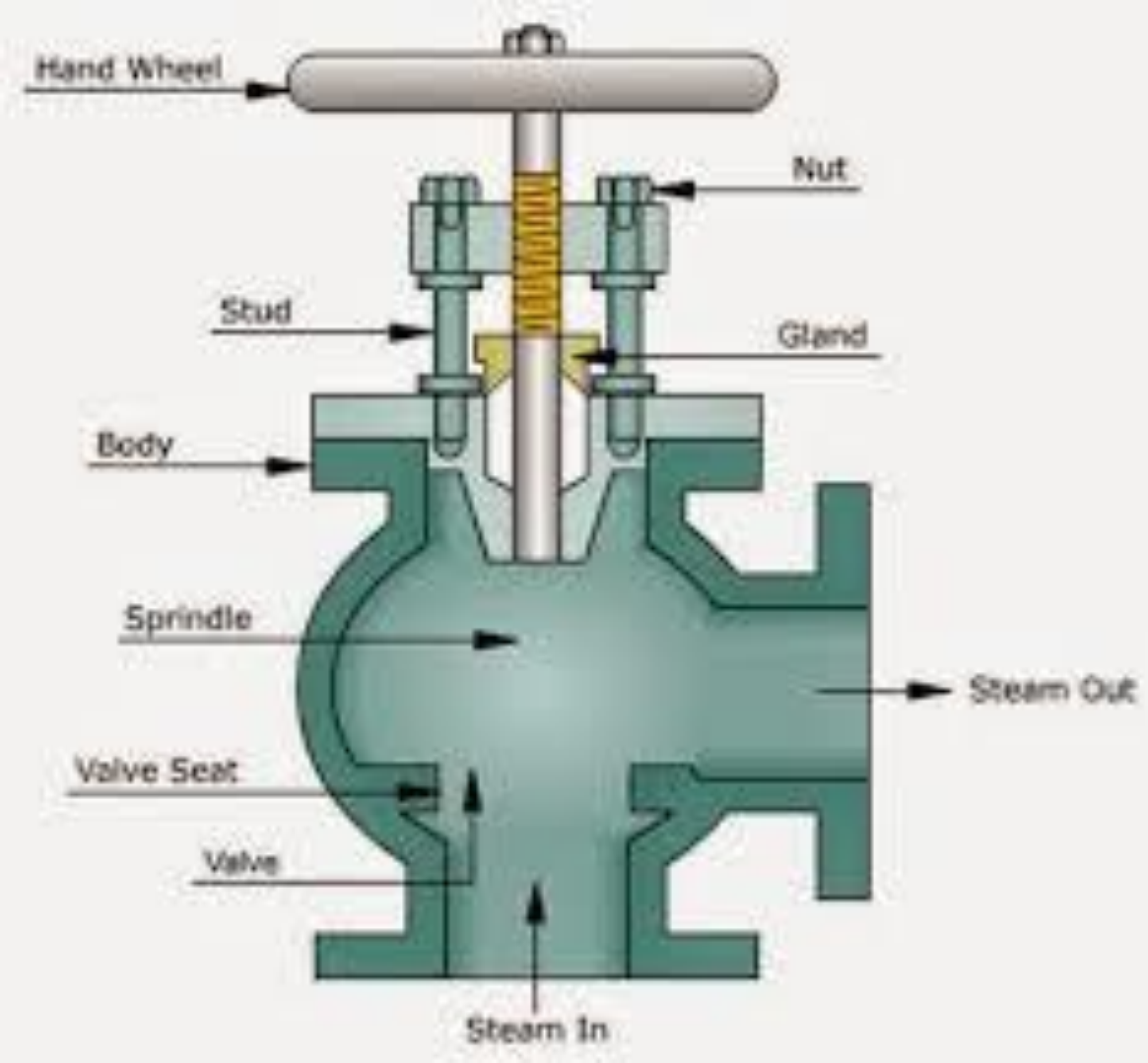
d) Siphon is filled with cold water to prevent the hot steam entering into the bourdon tube and spring tube remains comparatively cool.



Steam stop valve

- A valve is a device that regulates the flow of a fluid (gases , fluidized solids slurries or liquids) by opening or closing or partially obstructing various passageways
- Function : ***to shut off or regulate the flow of steam from the boiler to the steam pipe or steam from the steam pipe to the engine***

Steam stop valve



Feed check valve

- To allow the feed water to pass in to the boiler

- To prevent the back flow of water from the boiler in the event of the failure of the feed pump

Blow off cock

- To drain out water from the boiler for internal cleaning inspection or other purposes

Mud and man holes

- To allow men to enter in to the boiler for inspection and repair

Classification of Boiler

Criteria	Types
Content of Tube	Fire Tube Boiler, Water Tube Boiler
Type of firing	Solid, Liquid & Gas Fired
Type of Circulation	Natural Circulation, Natural Assisted or Controlled Circulation, Forced Circulation
Steam Pressure	Sub Critical Boiler, Super Critical Boiler
Draught	Natural Draught, Mechanized Draught(Forced, Induced, Balanced)

Classification of boilers

- Horizontal, vertical or inclined
- Fire tube and water tube
- Externally fired and internally fired
- Forced circulation and natural circulation
- High pressure and low pressure
- Stationary and portable
- Single tube and multi tube

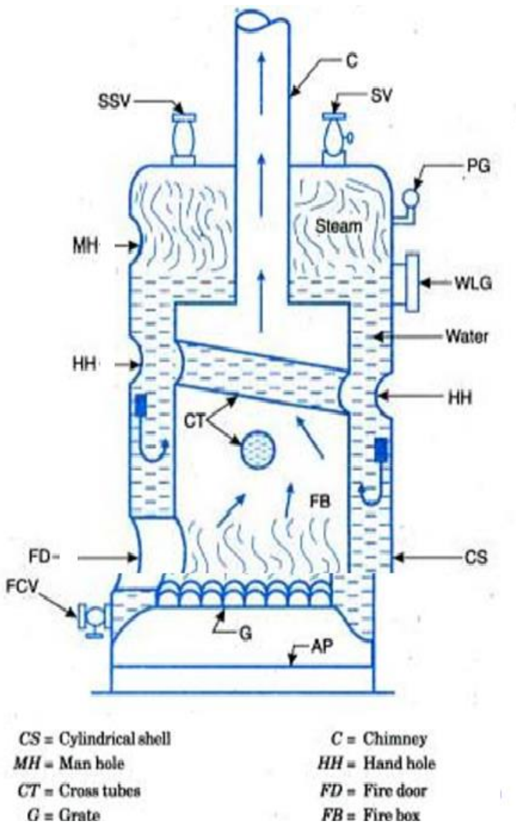
Horizontal, vertical or inclined

- According to geometric orientation of boiler..

- If the axis of the boiler is horizontal, vertical or inclined then it is called horizontal, vertical or inclined boiler respectively

Horizontal, vertical or inclined

Vertical Boiler



Horizontal Boiler

CONTENT OF TUBES

Fire Tube

- In fire tube boiler hot flue gas will be moved inside the tubes & water outside the tube.
- In fire tube boiler mode of firing is generally **internally fired**.
- In fire tube boiler operating pressure limited to 25 kg/cm²

Cochran, Lancashire and locomotive boilers

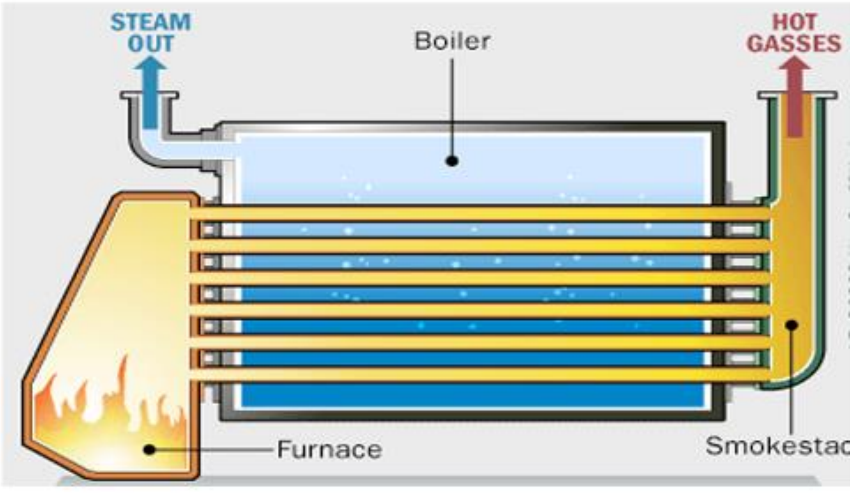
Water Tube

- In water tube boiler water will be moved inside the tube & hot flue gases outside the tubes.
- Mode of firing is **externally fired**.
- Operating pressure can exceed 125 kg/cm² or more

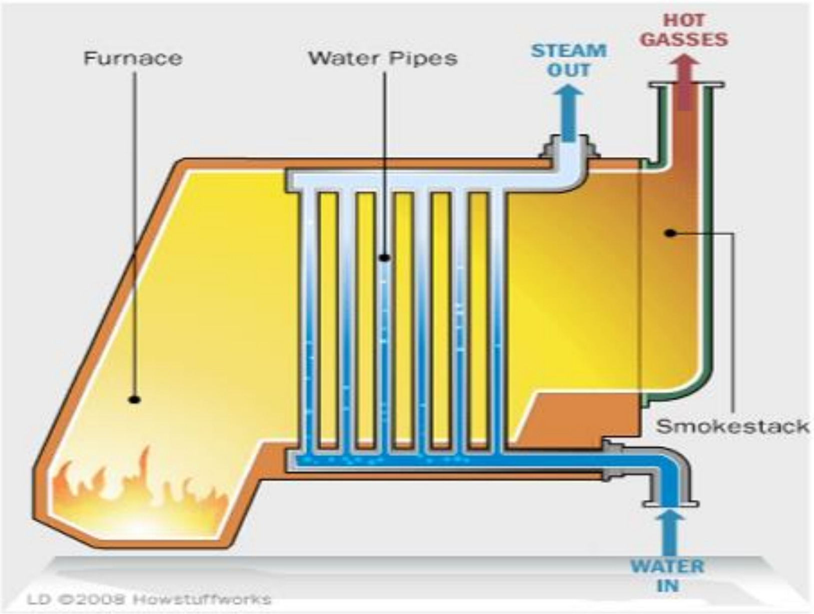
Babcock and Wilcox, Stirling, Yarrow boiler

Fire tube and water tube

Fire Tube Boiler



Water Tube Boiler



CONTENT OF TUBES

Externally fired

- The boiler is known as externally fired if the fire is outside the shell

internally fired

- The boiler is known as internally fired if the furnace is located inside the boiler shell.

TYPE OF CIRCULATION

Natural Circulation

- Density Difference is the driving force.
- Limited to boiler with drum operating pressure around 175 kg/cm^2(g).

Assisted/Controlled Circulation

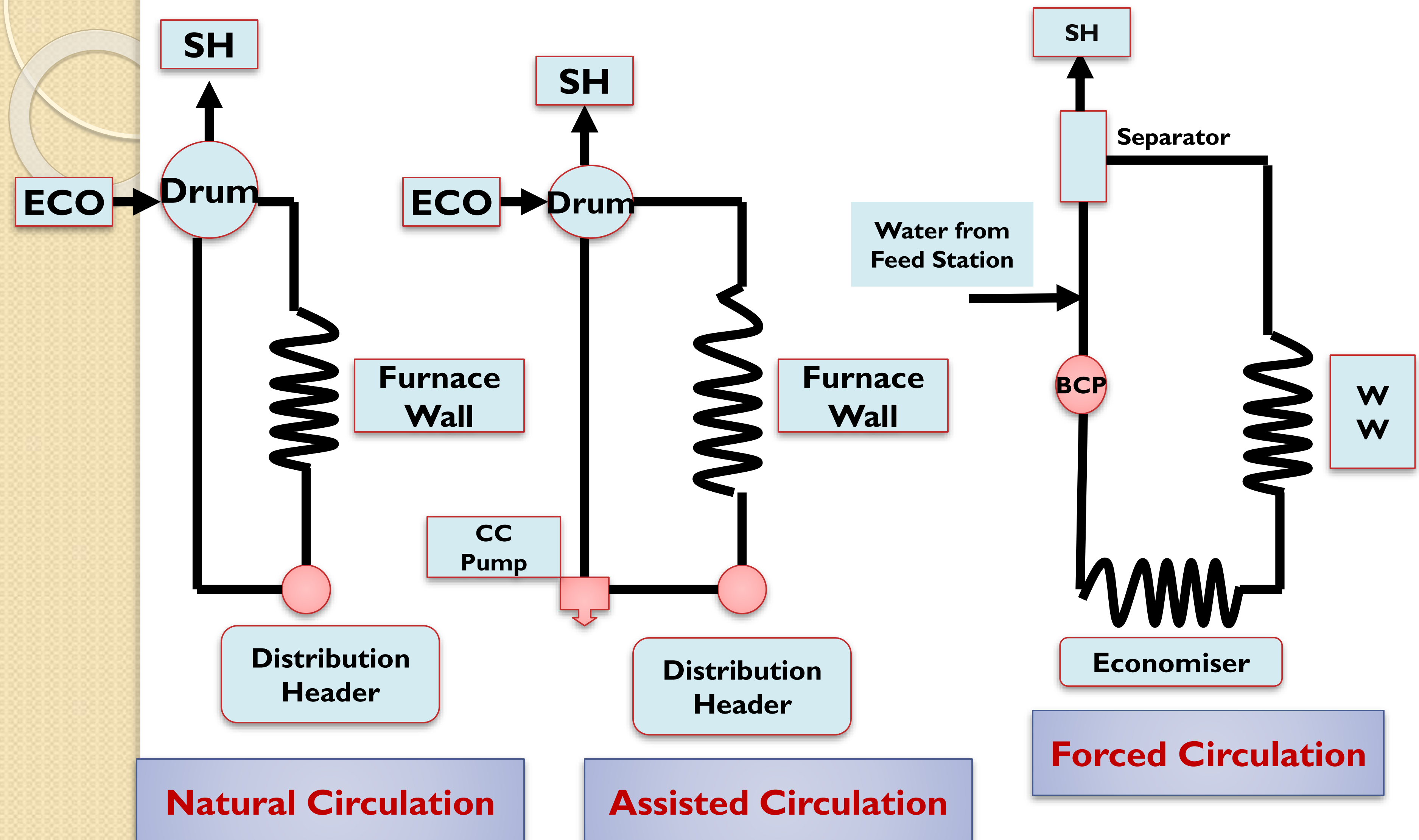
- Beyond 175 kg/cm^2(g) pressure in a re circulation system, circulation through the evaporator is to be assisted with mechanical pumps to overcome frictional losses in the tubes.
- A pump called **boiler circulation pump** will be placed in the down comer between the Drum & water wall ring header to do this function is called controlled circulation.

Forced Circulation

- Mechanical pumps are used to over come the frictional losses
- Operating pressure is above 224.6 kg/cm2(g)

Lancashire, Babcock and Wilcox

Velox, Lamont, Benson boiler



SH
ECO
Drum
Furnace Wall
Distribution Header
Natural Circulation
SH
ECO
Drum
CC Pump
Furnace Wall
Distribution Header
Assisted Circulation
SH
Separator
Water from Feed Station
BCP
W W
Economiser
Forced Circulation

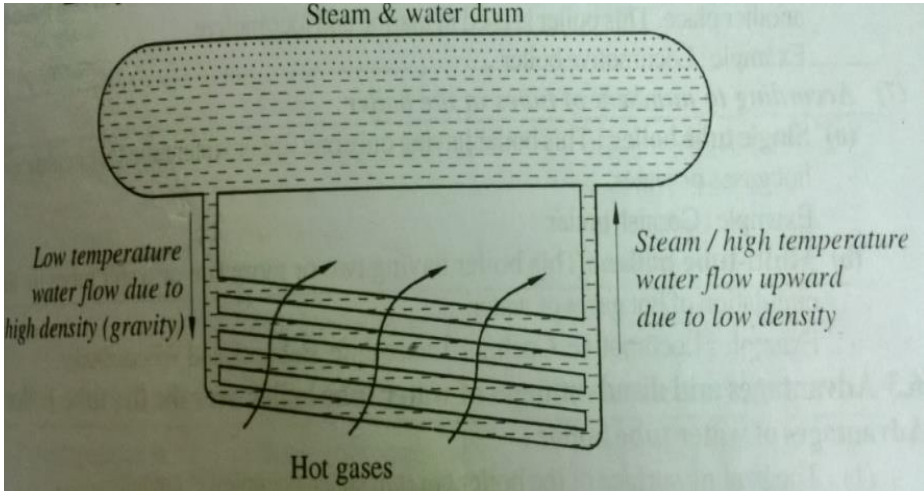
High Pressure & low Pressure Boilers

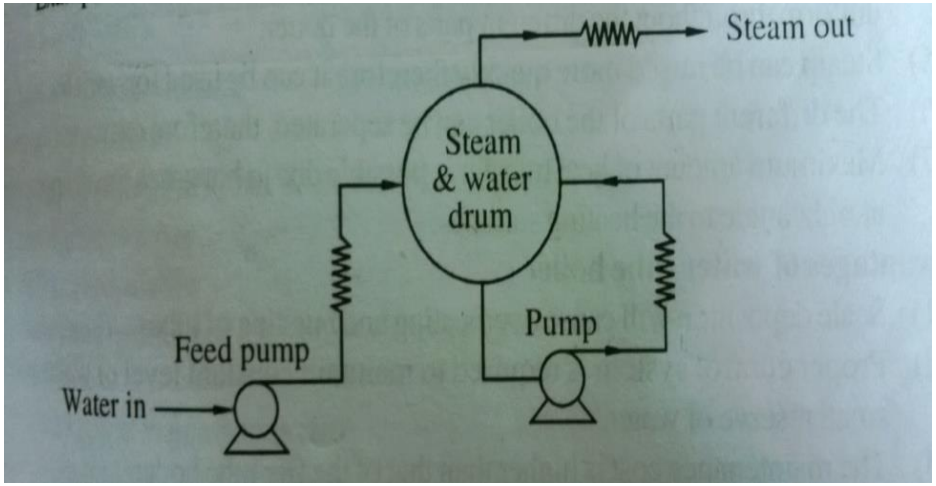
- The boilers which produce steam at pressure of 80 bar and above are called high pressure boiler. ex. Velox
- The boiler which produce steam at pressure below 80 bar are called low pressure boiler. ex. cochran

Forced circulation and natural circulation

Natural Circulation Boilers

Forced Circulation Boilers





STEAM PRESSURE

Sub Critical Boiler

- Boilers Operating below the Critical Pressure(224.6 kg/cm^2(g)).
- These are recirculation type or once through .
- Steam Drum is required to separate water & steam.

Super Critical Boiler

- Boilers Operating above Critical Pressure (224.6 kg/cm^2(g)) & Critical Temp (374 ^{0}C)
- These are only Once Through Type.
- Drum is not required as cycle medium is a single phase fluid having homogenous property.

Impact of critical point on the Boiling Process

- Beyond critical point of water, the latent heat of vaporization becomes zero and there is no distinction between liquid and vapor phase of water.

Absolute Pressure (Bar)	Saturation Temperature (°C)	Latent Heat (K J/Kg.)
50	264	1640
150	342	1004
200	366	592
221	374	0

Stationary and portable

- Stationary boilers are used for power plant-steam, for central station utility power plants, for plant process steam etc

- Mobile or portable boilers include locomotive type, and other small unit for temporary use at sites

Single tube and multi tube

- The fire tube boilers are classified as single tube or multi-tube boilers, depending upon whether the fire tube is one or more than one.

Examples of single tube boilers are Cornish and simple vertical boiler

DRAUGHT

Boiler draught is the pressure difference between the atmosphere and the pressure inside the boiler.

Draught is the pressure difference which is necessary to draw the required quantity of air for combustion and to remove the flue gases out of the system.

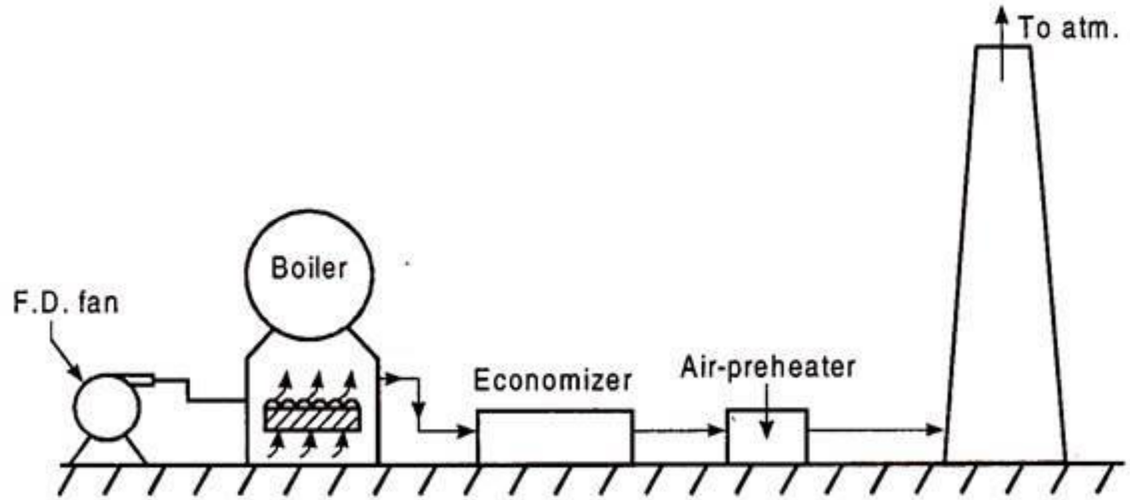
Thus the object of producing draught in a boiler is:

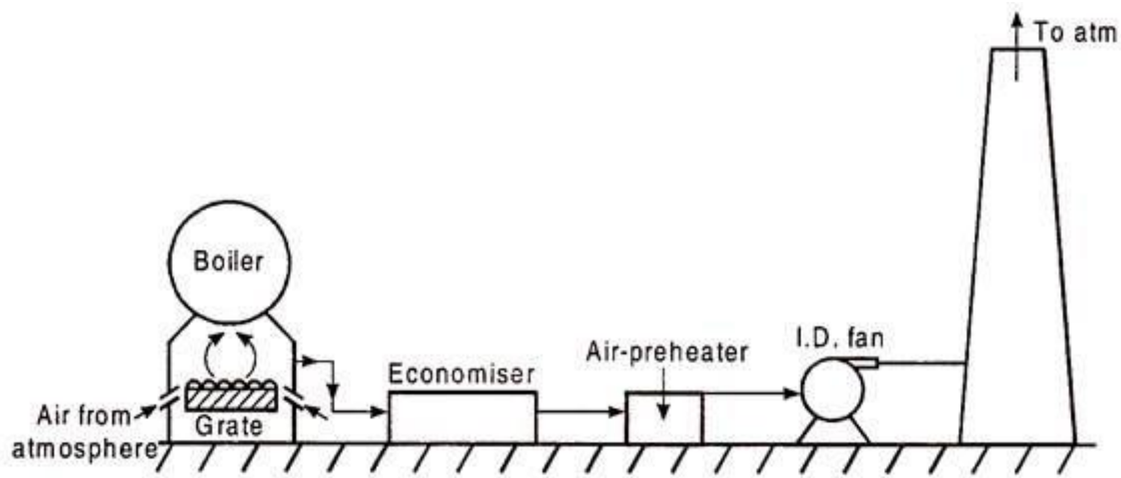
(i) To provide sufficient quantity of air for combustion

(ii) To make the resulting hot gases, to flow through the system

(iii) To discharge these gases to the atmosphere through the chimney.

Usually this drought (pressure difference) in boiler is of small magnitude and is measured in mm of water column by means of draught gauge/manometer.


To atm.
Boiler
F.D. fan
Economizer
Air-preheater


To atm.
Boiler
I.D. fan
Air-preheater
Economiser
Air from
atmosphere
Grate

DRAUGHT

Natural Draught

The draught required for the flow of air & gas inside the boiler is created by chimney alone

Mechanized Draught

Forced

- Fans are used to draw air from atmosphere & push into the furnace.
- The entire boiler will be kept above atmospheric pressure

Induced

- Fans installed at the outlet of boiler, evacuate the gases from furnace. So a negative Pressure is developed in furnace & air from atmosphere enters the furnace

Balanced

Both Forced & Induced draught fans are used to derive the benefits of both systems.

Comparison of fire tube and water tube boilers

Particulars	Fire-tube boilers	Water-tube boilers
Position of water and hot gases	Hot gases inside the tubes and water outside the tubes	Water inside the tubes and hot gases outside the tubes
Mode of firing	Generally internally fired	Externally fired
Operation pressure	Limited to 16 bar	Can go up to 100 bar
Rate of steam production	Lower	Higher
Suitability	Not suitable for large power plants	Suitable for large power plants
Risk on bursting	Involves lesser risk of explosion due to lower pressure	More risk on bursting due to high pressure
Floor area	For a given power it occupies more floor area	For a given power it occupies less floor area
Construction	Difficult	Simple

Fluidized Bed (FBC) Boiler

An Overview-

•Fluidized bed combustion has emerged as a viable alternative and has significant advantages over conventional firing system and offers multiple benefits –

- compact boiler design,
- fuel flexibility,
- higher combustion efficiency and
- reduced emission of noxious pollutants such as SOx and NOx.

The fuels burnt in these boilers include coal, washery rejects, rice husk, bagasse & other agricultural wastes. The fluidized bed boilers have a wide capacity range.

Mechanism of Fluidised Bed Combustion

- When an evenly distributed air or gas is passed upward through a finely divided bed of solid particles such as sand supported on a fine mesh, **the particles are undisturbed at low velocity**.
- As air velocity is gradually increased, a stage is reached when the individual particles are suspended in the air stream – the bed is called "**fluidized**".

- With further increase in air velocity, there is **bubble formation**, **vigorous turbulence**, **rapid mixing** and **formation of dense defined bed surface**.
- The bed of solid particles exhibits the properties of a boiling liquid and assumes the appearance of a fluid – **"bubbling fluidized bed"**.

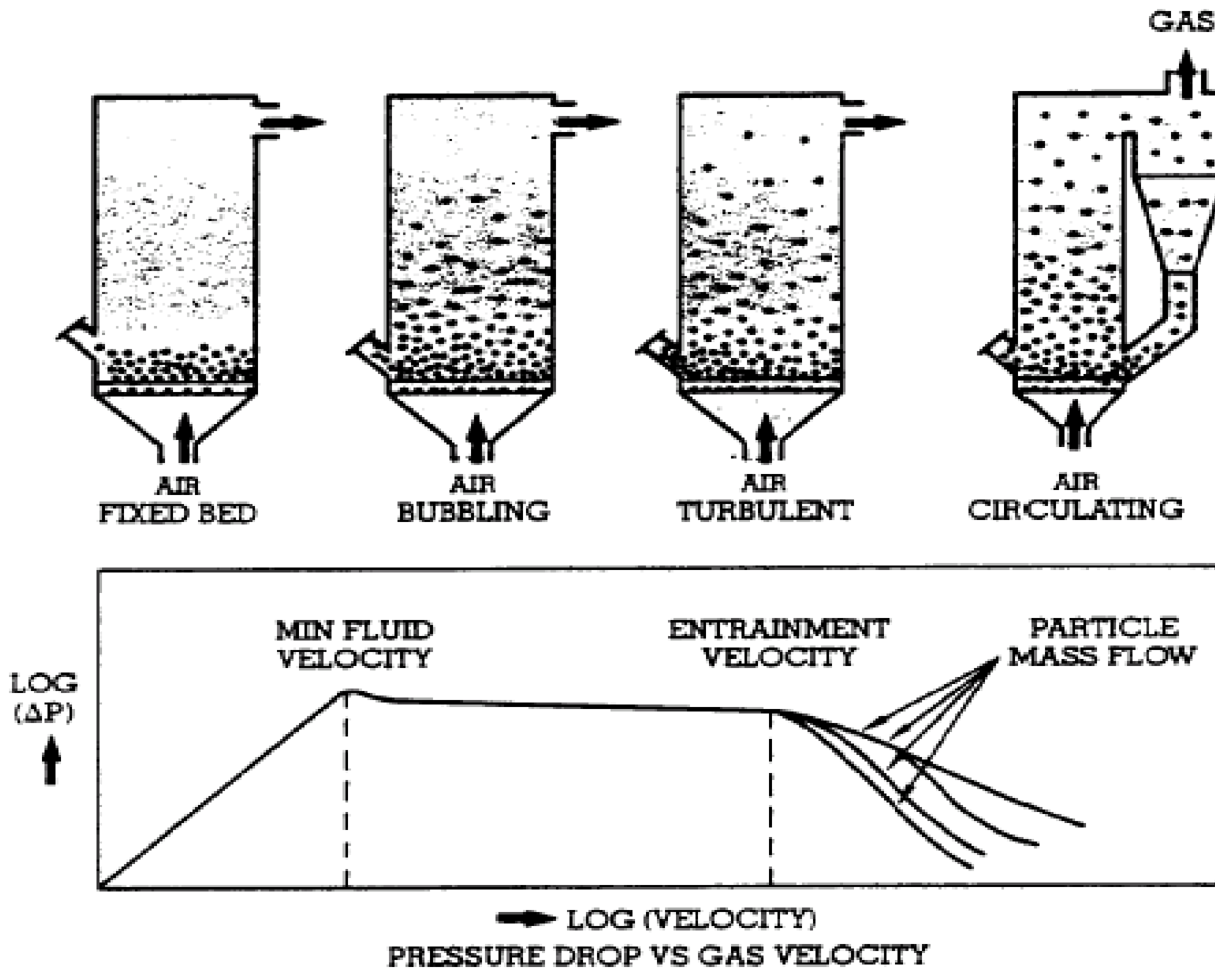
- At higher velocities, bubbles disappear, and particles are blown out of the bed. Therefore, some amounts of particles have to be recirculated to maintain a stable system – **"circulating fluidised bed".**

- Fluidization depends largely on the particle size and the air velocity.

- If sand particles in a fluidized state is heated to the ignition temperatures of coal, and coal is injected continuously into the bed, the coal will burn rapidly and bed attains a uniform temperature.
- The fluidized bed combustion (FBC) takes place at about 840^{O}C to 950^{O}C.

- ➢Since this temperature is much below the ash fusion temperature, melting of ash and associated problems are avoided.
- ➢The lower combustion temperature is achieved because of
    - ✓High coefficient of heat transfer due to rapid mixing in the fluidized bed and
    - ✓effective extraction of heat from the bed through in-bed heat transfer tubes and walls of the bed.
- ➢The gas velocity is maintained between minimum fluidisation velocity and particle entrainment velocity. This ensures stable operation of the bed and avoids particle entrainment in the gas stream.

- •Combustion process requires the three "T"s that is Time, Temperature and Turbulence. In FBC,
- •turbulence is promoted by fluidization. Improved mixing generates evenly distributed heat at lower temperature.
- •Residence time is many times greater than conventional grate firing.
- •Thus an FBC system releases heat more efficiently at lower temperatures.



principle of fluidisation

Fixing, bubbling and fast fluidized beds

As the velocity of a gas flowing through a bed of particles increases, a value is reaches when the bed fluidizes and bubbles form as in a boiling liquid. At higher velocities the bubbles disappear; and the solids are rapidly blown out of the bed and must be recycled to maintain a stable system.

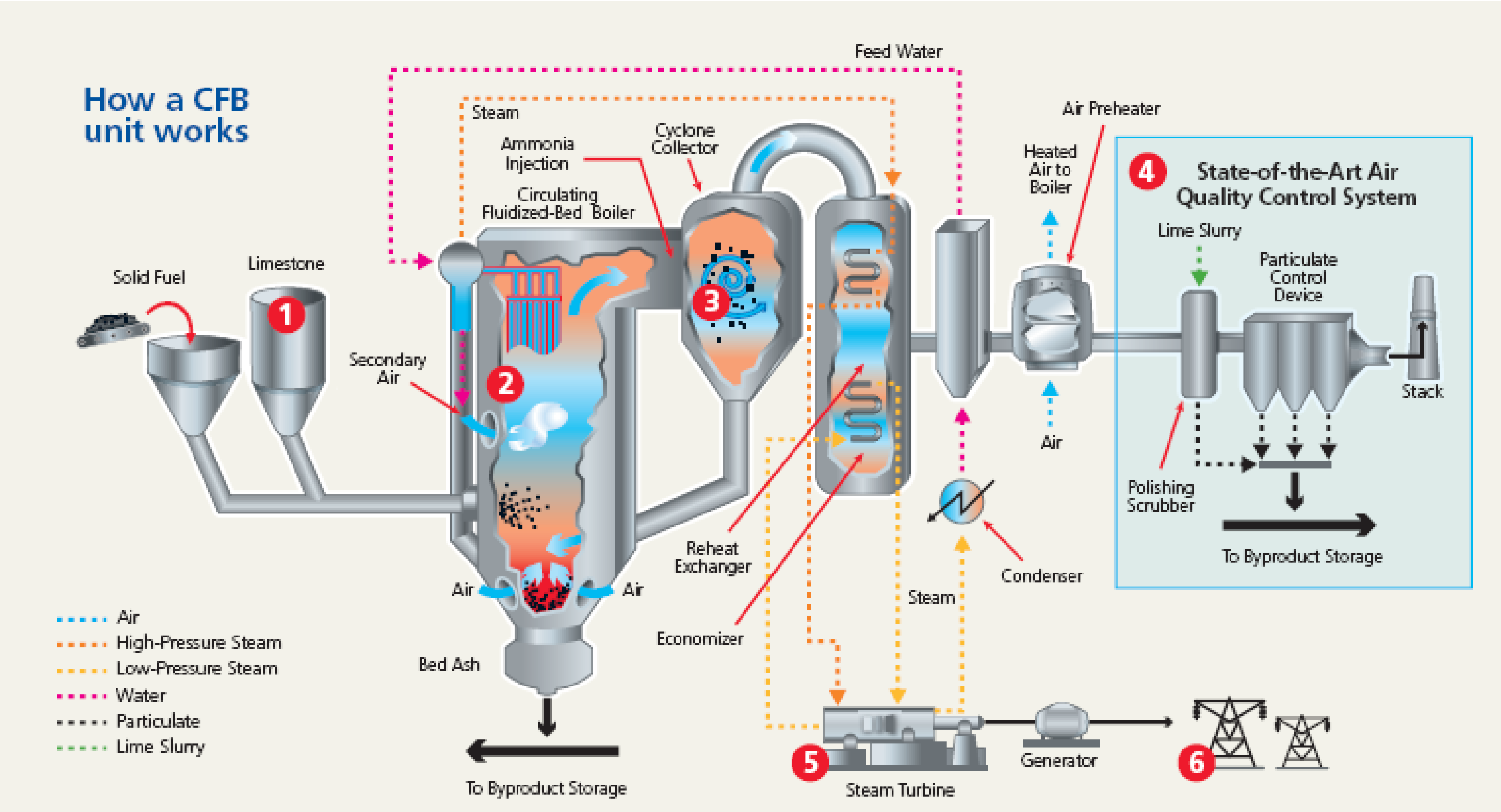
•Since limestone is used as particle bed, control of sulfur dioxide and nitrogen oxide emissions in the combustion chamber is achieved without any additional control equipment. This is one of the major advantages over conventional boilers.

Types of Fluidised Bed Combustion Boilers

There are three basic types of fluidised bed combustion boilers:

1. Atmospheric Fluidised Bed Combustion System (AFBC)
2. Pressurised Fluidised Bed Combustion System (PFBC).
3. Circulating (fast) Fluidised Bed Combustion system(CFBC)

Circulating Fluidized-Bed (CFB) Boiler



1. Fuel Input

Fuel and limestone are fed into the combustion chamber of the boiler while air (primary and secondary) is blown in to "fluidize" the mixture. The fluidized mixture burns at a relatively low temperature and produces heat. The limestone absorbs sulfur dioxide (SO_2), and the low-burning temperature limits the formation of nitrogen oxide (NO_x) – two gases associated with the combustion of solid fuels.

2. CFB Boiler

Heat from the combustion process boils the water in the water tubes turning it into high-energy steam. Ammonia is injected into the boiler outlet to further reduce NO_x emissions.

3. Cyclone Collector

The cyclone is used to return ash and unburned fuel to the combustion chamber for re-burning, making the process more efficient.

4. State-of-the-Art Air Quality Control System

After combustion, lime is injected into the "polishing scrubber" to capture more of the SO_2. A "baghouse" (particulate control device) collects dust particles (particulate matter) that escape during the combustion process.

5. Steam Turbine

The high-pressure steam spins the turbine connected to the generator, which converts mechanical energy into electricity.

6. Transmission Lines

The electricity produced from the steam turbine/generator is routed through substations along transmission lines and delivered to distribution systems for customer use.

CLECO

TYPE OF FIRING

- Solid
  - AFBC
  - CFBC
  - PC Fired
- Liquid
- Gas
  - WHRB

AFBC – Atmospheric Fluidized Bed Combustion

- Bed Material Used – Crushed Refractory(+ 0.8 mm to -2.8 mm)
- Velocity – 3-5 m/sec
- Coal – F-Grade, Washery Reject
- Combustion Eff- 80-85%

CFBC – Circulating Fluidized Bed Combustion

- Bed Material Used - Crushed Refractory (+ 0.8 mm to -2.8 mm)
- Velocity – 7-8 m/s.
- Coal – F-Grade, Washery Reject
- Combustion Eff.- 95 %

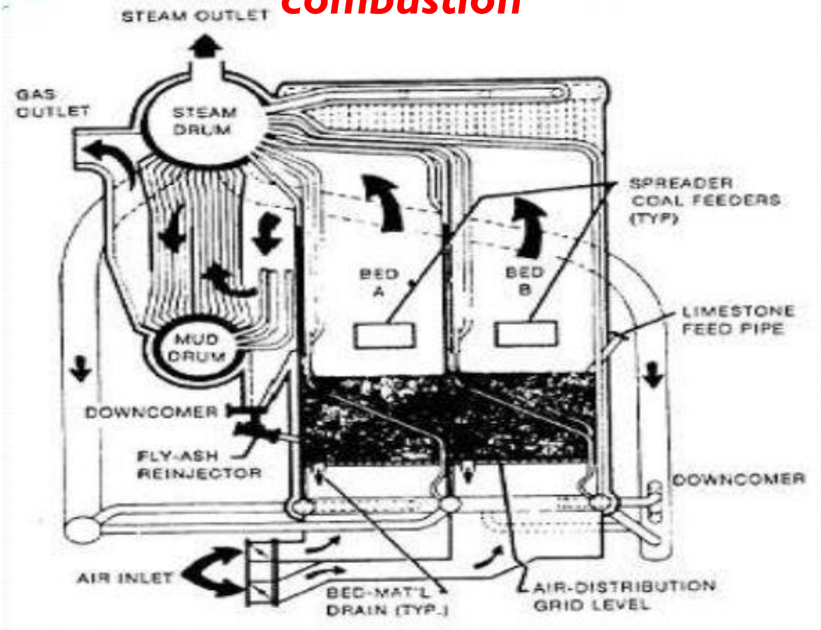
PC Fired – Pulverized Coal Fired Boiler.

- Coal:F Grade(3000-3500 Kcal/Kg) Size is 65µto 80µ.
- No Bed is Required
- Combustion Eff : 99 %

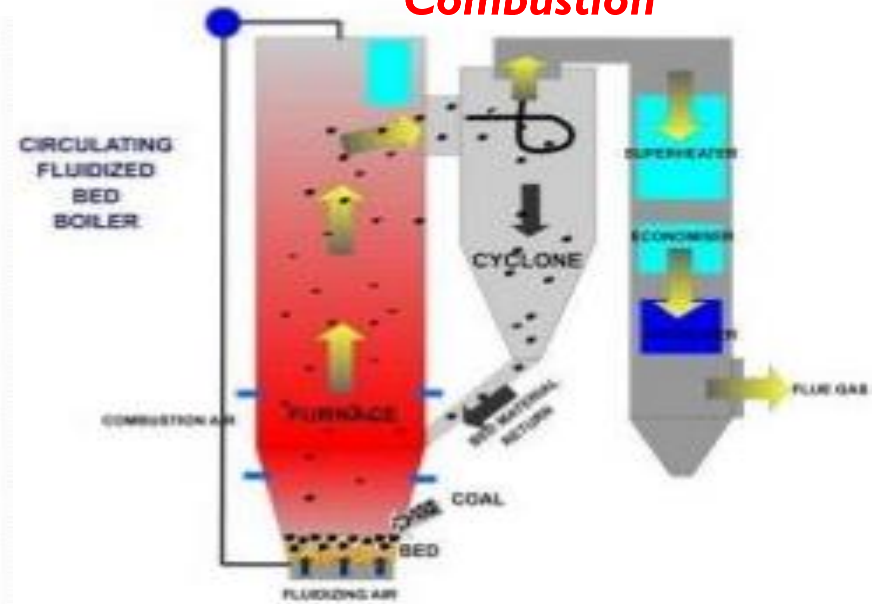
WHRB – Waste Heat Recovery Boiler

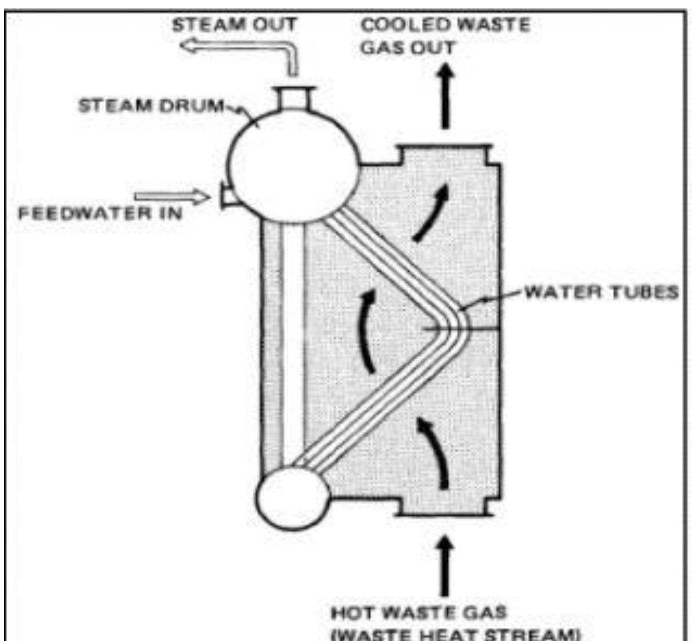
- Waste Heat from Flue Gas of Other process used in boiler for Steam generation

Atmospheric fluidised bed combustion

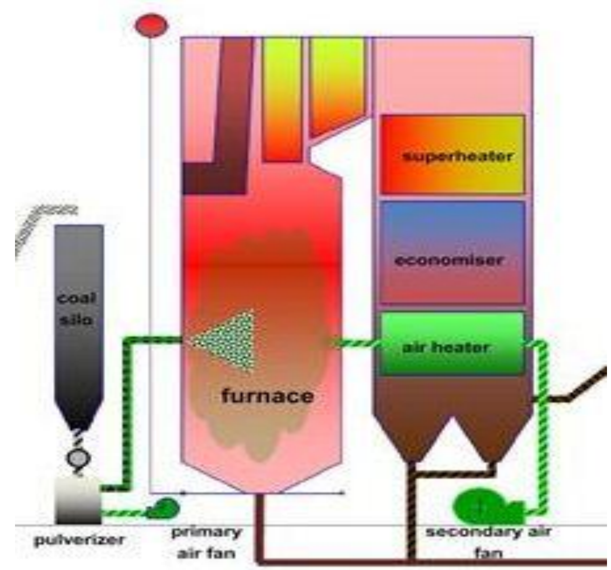


Circulating Fluidized Bed Combustion





Pulverized coal-fired



Lancashire boiler

- Reliable, has simplicity of design, ease of operation and less operating and maintenance costs
- It is one of the most commonly used stationary boilers
- It is normally used in sugar mills, textile industries where **power generation** as well as **process heating** is required..

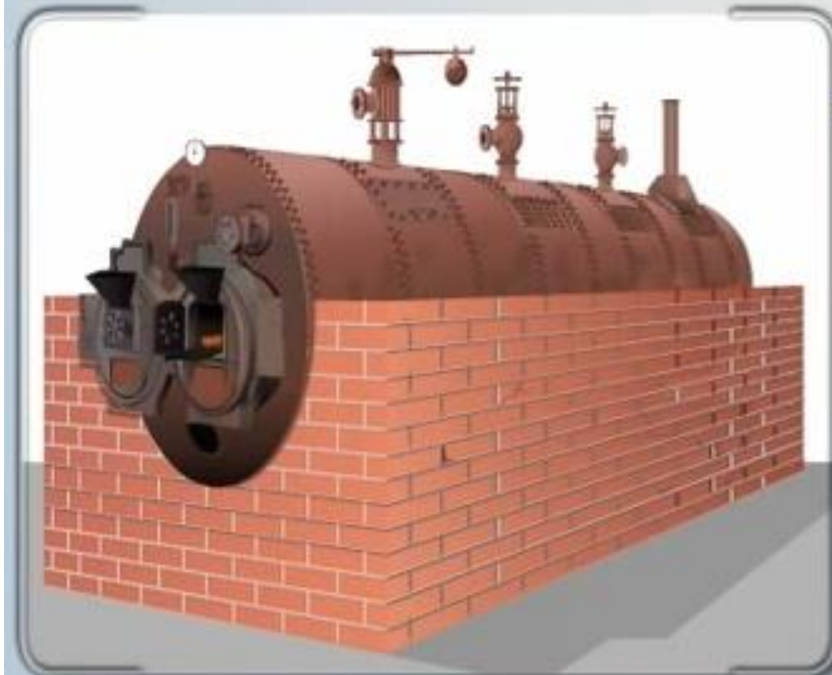
Lancashire boiler

characteristics

- ➢ Horizontal
- ➢ Multi Tubes
- ➢ Fire Tube
- ➢ Internally Fired
- ➢ Natural circulated Boiler

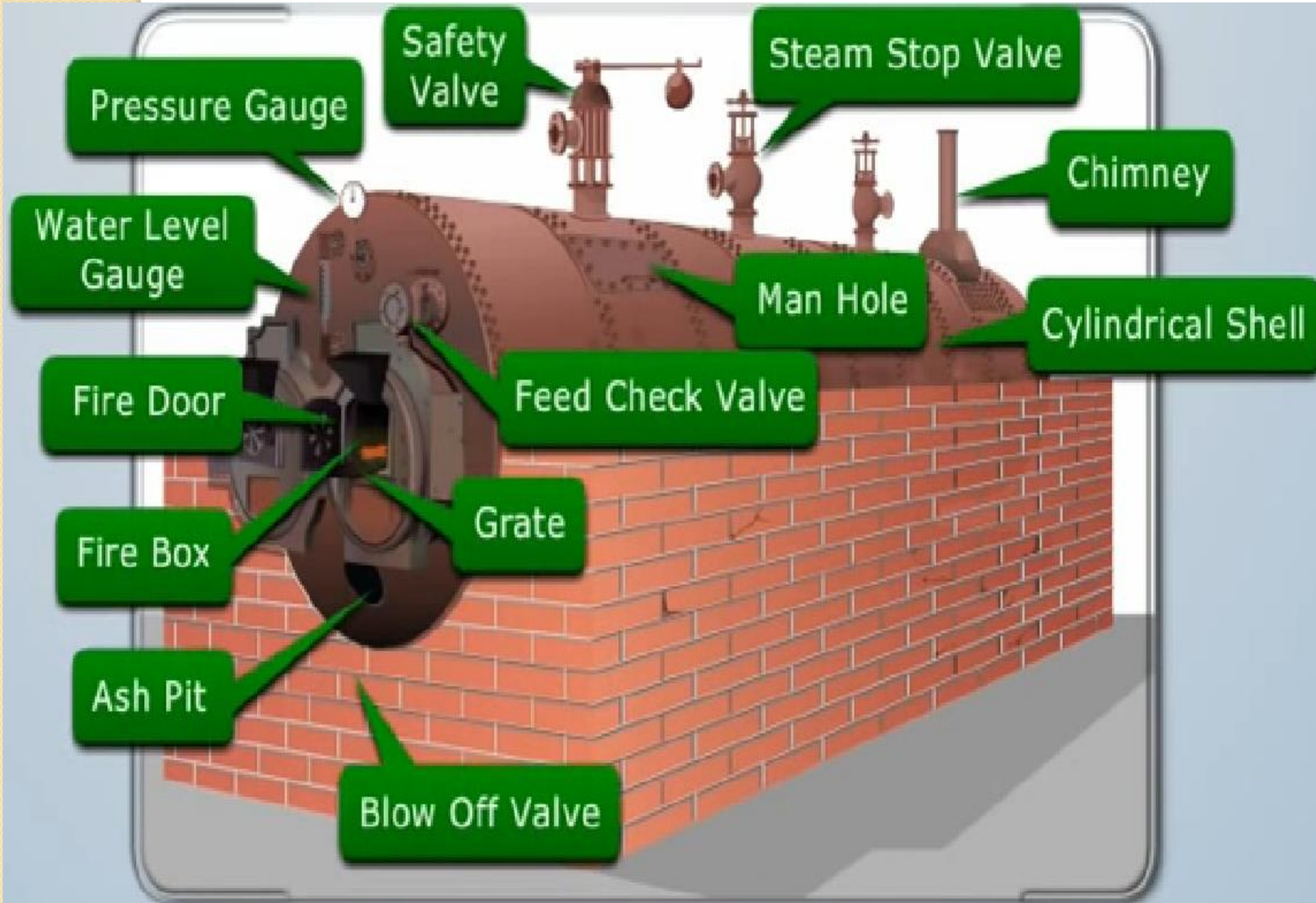
Specification

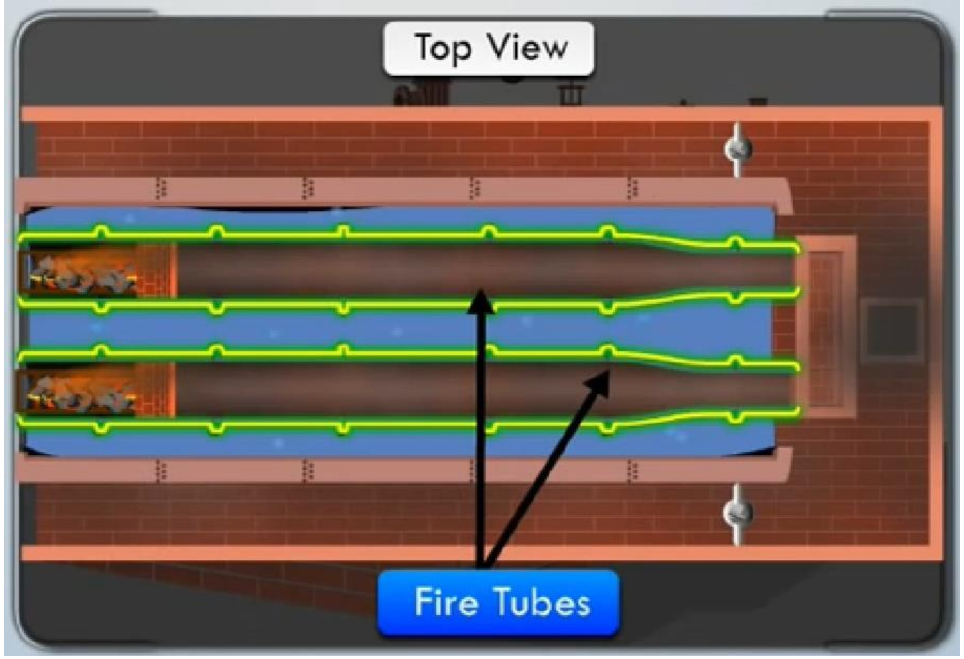
- ➢ Working Pressure: 16 bar maximum.
- ➢ Steam capacity : 9000 kg/hr.
- ➢ Efficiency 50% to 70%.

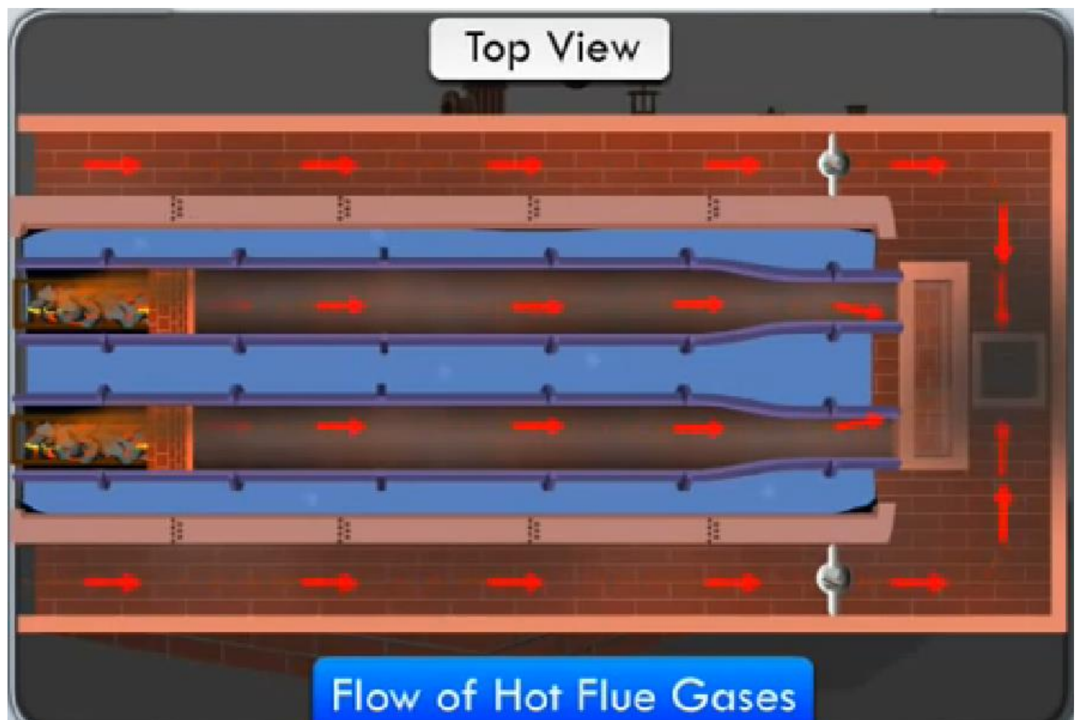


Important Features	Details
Boiler Type	Stationary, Horizontal, Low Pressure, Internally Fired, Fire Tube Boiler, Natural Circulation
Pressure Range	16 bar (maximum)
Steam Production Rate	9000 kg/hr
Efficiency	50% to 70% (depending upon fuel type)
Boiler Specification	Diameter of shell- 2 - 3m Length of Shell- 7 -9m

Lancashire Boiler is a **Low Pressure, Internally Fired, Stationary Fire Tube Boiler** with **Natural Circulation.**


Safety Valve
Steam Stop Valve
Pressure Gauge
Chimney
Water Level Gauge
Man Hole
Cylindrical Shell
Fire Door
Feed Check Valve
Grate
Fire Box
Ash Pit
Blow Off Valve


Top View
Fire Tubes


Top View
Flow of Hot Flue Gases

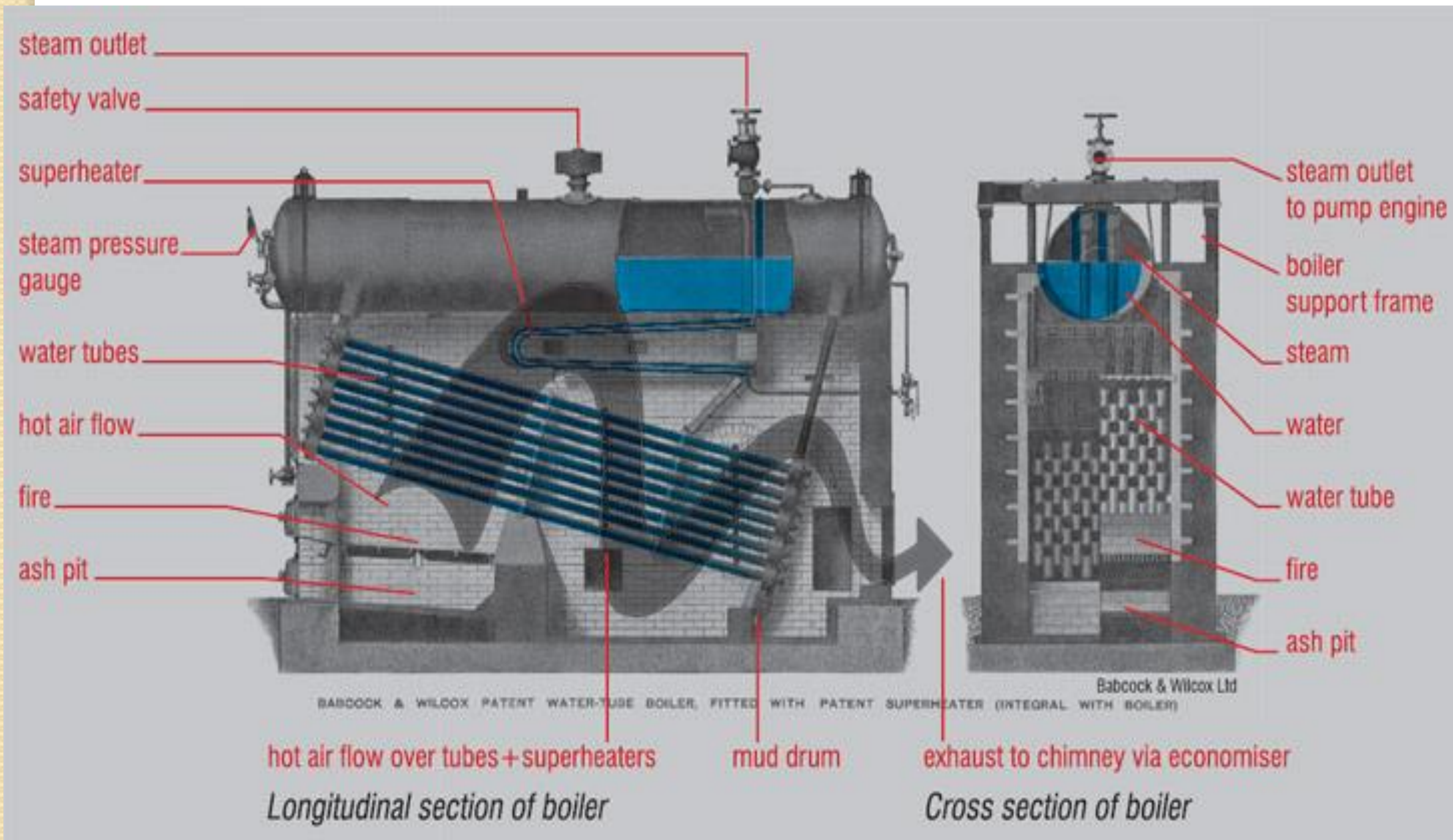
Cont…

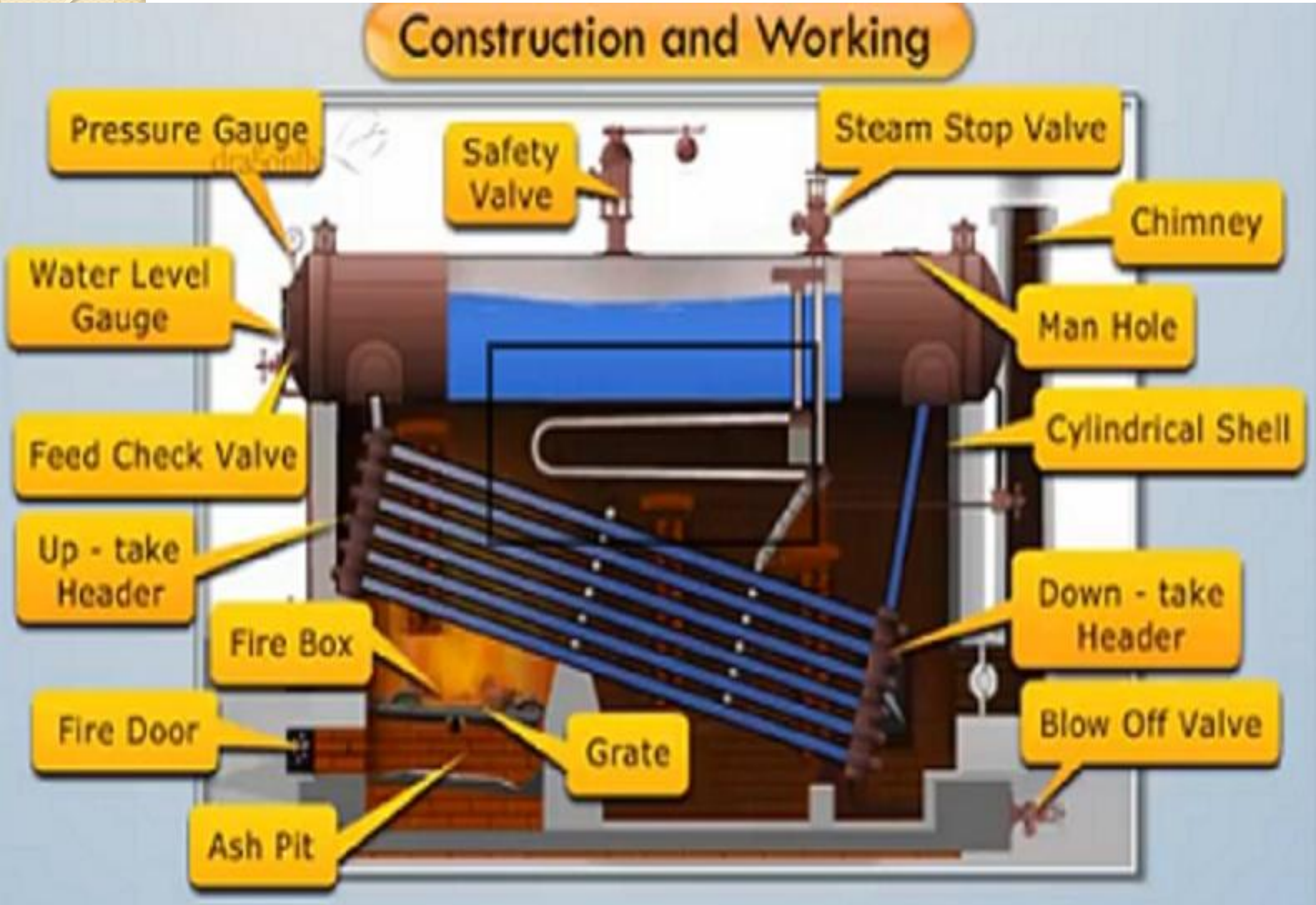
- Consists of cylindrical shell inside which two large tubes are spaced

- Shell is constructed with several rings of cylindrical from it is placed horizontally over a brick work which forms several channels for the flow of hot gases

- The furnace is placed at the front end of each tube

Babcock and Wilcox boiler




Construction and Working
Pressure Gauge
Safety Valve
Steam Stop Valve
Chimney
Water Level Gauge
Man Hole
Feed Check Valve
Cylindrical Shell
Up - take Header
Down - take Header
Fire Box
Fire Door
Grate
Blow Off Valve
Ash Pit

Babcock and Wilcox boiler

Characteristics of Boiler

- Horizontal
- Multi Tubes
- Water tube
- Externally Fired
- Natural circulation of water
- Forced circulation of air and hot gases
- Solid as well as liquid fuel fired

Specification of Boiler

- Working Pressure: 40 bar maximum.
- Steam capacity : 40,000 kg/hr.
- Efficiency 60% to 80%.

Cont…

- It consists of a drum connected to a series of front end and rear end header by short riser tubes

- To these headers are connected a series of inclined (15^0 or more) water tubes

- A hand hole is provided in the header in front of each tube for cleaning and inspection of tubes

Cont…

- Feed valve is provided to fill the drum and inclined tubes with water
- Through the fire door fuel is supplied to grate where it is burnt
- The hot gases are forced to move upwards between the tubes by baffle plates
- The water from the drums flows through the inclined tubes via down take header and goes back into the shell in the form of water and steam via uptake header

Cochran boiler

- One of the best types of vertical multi-tube boiler
- Consists of a cylindrical shell with a dome shaped top where the space is provided for steam
- The furnace is one piece construction and is seamless

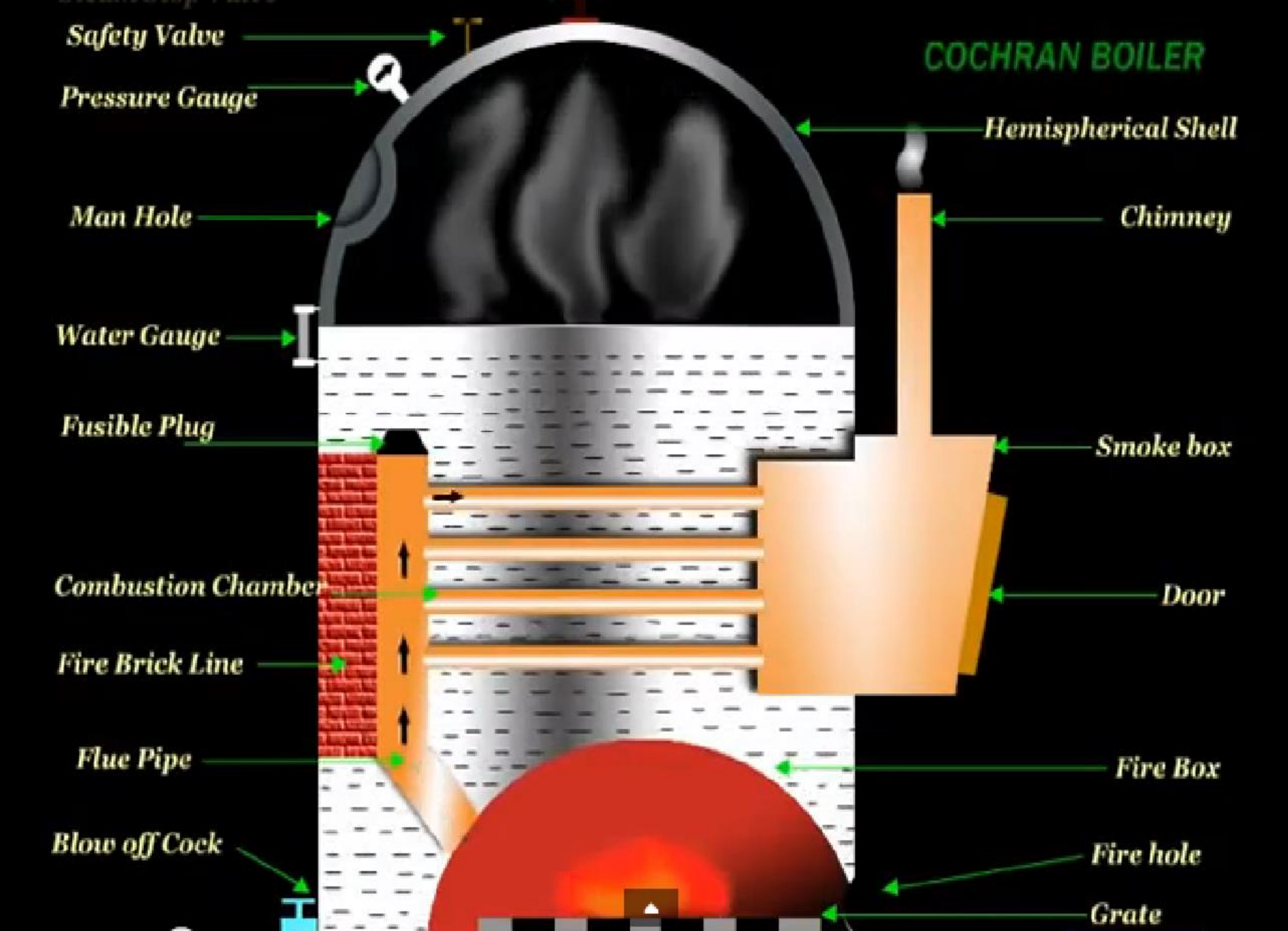
Cont..

- Its crown has a hemispherical shape and thus provides maximum volume of space
- The fuel is burnt on the grate and ash is collected and disposed from the ash pit
- The gases of combustion produced by burning the fuel enter the combustion chamber through the flue tube

- They strike against fire brick lining which directs them to pass through number of horizontal tubes, being surrounded by water

- After which the gases escape to the atmosphere through the smoke box and chimney

- A number of hand holes are provided around the outer shell for cleaning purposes


COCHRAN BOILER
Safety Valve
Pressure Gauge
Hemispherical Shell
Man Hole
Chimney
Water Gauge
Fusible Plug
Smoke box
Combustion Chamber
Door
Fire Brick Line
Flue Pipe
Fire Box
Blow off Cock
Fire hole
Grate

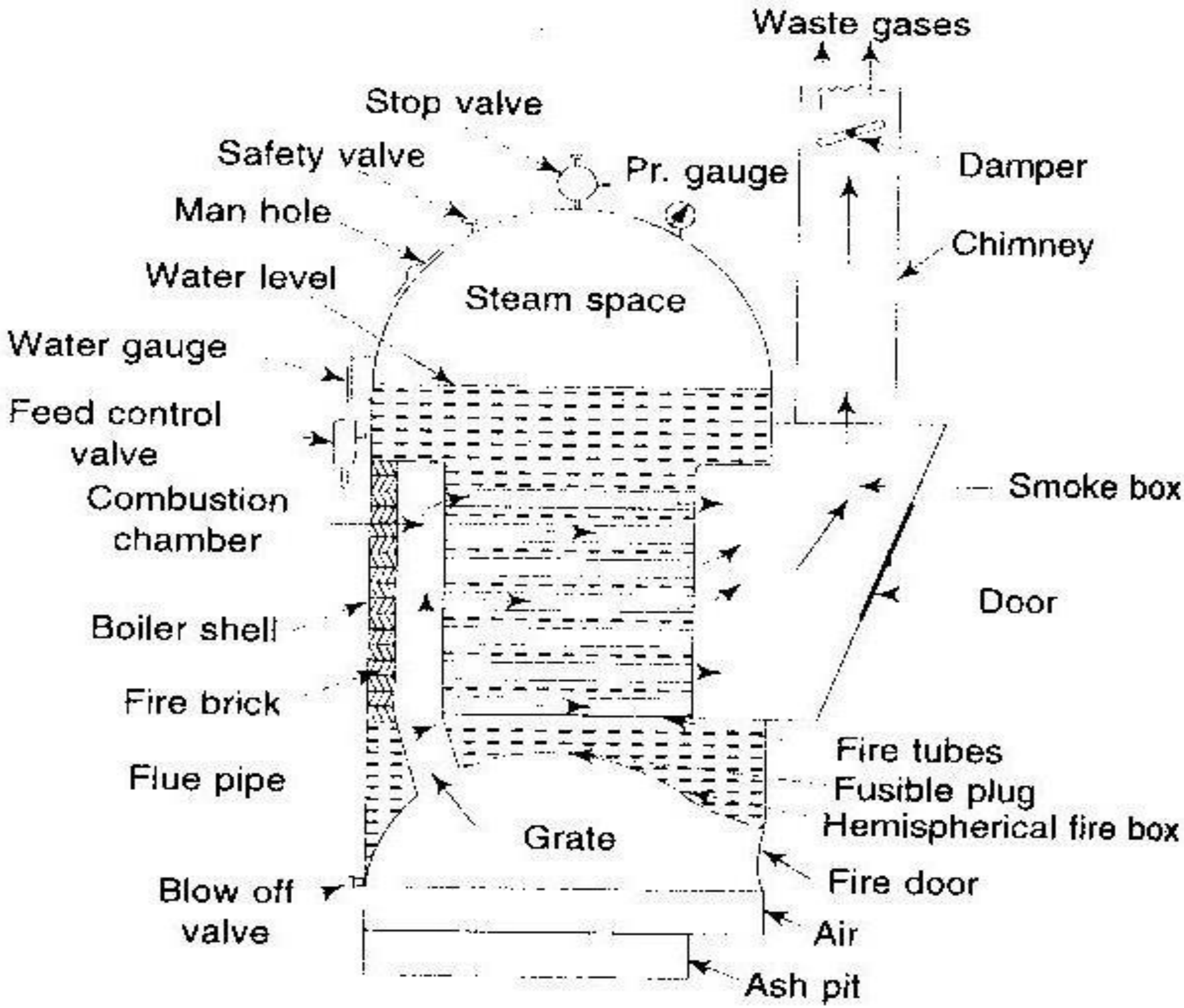
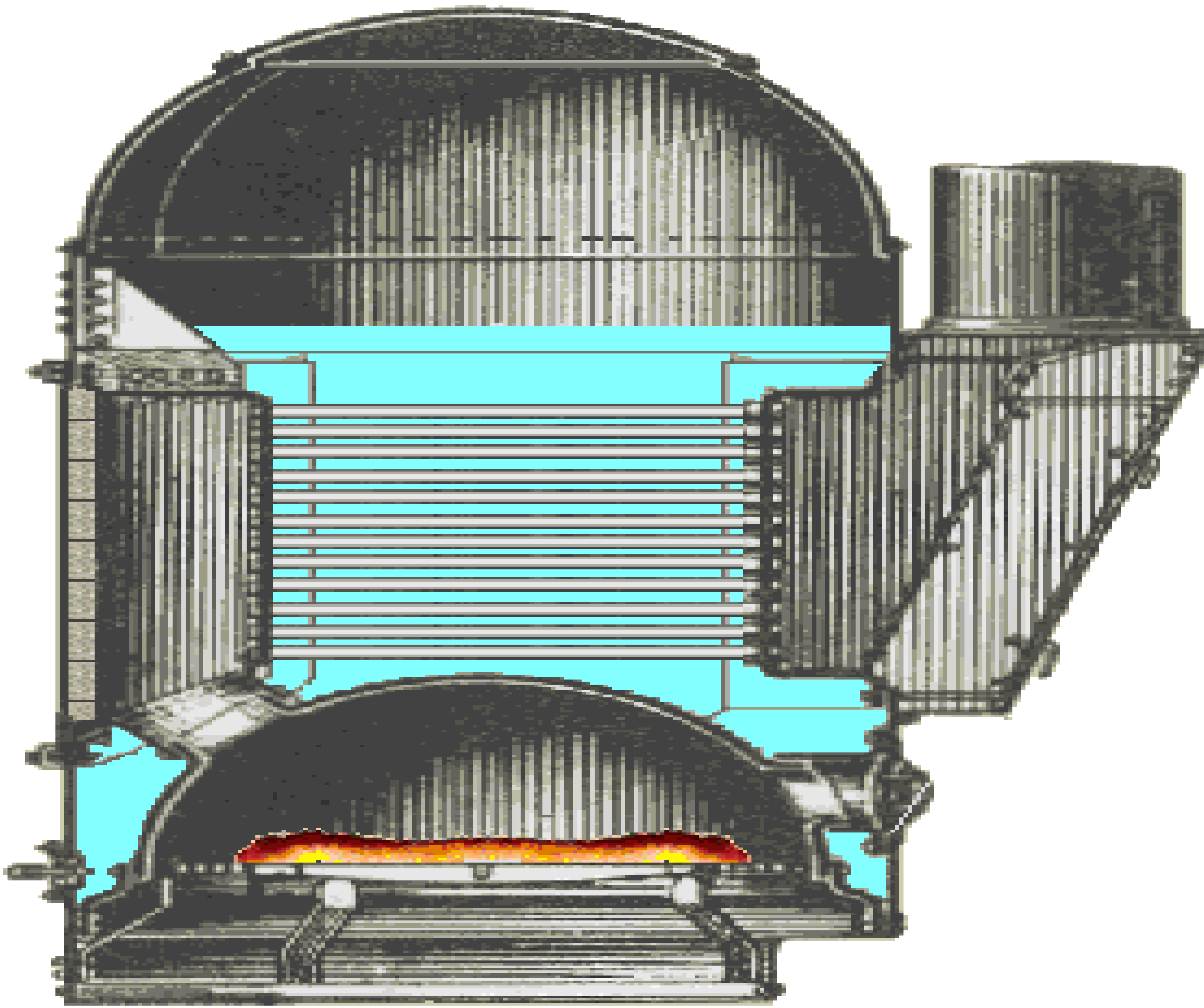


Fig. 15.1 *Cochran boiler*



Performance of a boiler

1. Boiler Performance
2. Boiler blow down
3. Boiler feed water treatment

Performance of a Boiler

1. Boiler performance

- **Causes of poor boiler performance**
  - **-Poor combustion**
  - **-Heat transfer surface fouling**
  - **-Poor operation and maintenance**
  - **-Deteriorating fuel and water quality**

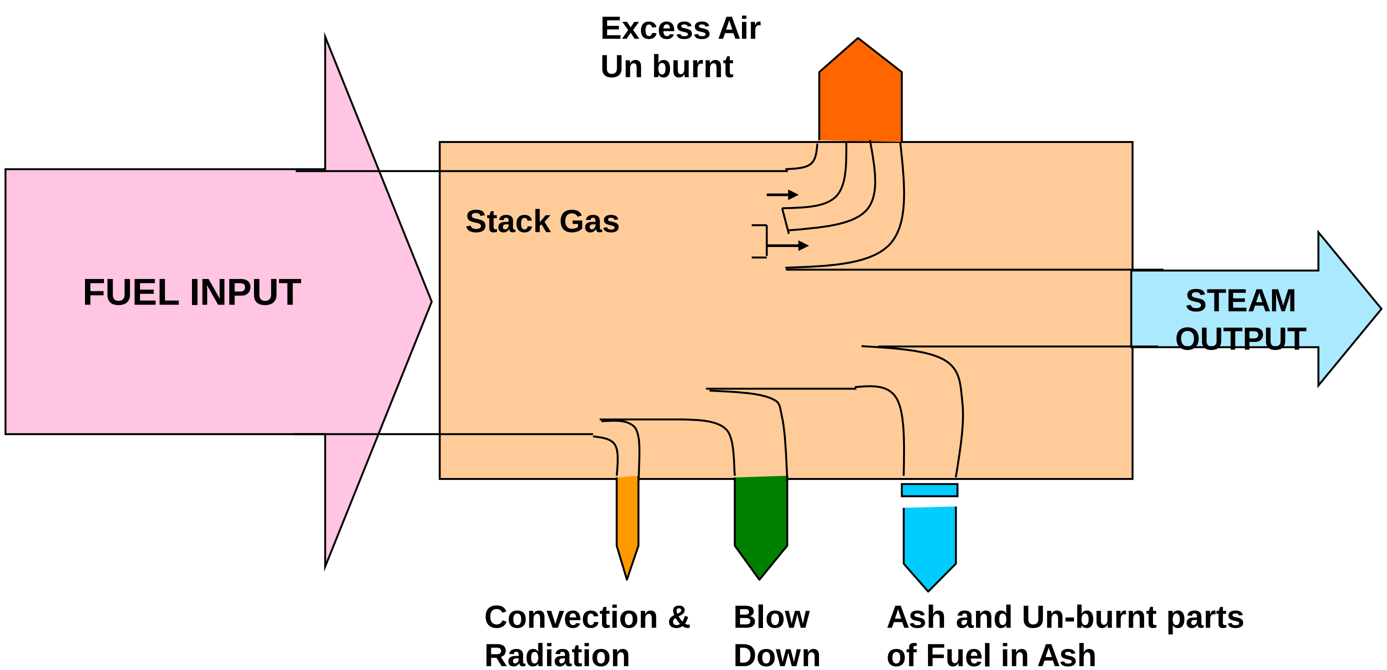
✓ **Heat balance: identify heat losses**

✓ **Boiler efficiency: determine deviation from best efficiency**

Performance of a Boiler

Heat Balance

An energy flow diagram describes geographically how energy is transformed from fuel into useful energy, heat and losses

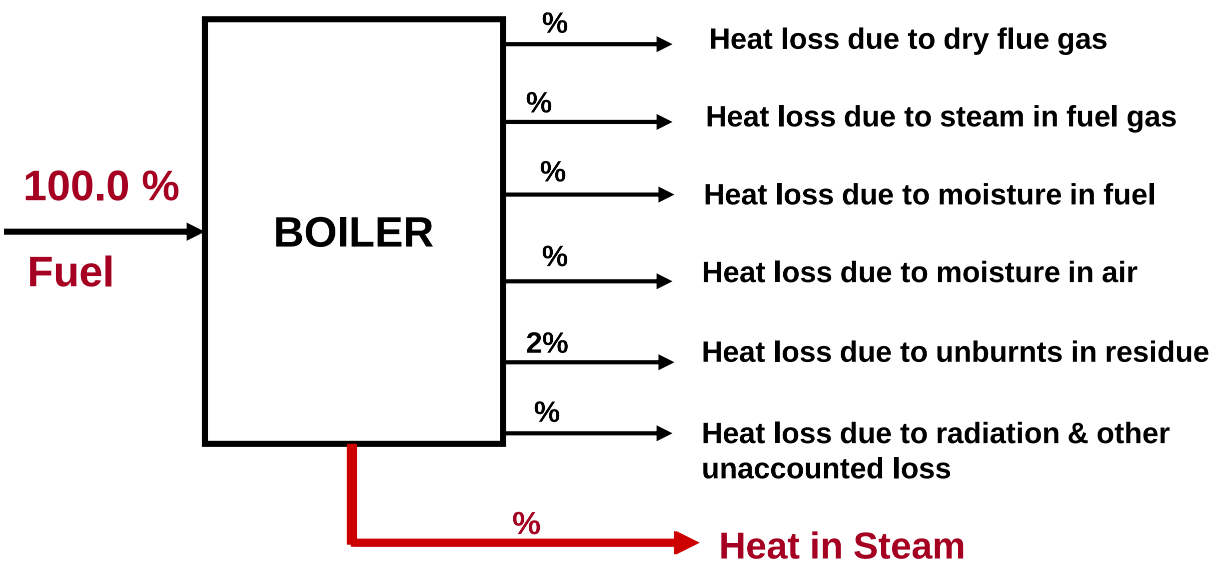


Performance of a Boiler

Heat Balance

Balancing total energy entering a boiler against the energy that leaves the boiler in different forms

Does anyone have any suggestions of what the two major heat losses are?



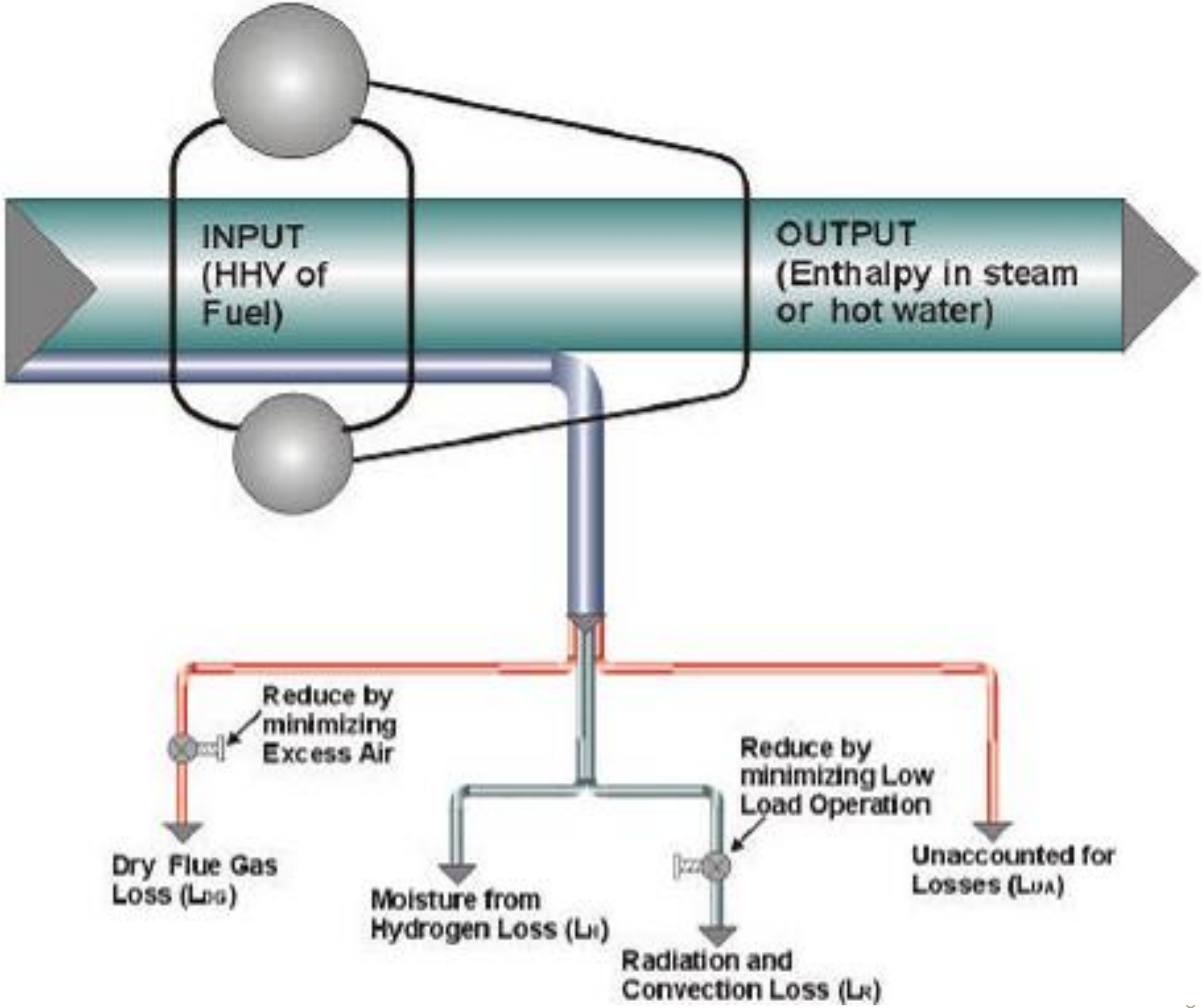
Performance of a Boiler

Heat Balance

Goal: improve energy efficiency by reducing *avoidable* losses

Avoidable losses include:

- Stack gas losses (excess air, stack gas temperature)
- Losses by unburnt fuel
- Blow down losses
- Condensate losses
- Convection and radiation


INPUT
(HHV of
Fuel)
OUTPUT
(Enthalpy in steam
or hot water)
Reduce by
minimizing
Excess Air
Reduce by
minimizing Low
Load Operation
Dry Flue Gas
Loss (L_{DG})
Moisture from
Hydrogen Loss (L_H)
Radiation and
Convection Loss (L_R)
Unaccounted for
Losses (L_{UA})

Performance of a Boiler

Boiler Efficiency

Thermal efficiency: % of (heat) energy input that is effectively useful in the generated steam.

BOILER EFFICENCY CALCULATION

1) DIRECT METHOD:

The energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.

2) INDIRECT METHOD:

The efficiency is the different between losses and energy input

Performance of a Boiler

"**Input-Output**" method

Boiler Efficiency : Direct Method

$$\text{Boiler efficiency } (\eta) = \frac{\text{Heat output}}{\text{Heat Input}} \times 100 = \frac{m_s \times (h_g - h_f)}{m_f \times GCV} \times 100$$

h_g - the enthalpy of saturated steam in kcal/kg of steam
h_f - the enthalpy of feed water in kcal/kg of water

Parameters to be monitored :

- Quantity of steam generated per hour (m_s) in kg/hr
- Quantity of fuel used per hour (m_f) in kg/hr
- The working pressure (in kg/cm^2(g)) and superheat temperature (^{o} C), if any
- The temperature of feed water (^{o} C)
- Type of fuel and gross calorific value of the fuel (GCV) in kcal/kg of fuel

Performance of a Boiler

Boiler Efficiency: Direct Method

Advantages

- Quick evaluation
- Few parameters for computation
- Few monitoring instruments
- Easy to compare evaporation ratios with benchmark figures

Disadvantages

- No explanation of low efficiency
- Various losses not calculated

Performance of a Boiler

heat loss method

Boiler Efficiency: Indirect Method

Efficiency of boiler (η) = 100 – (i+ii+iii+iv+v+vi+vii)

Principle losses:

i) Dry flue gas

ii) Evaporation of water formed due to H_2 in fuel

iii) Evaporation of moisture in fuel

iv) Moisture present in combustion air

v) Unburnt fuel in fly ash

vi) Unburnt fuel in bottom ash

vii) Radiation and other unaccounted losses

Performance of a Boiler

Boiler Efficiency: Indirect Method

Required calculation data

- Ultimate analysis of fuel (H, O, N, S, C, moisture content, ash content)
- % oxygen or CO_2 in the flue gas
- Fuel gas temperature in ◦C (T_f)
- Ambient temperature in ◦C (T_a) and humidity of air in kg/kg of dry air
- GCV of fuel in kcal/kg
- % combustible in ash (in case of solid fuels)
- GCV of ash in kcal/kg (in case of solid fuels)

Performance of a Boiler

Boiler Efficiency: Indirect Method

Advantages

- Complete mass and energy balance for each individual stream
- Makes it easier to identify options to improve boiler efficiency

Disadvantages

- Time consuming
- Requires lab facilities for analysis

Measurements Required for Performance Assessment

Flue gas analysis
1. Percentage of CO2 or O2in flue gas
2. Percentage of CO in flue gas
3. Temperature of flue gas

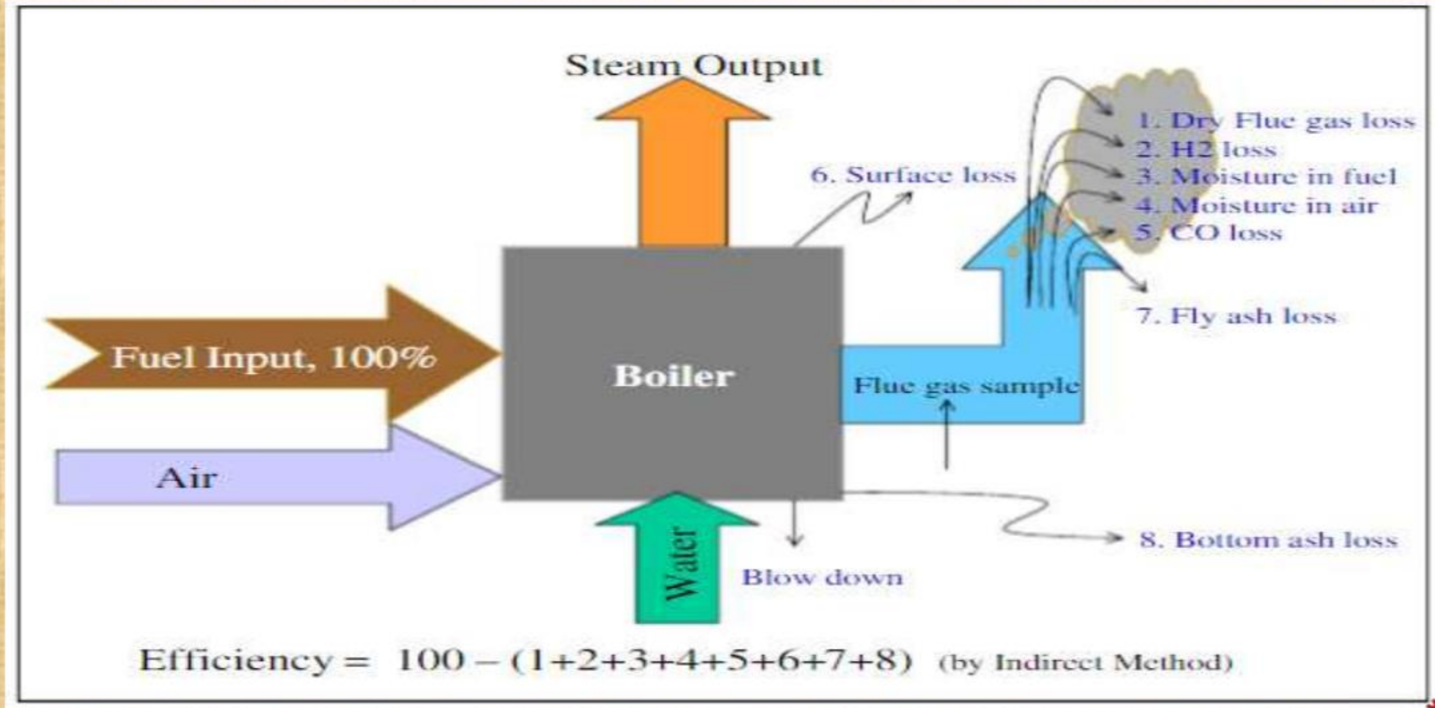
Water condition
1. Total dissolved solids (TDS)
2. pH
3. Blow down rate and quantity

Pressure measurements for
1. Steam
2. Fuel
3. Combustion air, both primary and secon dary
4. Draft

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

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

Indirect Method



Indirect Method

L1- Loss due to dry flue gas (sensible heat)
L2- Loss due to hydrogen in fuel (H2)
L3 -Loss due to moisture in fuel (H2O)
L4 - Loss due to moisture in air (H2O)
L5 - Loss due to carbon monoxide (CO)
L6-Loss due to surface radiation, convection and other unaccounted

For Solid Fuel

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)

Instrument used for Boiler performance analysis

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

Various Losses Associated With The Operation of A Boiler

1. Heat loss due to dry flue gas

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

$$L_1 = \frac{m \, x \, C_p \, x (T_f - T_a)}{GCV \; of \; fuel} \, x \, 100$$

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

T_f = Flue gas temperature in °C

T_a = Ambient temperature in °C

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

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

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

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

where

M = kg of moisture in fuel in 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

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

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

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:

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

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:

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 water tube boiler = 2 to 3%**
- **For power station boiler = 0.4 to 1%**

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

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)

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

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

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

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

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)			

Example: Boiler Efficiency Calculation (coal fired)

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 Calculation by Indirect Method

Step – 1 Find theoretical air requirement

Theoretical air required for complete combustion	=	$[(11.6 x C) + \{34.8 x (H_2 - O_2/8)\} + (4.35 x S)]/100$ kg/kg of coal
	=	[(11.6 x 41.65) + {34.8 x (2.0413 – 14.48/8)} + (4.35 x 0)] / 100
	=	**4.91 kg / kg of coal**

Step – 2 Find theoretical CO_2 %

% CO_2 at theoretical condition (CO_2)$_t$	=	$\frac{Moles\ of\ C}{Moles\ of\ N_2 + Moles\ of\ C}$
Where, 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 N_2	=	$\frac{4.91 x 77/100}{28} + \frac{0.016}{28} = 0.1356$
Where moles of C	=	0.4165/12 = 0.0347
(CO_2)$_t$	=	$\frac{0.0347}{0.1332 + 0.0347}$
(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) $= \dfrac{7900\,x[(CO_2\%)_t - (CO_2\%)_a]}{(CO_2)_a\%\ x\,[100 - (CO_2\%)_t]}$

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

= **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

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

= **7.54 kg / kg of coal**

Step – 6 To find all losses

1. % Heat loss in dry flue gas (L_1)

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

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

L_1 = **7.88 %**

2. % Heat loss due to formation of water from H_2 in fuel (L_2)

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

$$= \frac{9 \text{ x } 0.02041 \text{ x } \{584 + 0.45 (190 - 31)\}}{3501} x 100$$

L_2 = **3.44 %**

3. % Heat loss due to moisture in fuel (L_3)	=	$\frac{M \times \{584 + C_p (T_f - T_a)\}}{GCV \text{ of fuel}} x\ 100$
	=	$\frac{M \times \{584 + C_p (T_f - T_a)\}}{GCV \text{ of fuel}} x\ 100$
L_3	=	**5.91 %**

4. % Heat loss due to moisture in air (L_4)	=	$\frac{AAS\ x\ humidity\ x\ C_p\ x (T_f - T_a)}{GCV\ of\ fuel} x\ 100$
	=	$\frac{7.13 x 0.0204 x 0.45 x (190 - 31)}{3501} x\ 100$
L_4	=	**0.29 %**

5. % Heat loss due to partial conversion of C to CO (L_5)	=	$\frac{\%CO\ x\ C}{\%CO + \%CO_2}\ x\ \frac{5744}{GCV\ of\ fuel}\ x\ 100$
	=	$\frac{0.55\ x\ 0.4165}{0.55 + 14}\ x\ \frac{5744}{3501}\ x\ 100$
L_5	=	**2.58 %**

6. Heat loss due to radiation and convection (L_6)	=	0.548 x [$(343/55.55)^4$ – $(304/55.55)^4$] + 1.957 x $(343 - 304)^{1.25}$ x sq.rt of [(196.85 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 of 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 %**			

Summary of Heat Balance of a 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 %			

Performance of a boiler

1. **Boiler Performance**
2. **Boiler blow down**
3. **Boiler feed water treatment**

Performance of a Boiler

2. Boiler Blow Down

- Controls '**total dissolved solids**' (TDS) in the water that is boiled
- Blows off water and replaces it with feed water
- Conductivity measured as indication of TDS levels
- Calculation of quantity blow down required:

$$\text{Blow down (\%)} = \frac{\text{Feed water TDS x \% Make up water}}{\text{Maximum Permissible TDS in Boiler water}}$$

Performance of a Boiler

Boiler Blow Down

Two types of blow down

- **Intermittent**
  - Manually operated valve reduces TDS
  - Large short-term increases in feed water
  - Substantial heat loss
- **Continuous**
  - Ensures constant TDS and steam purity
  - Heat lost can be recovered
  - Common in high-pressure boilers

Performance of a Boiler

Boiler Blow Down

Benefits

- Lower pretreatment costs
- Less make-up water consumption
- Reduced maintenance downtime
- Increased boiler life
- Lower consumption of treatment chemicals

Performance of a boiler

1. **Boiler Performance**
2. **Boiler blow down**
3. **Boiler feed water treatment**

Performance of a Boiler

3. Boiler Feed Water Treatment

- **Quality of steam depend on water treatment to control**
  - Steam purity
  - Deposits
  - Corrosion
- **Efficient heat transfer only if boiler water is free from deposit-forming solids.**

Boiler performance, efficiency, and service life are direct products of selecting and controlling feed water used in the boiler.

Performance of a Boiler

Boiler Feed Water Treatment

Deposit control

- To avoid efficiency losses and reduced heat transfer
- Hardness salts of calcium and magnesium
    - Alkaline hardness: removed by boiling
    - Non-alkaline: difficult to remove
- Silica forms hard silica scales

Performance of a Boiler

Boiler Feed Water Treatment

Internal water treatment

- Chemicals added to boiler to prevent scale
- Different chemicals for different water types

- **Conditions:**
  - Feed water is low in hardness salts
  - Low pressure, high TDS content is tolerated
  - Small water quantities treated
- **Internal treatment alone not recommended**

Performance of a Boiler

Boiler Feed Water Treatment

External water treatment:

- Removal of suspended/dissolved solids and dissolved gases
- Pre-treatment: sedimentation and settling
- First treatment stage: removal of salts
- **Processes**
  a) Ion exchange
  b) Demineralization
  c) De-aeration
  d) Reverse osmosis

Introduction

Type of boilers

Performance of a boiler

Energy efficiency opportunities

Energy Efficiency Opportunities

1. Stack temperature control
2. Feed water preheating using economizers
3. Combustion air pre-heating
4. Incomplete combustion minimization
5. Excess air control
6. Avoid radiation and convection heat loss
7. Automatic blow down control
8. Reduction of scaling and soot losses
9. Reduction of boiler steam pressure
10. Variable speed control
11. Controlling boiler loading
12. Proper boiler scheduling
13. Boiler replacement

Energy Efficiency Opportunities

1. Stack Temperature Control

- Keep as low as possible
- If >200°C then recover waste heat

2. Feed Water Preheating Economizers

- Potential to recover heat from 200 – 300^{o}C flue gases leaving a modern 3-pass shell boiler

3. Combustion Air Preheating

- If combustion air raised by 20°C = 1% improve thermal efficiency

Energy Efficiency Opportunities

4. Minimize Incomplete Combustion

- **Symptoms:**
  - Smoke, high CO levels in exit flue gas
- **Causes:**
  - Air shortage, fuel surplus, poor fuel distribution
  - Poor mixing of fuel and air
- **Oil-fired boiler:**
  - Improper viscosity, worn tops, carbonization on tips, deterioration of diffusers or spinner plates
- **Coal-fired boiler: non-uniform coal size**

Energy Efficiency Opportunities

5. Excess Air Control

- Excess air required for complete combustion
- Optimum excess air levels varies
- 1% excess air reduction = 0.6% efficiency rise
- Portable or continuous oxygen analyzers

Energy Efficiency Opportunities

6. Radiation and Convection Heat Loss Minimization

- Fixed heat loss from boiler shell, regardless of boiler output
- Repairing insulation can reduce loss

7. Automatic Blow Down Control

- Sense and respond to boiler water conductivity and pH

Energy Efficiency Opportunities

8. Scaling and Soot Loss Reduction

- Every 22^{o}C increase in stack temperature = 1% efficiency loss
- 3 mm of soot = 2.5% fuel increase

9. Reduced Boiler Steam Pressure

- Lower steam pressure

  = lower saturated steam temperature

  = lower flue gas temperature
- Steam generation pressure dictated by process

Energy Efficiency Opportunities

10. Variable Speed Control for Fans, Blowers and Pumps

- Suited for fans, blowers, pumps
- Should be considered if boiler loads are variable

11. Control Boiler Loading

- Maximum boiler efficiency: 65-85% of rated load
- Significant efficiency loss: < 25% of rated load

Energy Efficiency Opportunities

12. Proper Boiler Scheduling

- Optimum efficiency: 65-85% of full load
- Few boilers at high loads is more efficient than large number at low loads

13. Boiler Replacement

Financially attractive if existing boiler is

- Old and inefficient
- Not capable of firing cheaper substitution fuel
- Over or under-sized for present requirements
- Not designed for ideal loading conditions

Factor Affecting Boiler Performance

- 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

Boilers

THANK YOU
FOR YOUR ATTENTION