Chapter 3

Fossil-fuel steam Generators

Introduction

- Steam generators are mainly used in both fossil-and nuclear-fuel electric generation power plants.
- Main components are:

a. Economizer
b. Boiler
c. Super heater
d. Reheater
e. Air pre-heater.

- Also there are some auxiliaries such as the stack, burners, fans and ash-handling equipments.

Steam Generators Classifications

1. Utility generators: those that are used for electric-power generating plants and they have two kinds:

a. Subcritical water-tube drum type
b. Supercritical once-through type, usually at 3500 Psia (240 Bar)

2. Industrial steam generators: they are used in industrial and institutional applications

Fossil-Fueled steam Generators Types

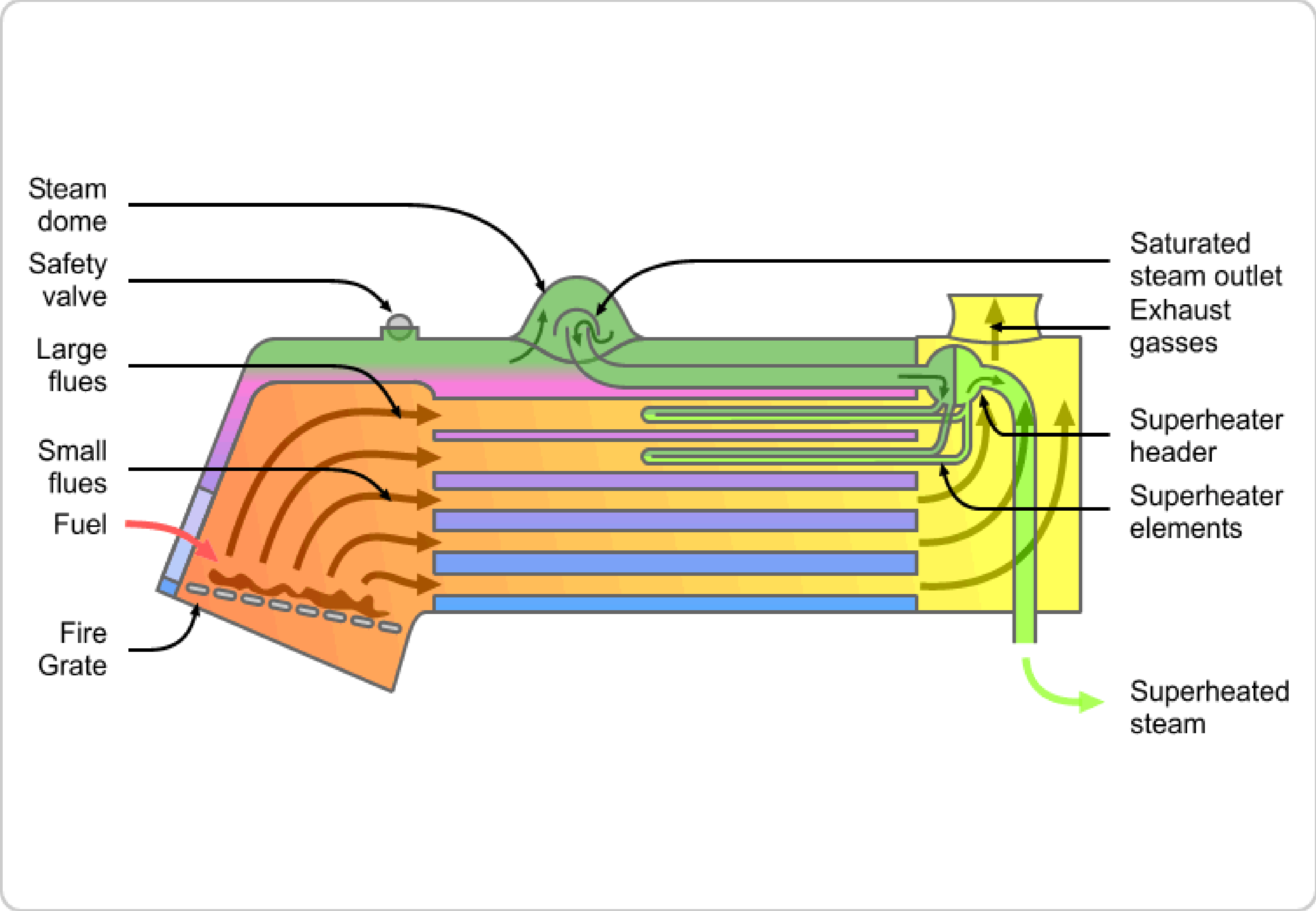
1. Fire-tube boilers
2. Water-tube boilers
3. Natural-circulation boilers
4. Controlled circulation boilers
5. Once-through flow
6. Subcritical pressure
7. Supercritical pressure

Comparison Between Utility and Industrial Steam Generators

Class	Operating pressure	Mass flow rate	Burning method	application
Utility steam generator	•1900-2600 psia for sub.C •3500 for sup.C	(1-10 x10^6) lbm/h (125-1250) Kg/s	•Pulverized coal or oil Natural gas	Electricity generation Power (125-1300)MW
Industrial steam generator	1500 psia	1x10^6 lbm/h 125 Kg/s	•Stoker coal and oil •Natural gas	•Industrial •institutional

Fire-tube Boiler

- They are the earliest form of boilers and are not used now a days in large utility power plants, but they are still used in industrial plants to produce saturated steam at the upper limits of 250 psig (18 bar)
- They are shell-type boilers: closed cylindrical vessel that contains water and an exposed portion to heat.
- They are stopped using because of the high stress at the shell that causes explosion in the extreme cases .



Fire- tube boiler

New Evolutions of Fire-type Boiler

1. Electric boiler, where electrodes embedded in water.
2. Fire-tube-boiler: vertical, horizontal or inclined tubes are placed, where hot gases pass through them. There are two types of fire-tube boiler:

a. Fire box, where the furnace is located within the shell together with the fire tubes.
b. Scotch marine: combustion takes place within one more cylindrical chambers that are situated inside and near the main shell at the bottom.

Water-tube boiler: early developments

The old model was developed by Gorge Babcock and Stephan Wilcox in 1867. The water-tube boiler was developed to overcome the fire-tube boiler problems such as:

1. Operating under extreme pressure and temperature needs a special design, where the diameter is large and the thickness of walls is also large.

How did the water tube-boiler has sorted out this problem?

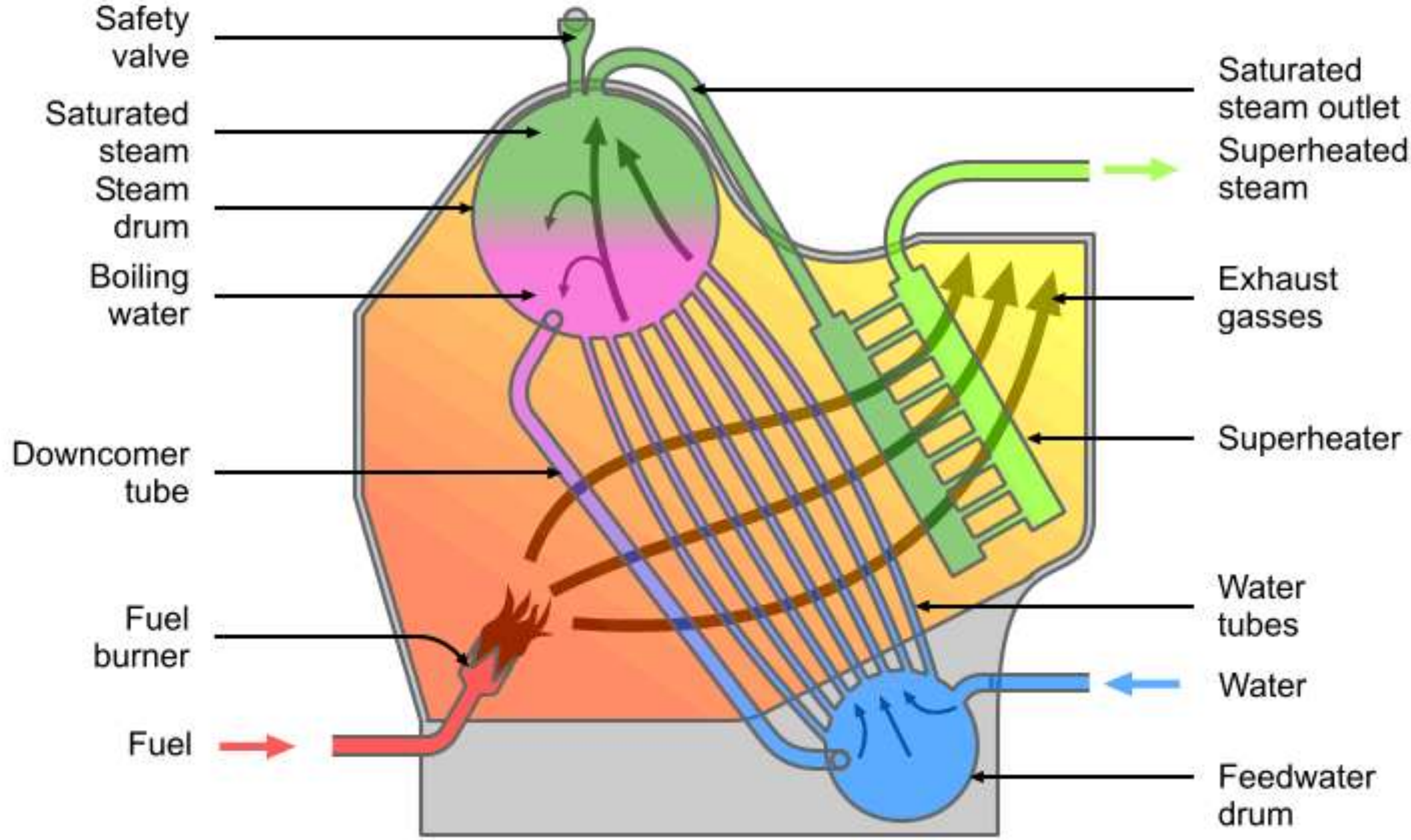
By putting the high pressure in the tubes, and the combustion gases on the outside.

Models of water-tube-boiler

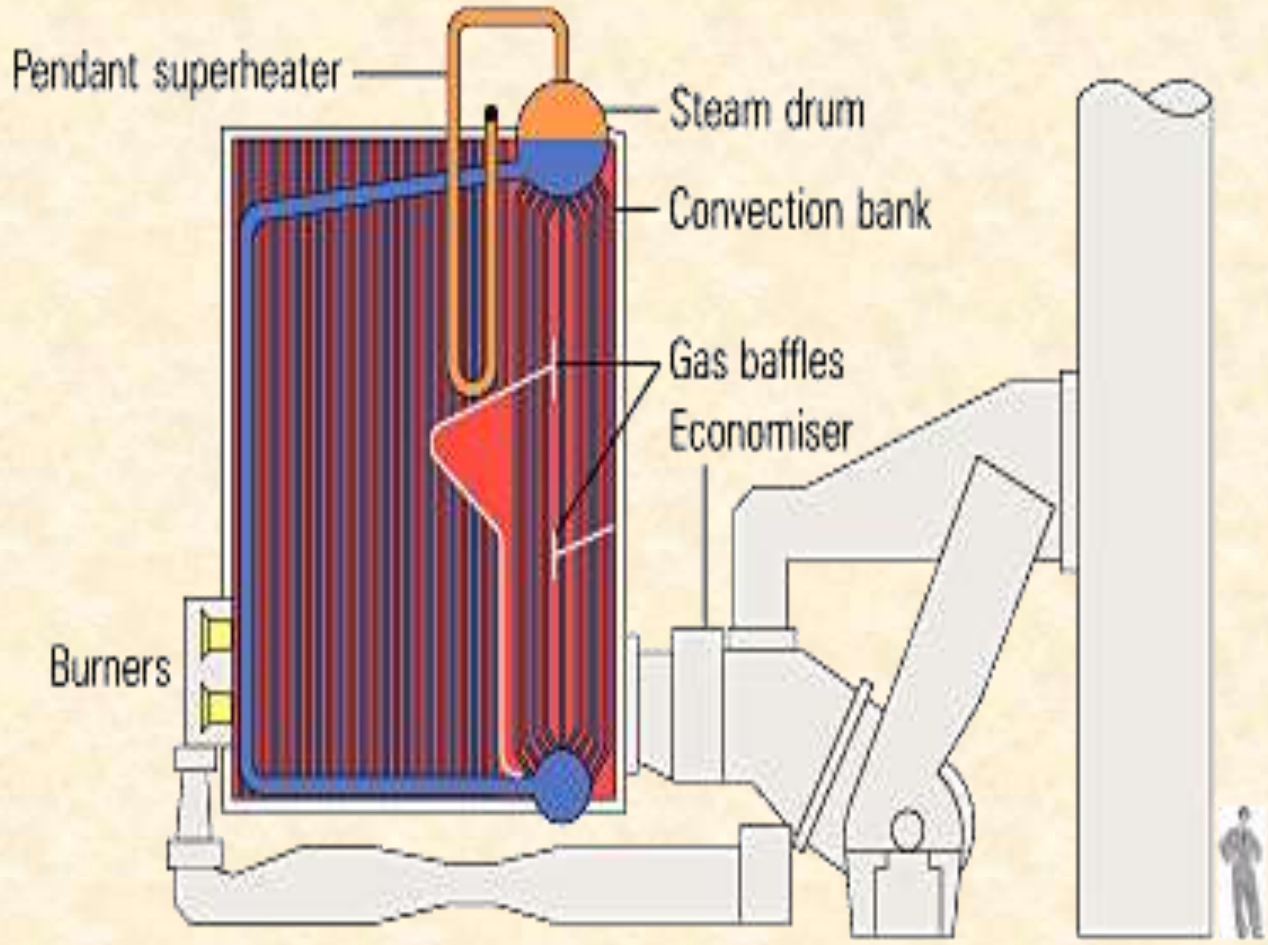
1. The straight-tube boiler: the tubes are straight 3-4 inch in outer diameter (OD) with 7-8 inch in spacing, connected to vertical headers. These headers are the down-comer or down-take , which supply saturated water. The other header is the riser or up-take, which receives water-steam mixture.
2. Bent-tube-boiler: it is bent, rather than straight tubes between several drums where they enter and leave rabidly

Recent Developments

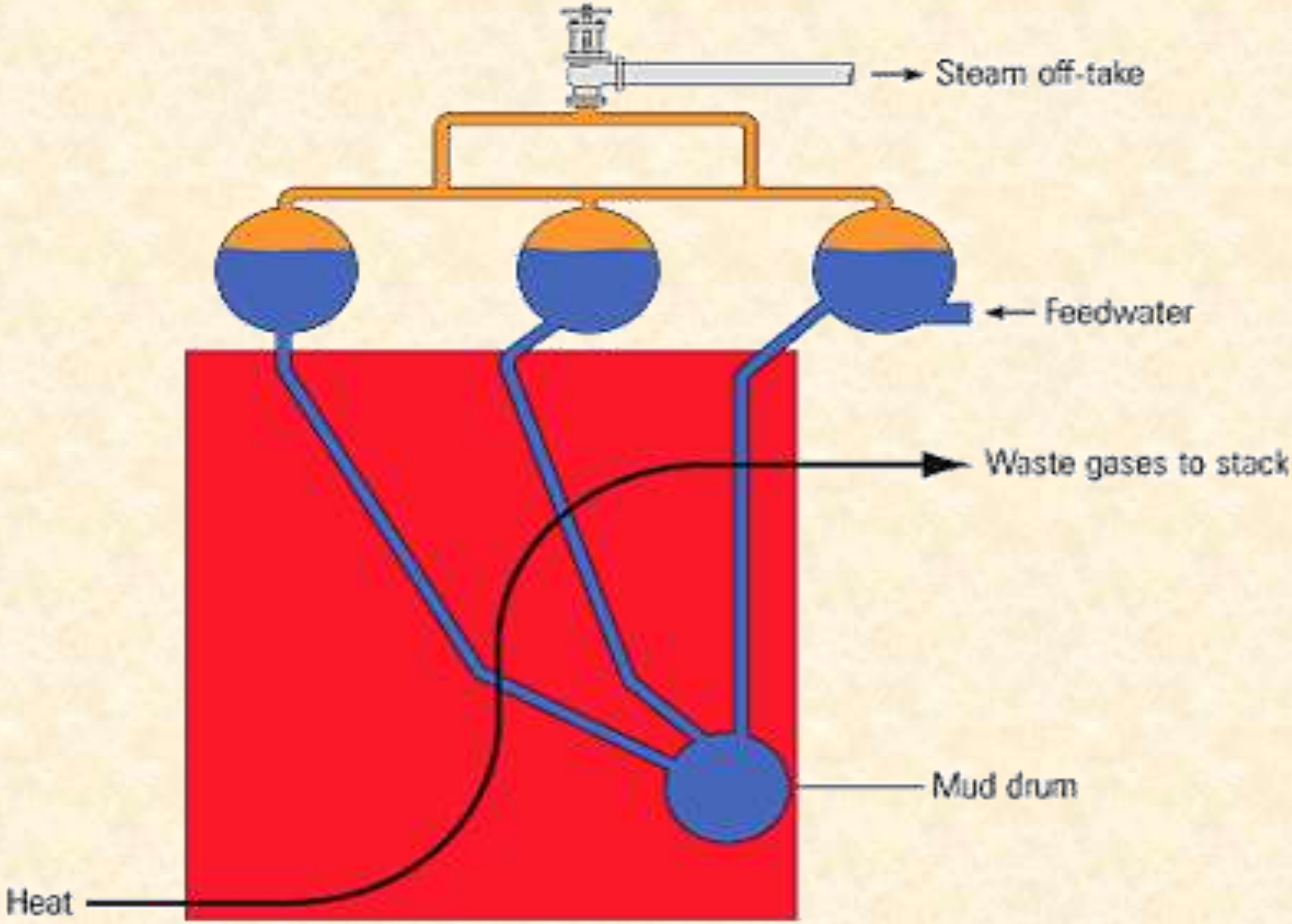
It includes the integration of furnace, economizer, boiler, super heater, reheater, and pre-heater. The modern high pressure steam generator requires more super heating and reheating surface and less boiler surface than older units. Air pre-heaters are also used in modern boilers using a forced-draft (FD) fan.



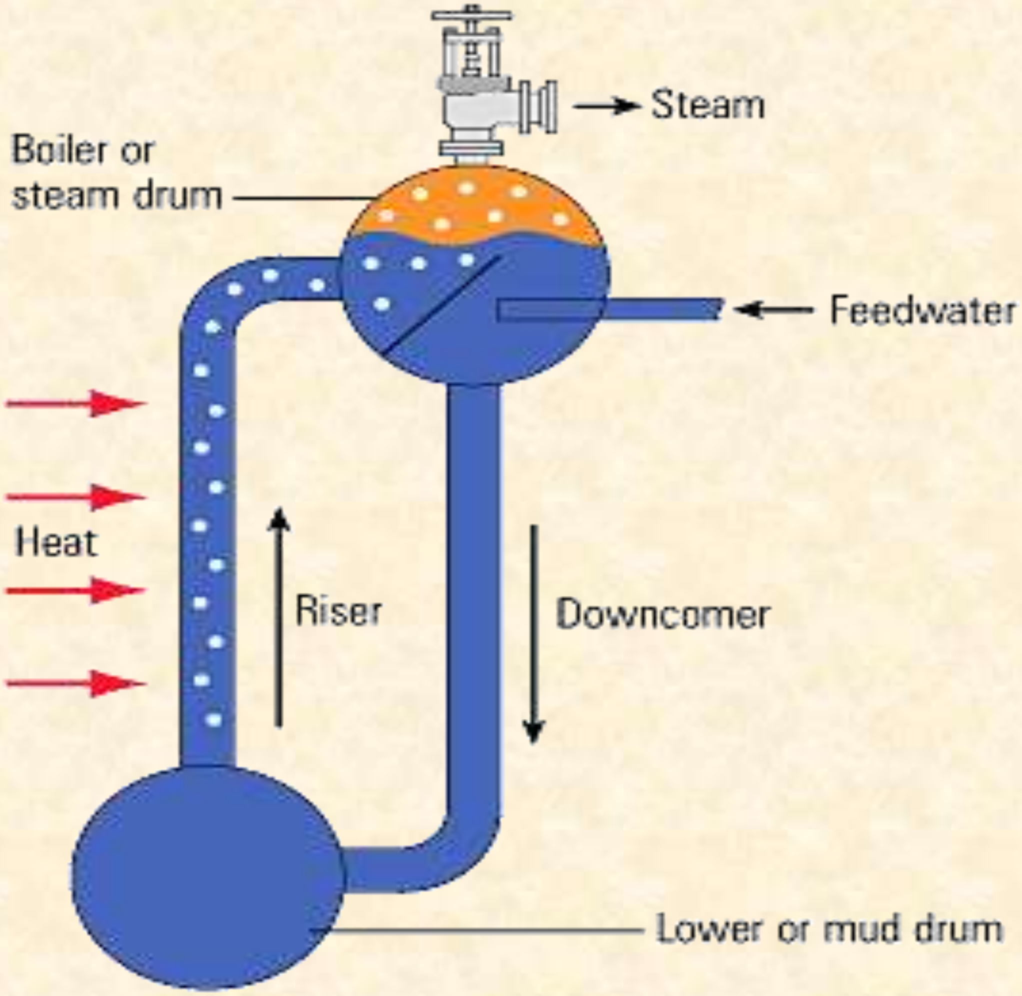
Water- tube boiler



Water- tube boiler



Bent- tube boiler
Stirlling boiler



Natural water circulation in a water tube boiler

The leaving gases are still have some exregy (availability) but it is accepted because:

1. The gas temperature should be above the dew point to prevent condensation, which may form acids that would corrode metal components in its path.
2. The gases must have enough buoyancy to rise in a high plume above the stack

The Boiler walls

The advent of the water-cooled furnace walls, called water walls. Water cooling is also used for super heater and economizer chambers walls.

The construction have varied among:

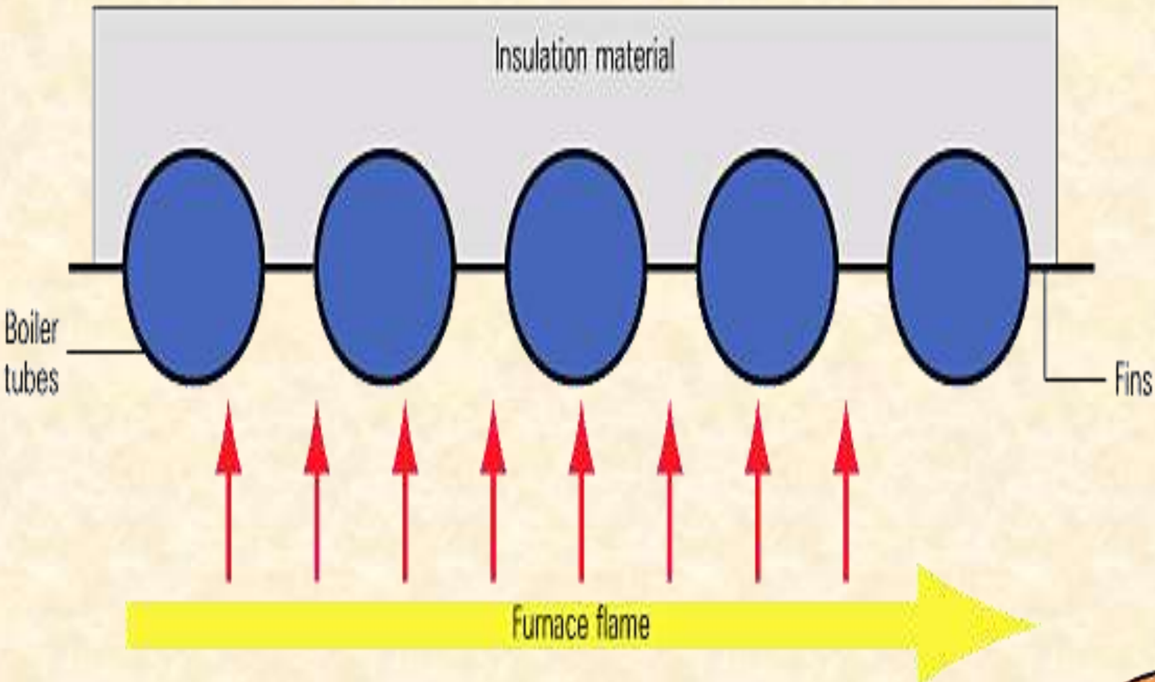
a) Bar tubes tangent to the refractory b) embedded in the refractory c) studded tubes d) membrane design.

Membrane design

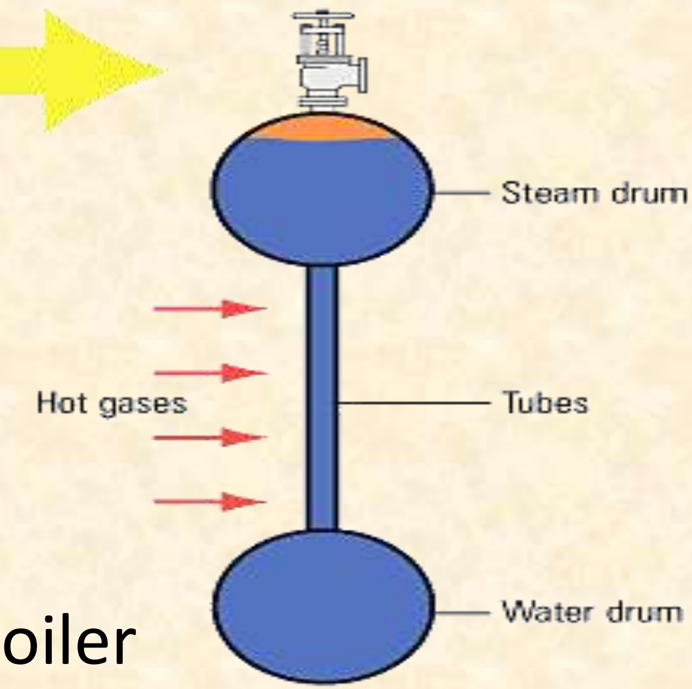
It is the most modern design. It consists of tubes spaced on centres slightly wider than their diameter and connected by bars or membranes welded to the tubes at their centrelines. The membranes acts as fins to increase heat transfer.

The Radiant boiler

It is the boiler that receives most of its heat by radiation and are designed for electric-generating stations that use coal or lignite for pulverized or cyclone furnace applications, oil or natural gas. They are limited to subcritical pressure (125-170) bar



Radiant boiler



Convection side of the boiler

Once through Boiler

It is also called the forced circulation, Benson or universal pressure boiler. It is applicable to all temperatures and pressures, but economically is suited to large sizes and pressure in the high subcritical and supercritical range.

In this type the feedwater goes through the economizer, furnace walls and super heater sections in one continuous pass, so no drum is required and no water recirculation takes place.

It demands a very high purity water because of the one through process and it is the only type that can be used by supercritical pressure operation.

Advantages of water-tube boilers

- They have a small water content, and therefore respond rapidly to load change and heat input.
- The small diameter tubes and steam drum mean that much higher steam pressures can be tolerated, and up to 160 bar may be used in power stations.
- The design may include many burners in any of the walls, giving horizontal, or vertical firing options, and the facility of control of temperature in various parts of the boiler. This is particularly important if the boiler has an integral super heater, and the temperature of the superheated steam needs to be controlled.
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Disadvantages of water-tube boilers

- They are not as simple to make in the packaged form as shell boilers, which means that more work is required on site.
- The option of multiple burners may give flexibility, but the 30 or more burners used in power stations means that complex control systems are necessary.

Water Circulation

- There are two types of circulation:

1. Natural circulation due to density difference between the saturated water and the two phase mixture
2. Forced circulation by using a pump. This method gives more pressure about 2300 psia (160 bar) and higher.

Departure from Nucleate Boiling (DNB)

DNB: the point at which the heat transfer from a pipe that contains two phase rapidly decreases due to the insulating effect of a steam blanket that forms on the rod surface when the temperature continues to increase, so full boiling is avoided as this will cause burnout or failure as a result of DNB.

How to Overcome the DNB Problem

1. Forced circulation: due to the presence of the pump, a turbulence is generated that breaks the steam film layer.
2. The tubes in the high-heat-absorbing areas of the furnace are provided with internal twisters and springs that would break the vapour film.
3. Internally grooved, corrugated tubes are also used, which also increases the turbulence.
4. Ribbed (rifled) helically on their inside surface tubes. This creates a centrifugal action that directs water droplets to the vapour film.

Natural Circulation driving pressure equations

$$\Delta p_d = (\rho_{dc} - \bar{\rho}_r) H \frac{g}{g_c} \tag{3-1}$$

where Δp_d = driving pressure, lb_f/ft^2 or N/m^2 (Pa)

ρ_{dc} = density of water in the downcomer, nearly saturated at the system pressure, lb_m/ft^3 or kg/m^3

$\bar{\rho}_r$ = average density of steam-water mixture in the riser, lb_m/ft^3 or kg/m^3

H = height of drum-water level above bottom header, ft or m

g = gravitational acceleration ft/s^2 or m/s^2

g_c = conversion factor 32.2 $lb_m \cdot ft/(lb_f \cdot s^2)$ or 1 $kg/(N \cdot s^2)$

The average density is a function of the void fraction

$$\alpha = \frac{\text{volume of vapor}}{\text{volume of vapor + liquid}}$$

and

$$x = \frac{1}{1 + [(1 - \alpha)/\alpha]\frac{1}{\psi}}$$

where

$$\psi = \frac{v_f}{v_g}S$$

X is the quality and S is the slip velocity as the steam is faster than the water.

$$S = \frac{\overline{V}_{s,g}}{\overline{V}_{s,f}} \tag{3-4}$$

where $\overline{V}_{s,g}$ and $\overline{V}_{s,f}$ are the average vapor and average liquid velocities at any one cross section of the riser. S has been measured experimentally and found to vary between 1 to less than 10 in most systems, approaching 1 at high pressures (where the liquid and vapor densities approach each other). It is, in general, fairly constant along the path length.

The axial heat flux distribution to the riser determines the quality distribution. In turn, using a reasonable value for S (between 1 and 2), a void fraction distribution is obtained. A mixture density distribution ρ_m is now found from

$$\rho_m = (1 - \alpha)\rho_f + \alpha\rho_g \tag{3-5}$$

where ρ_f and ρ_g are densities (reciprocals of the specific volumes) of the saturated liquid and vapor, respectively. The average mixture distribution in the riser $\overline{\rho}_r$ is now obtained from

$$\overline{\rho}_r = \frac{\int_o^H \rho_m(z)\, dz}{H} \tag{3-6}$$

where z is the axial distance from the bottom of the riser. In the case of uniform axial heating, the solution of the above integral is [2]

$$\overline{\rho}_r = \rho_f - \frac{\rho_f - \rho_g}{1 - \psi}\left\{1 - \left[\frac{1}{\alpha_e(1 - \psi)} - 1\right] \ln\frac{1}{1 - \alpha_e(1 - \psi)}\right\} \tag{3-7}$$

1. The driving pressure should balance the pressure losses of the single and two-phase fluids in the loop.
2. If the driving pressure is too low for the desired flow rate a pump is added to assist in circulation

The steam drum

Steam drum: is where feed-water from economizer is fed, saturated steam is separated from the boiling water and the remaining water is circulated above. The drum is also used for chemical water treatment and blow down to reduce solids in the water. Steam drums are provided in all modern generators except the once-through types.

The drum should stand the flow rate changes and prevent the carryover of water towards the supper-heater which may lead to distortion or burnout.

Steam is separated in the drum by two methods:

a) Gravity separation b) Mechanical separation

Gravity separation

Factors that affect the gravity separation is:

1. Steam velocity
2. Positions of the down comer and riser nozzle with respect to the steam outlet
3. Operating pressure

Gravity separation is economical only for low-steam-capacity, low pressure service.

Mechanical separation

It has three steps:

1. Primary separation: removes most of the water from the steam and prevents the carry under of steam with the recirculating water to down-comer and risers. Baffle plates and the bent or corrugated plates are used for primary separation.
2. Secondary separation, also called steam scrubbing or drying. It removes mist or fine droplets and solids from steam. Screens, bent or corrugated plates and centrifugal separators are considered types of the secondary separation.
3. Centrifugal separation is used at high pressures and it is called cyclone or turbo separators.

Typical utility steam drums range in length to more than 100 ft in diameter to more than 15 ft long and flow rate in terms of hundreds tons per hour

Superheaters and Reheaters

Superheaters are one of the most important accessories of boiler that improves the thermal efficiency.

In super heaters there should not be any fins as it increases the thermal stresses and carful should be taken when choosing the super-heater material that is stand for high temp and corrosion resistance.

Super-heater types

1. Convection super-heater: it is the earliest type of super-heater and it is located above or behind banks of water tubes to protect them from direct flam or fire

Parameters that increase the convection

a. Increasing the fuel-and air flow (combustion gas flow).
b. Increasing the mass flow rate of the steam.

Convection super-heaters are used for low temperature.

Radiant Super heater

They are placed exposed to the heat source which requires the improvement of metal temperatures.

Radiation is proportional to $T^4{}_f - T^4{}_w$ where T_f and T_w are the flame and tube wall absolute temperature. T_f is greater than T_w so radiation is mainly dependent on the flam temperature. As the steam flow rate increases the exit temperature become lower as T_w goes up.

Radiant and convective super-heaters and re-heaters are used for high-temperature steam.

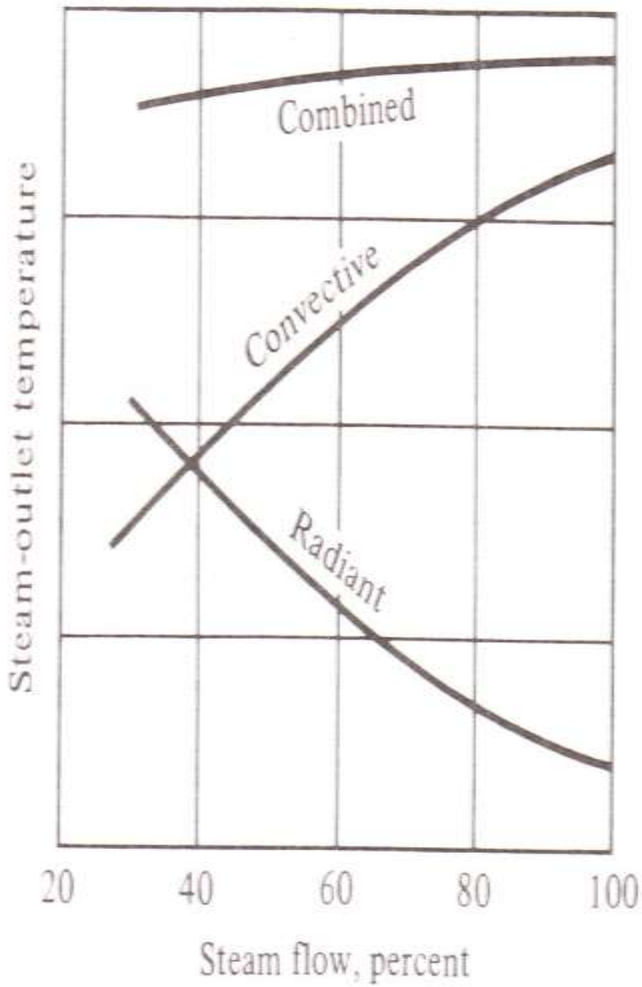

Figure 3-10 Exit-temperature response of convective, radiant, and combined (in-series) superheaters.

Re-heaters

They are the same as the super-heaters but as their exit temperature is a little bite less than super-heaters and their pressure is 20%-25% less than the super-heater, they can stand less quality material alloys.

Mechanical construction of the Super-heater sections

1. Pendant
2. Inverted
3. horizontal

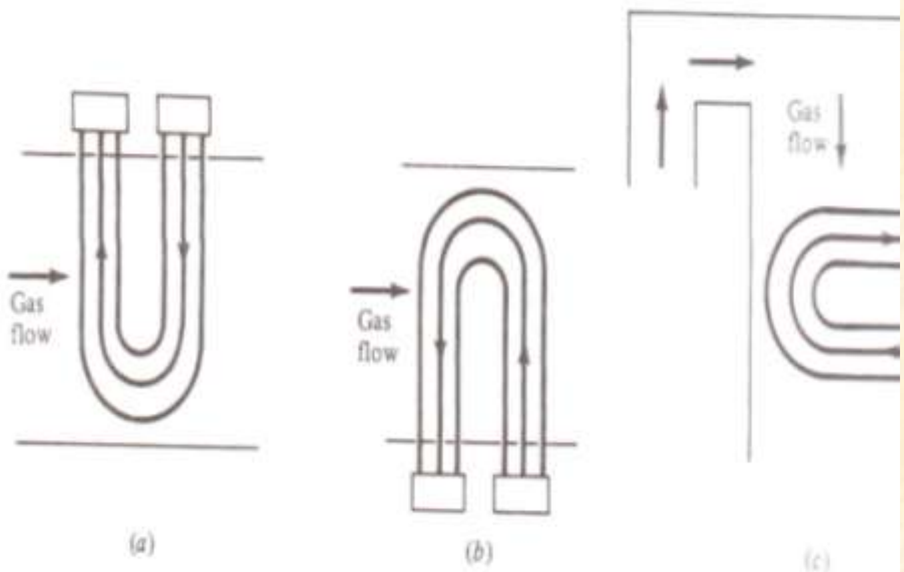

Figure 3-11 Schematic diagram showing (*a*) pendant, (*b*) inverted, and (*c*) horizontal sup reheaters.