POWER PLANT ENGINEERING

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Steam Generators

- Boiler, How it works

Steam Generators

A *steam generator* is a complex combination of economizer, boiler, superheater, reheater, and air preheater. In addition, it has various auxiliaries, such as stokers, pulverizers, burners, fans, emission control equipment, stack, and ash-handling equipment. A *boiler* is that portion of the steam generator where saturated liquid is converted to saturated steam, although it may be difficult to separate it, physically, from the economizer. The term "boiler" is often used to mean the whole steam generator in the literature, however. Steam generators are classified in different ways. They may, for example, be classified as either (1) utility or (2) industrial steam generators.

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.

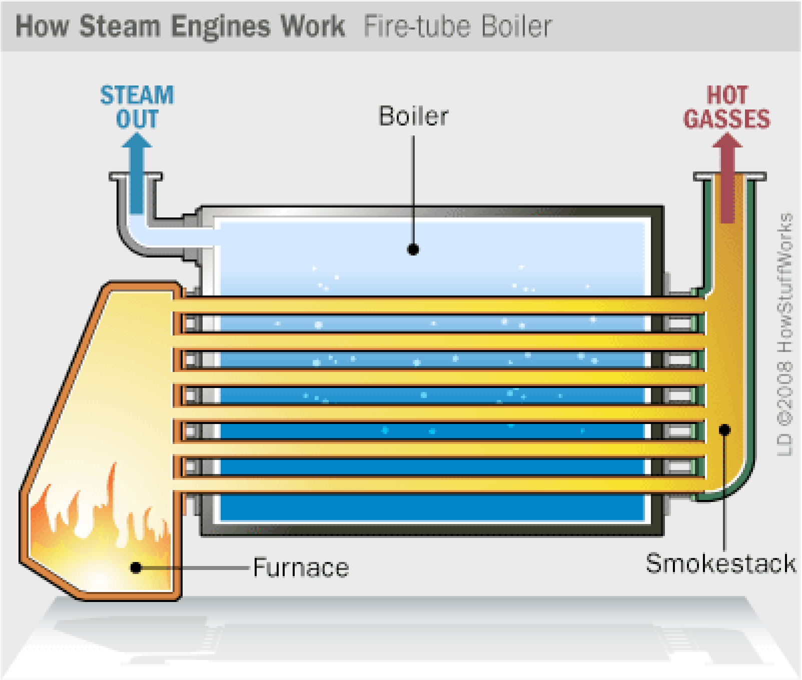
(viii) Should be capable of quick starting and loading.

CLASSIFICATION OF BOILERS

According to what flows in the TUBE

1. Fire tube.
2. Water tube.

1. Fire Tube Boiler



Fire-tube boilers have been used in various early forms to produce steam for industri purposes since the late eighteenth century. They are no longer used in large utili powerplants. They are covered here, however, for historical reasons and, by contras to emphasize the modern water-tube variety. Fire-tube boilers are still used in industri plants to produce saturated steam at the upper limits of 250 psig (about 18 bar) pressu and 50,000 lb_m/h (6.3 kg/s) capacity. Although their size has increased, their gene design has not changed appreciably in the past 25 years.

The fire-tube boiler is a special form of the shell-type boiler. A *shell-type boil* is a closed, usually cylindrical, vessel or shell that contains water. A portion of th shell, such as its underside, is simply exposed to heat, such as gases from an externally fired flame. The shell boiler evolved into more modern forms such as the *electric boiler*, in which heat is supplied by electrodes embedded in the water, or the *accumulator*, in which heat is supplied by steam from an outside source passing through tubes within the shell. In both cases the shell itself is no longer exposed to heat.

The shell boiler evolved into the *fire-tube boiler*. Hot gases, instead of steam, were now made to pass through the tubes. Because of improved heat transfer the fire-tube boiler is much more efficient than the original shell boiler and can reach efficiencies of about 70 percent.

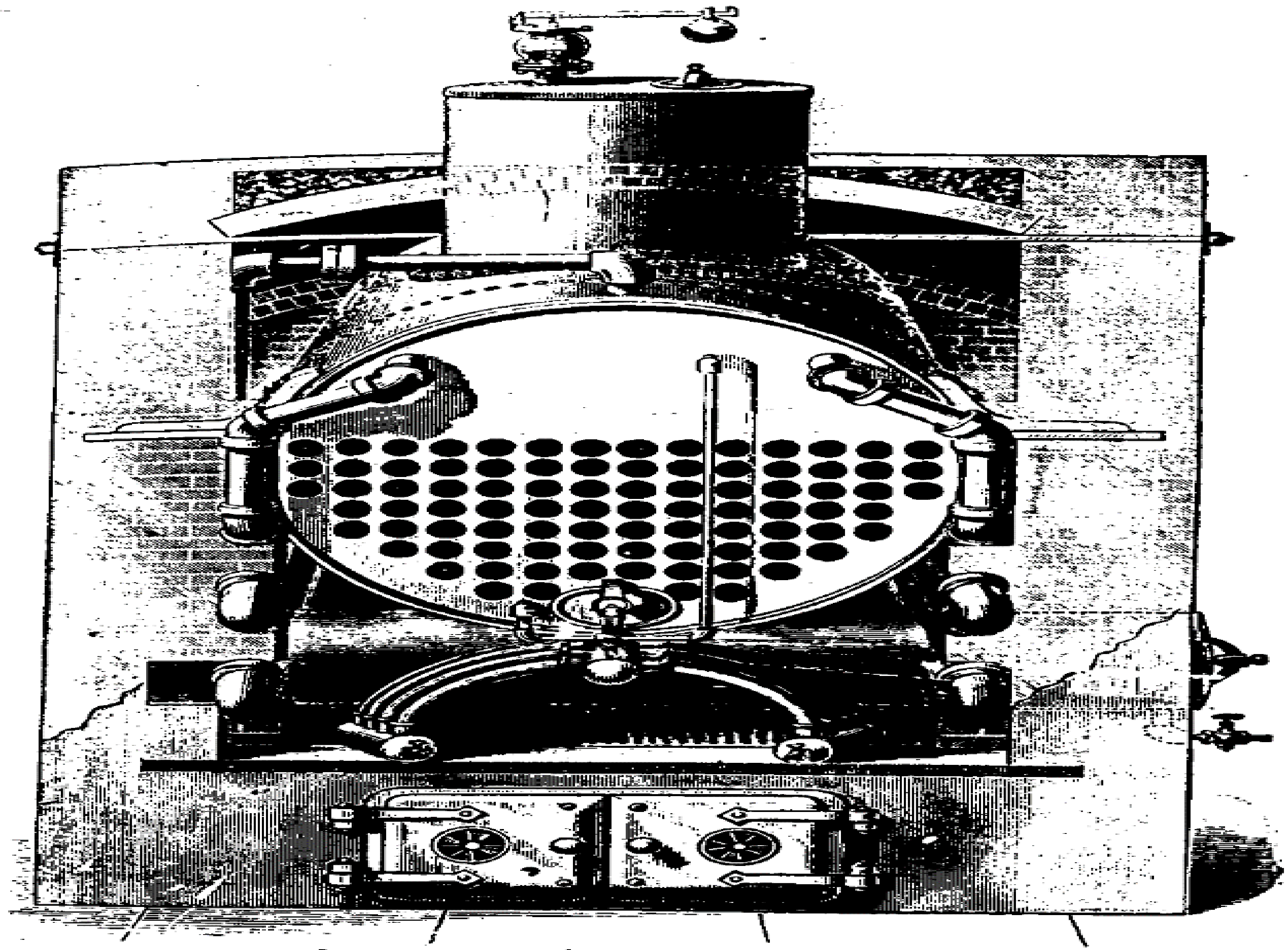


Figure 3-1 The Stead fire-tube steam generator

The fire tubes were placed in horizontal, vertical, or inclined positions. The most common was the horizontal-tube boiler. Figure 3-1 shows such an early fire-tube boiler. Figure 3-2 shows a simplified sketch of such a boiler. The furnace and grates are located underneath the front end of the shell. The gases pass horizontally along its underside to the rear, reverse direction, and pass through the horizontal tubes to the stack at the front.

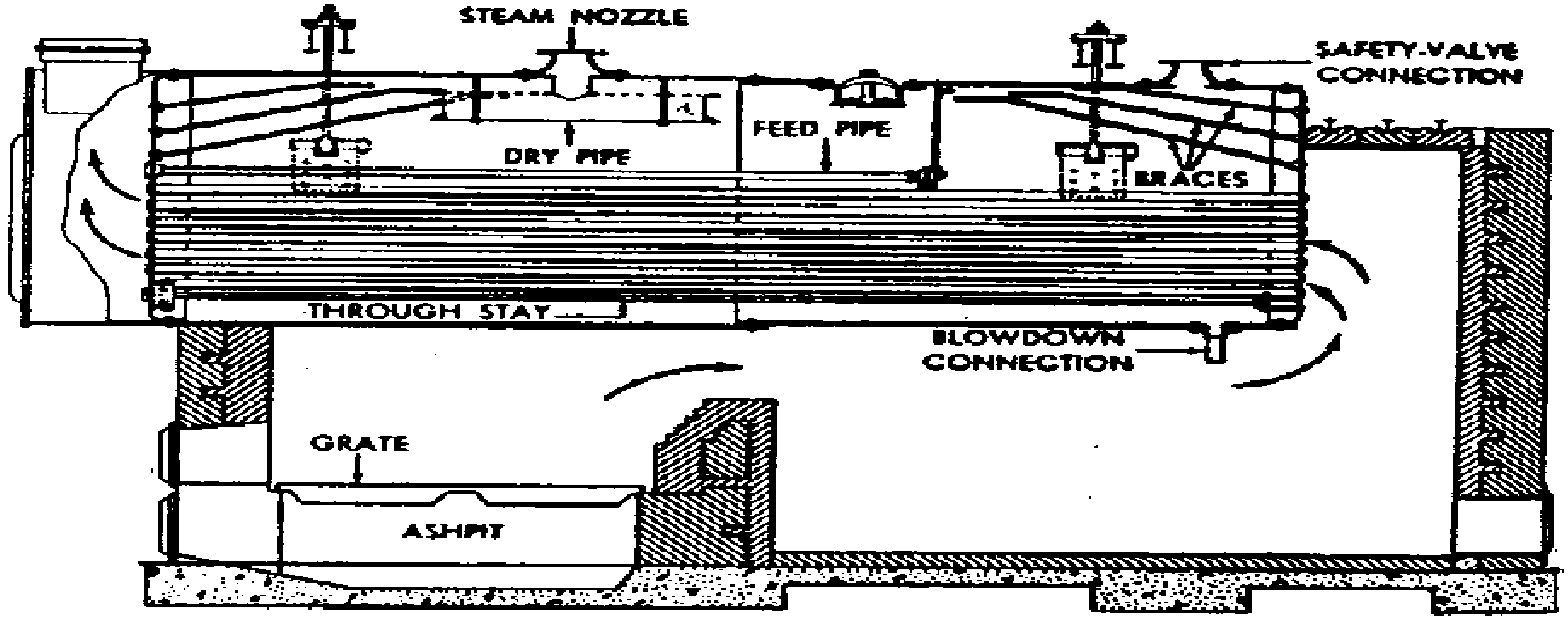


Figure 3-2 Schematic of an early horizontal-tube fire-tube boiler

There are two types of fire-tube boilers: (1) the fire-box and (2) the scotch marine. In the *fire box boiler*, the furnace, or fire box, is located within the shell, together with the fire tubes. In the *scotch marine boiler* (Fig. 3-3), combustion takes place within one or more cylindrical chambers that are usually situated inside and near the bottom of the main shell. The gases leave these chambers at the rear, reverse direction, and return through the fire tubes to the front and out through the stack. Scotch marine boilers are usually specified with liquid or gas fuels.

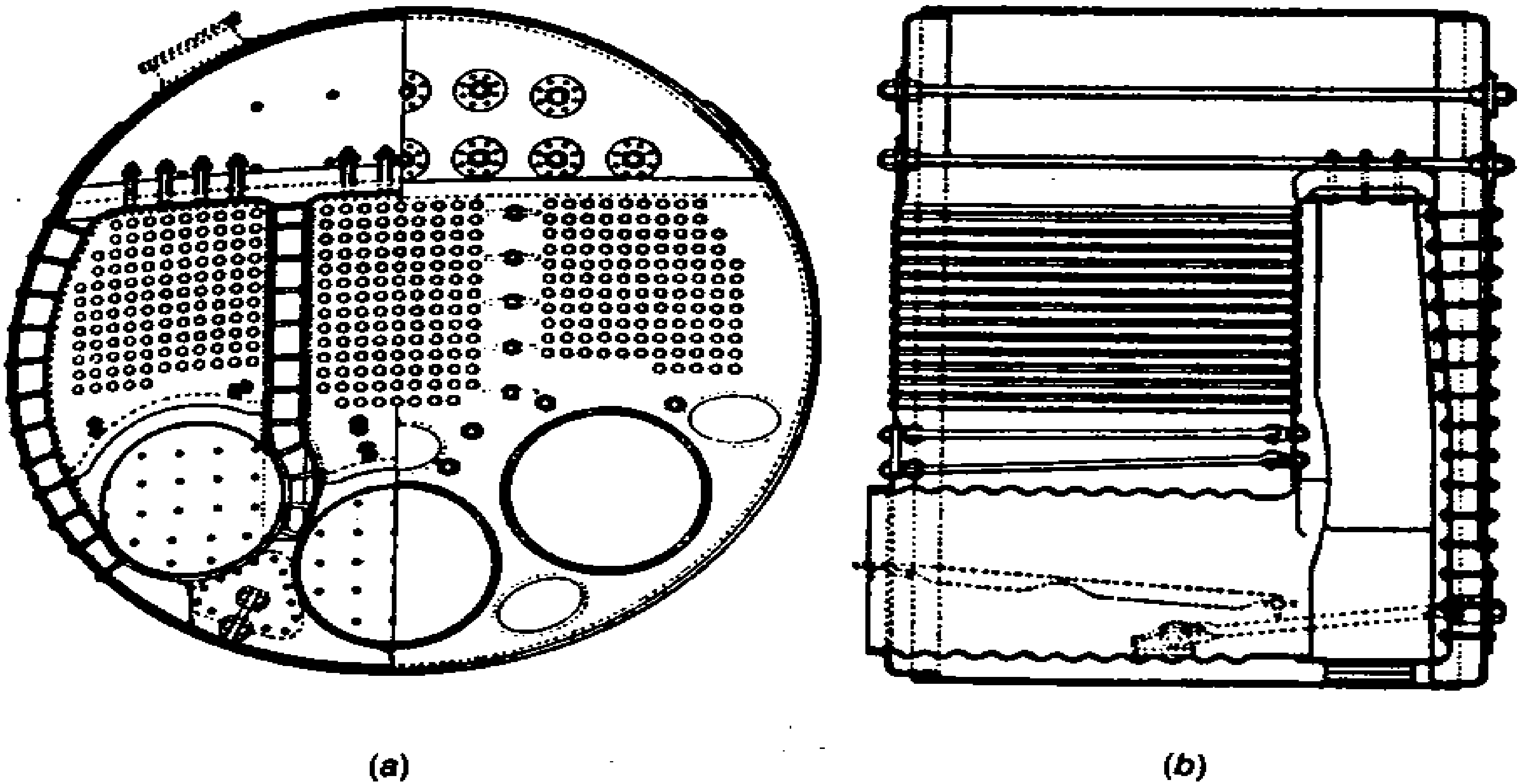


Figure 3-3 Schematic of an early scotch marine boiler.

Because boiling occurs in the same compartment where water is, fire-tube boilers are limited to saturated-steam production. They are presently confined to relatively small capacities and low steam pressures, such as supplying steam for space heating and, in decreasing numbers, for railroad locomotive service. The largest scotch marine boiler offered in the United States today is rated at 2000 boiler horsepower (blhp),* contains two combustion chambers within a 13-ft diameter, 30-ft-long shell.

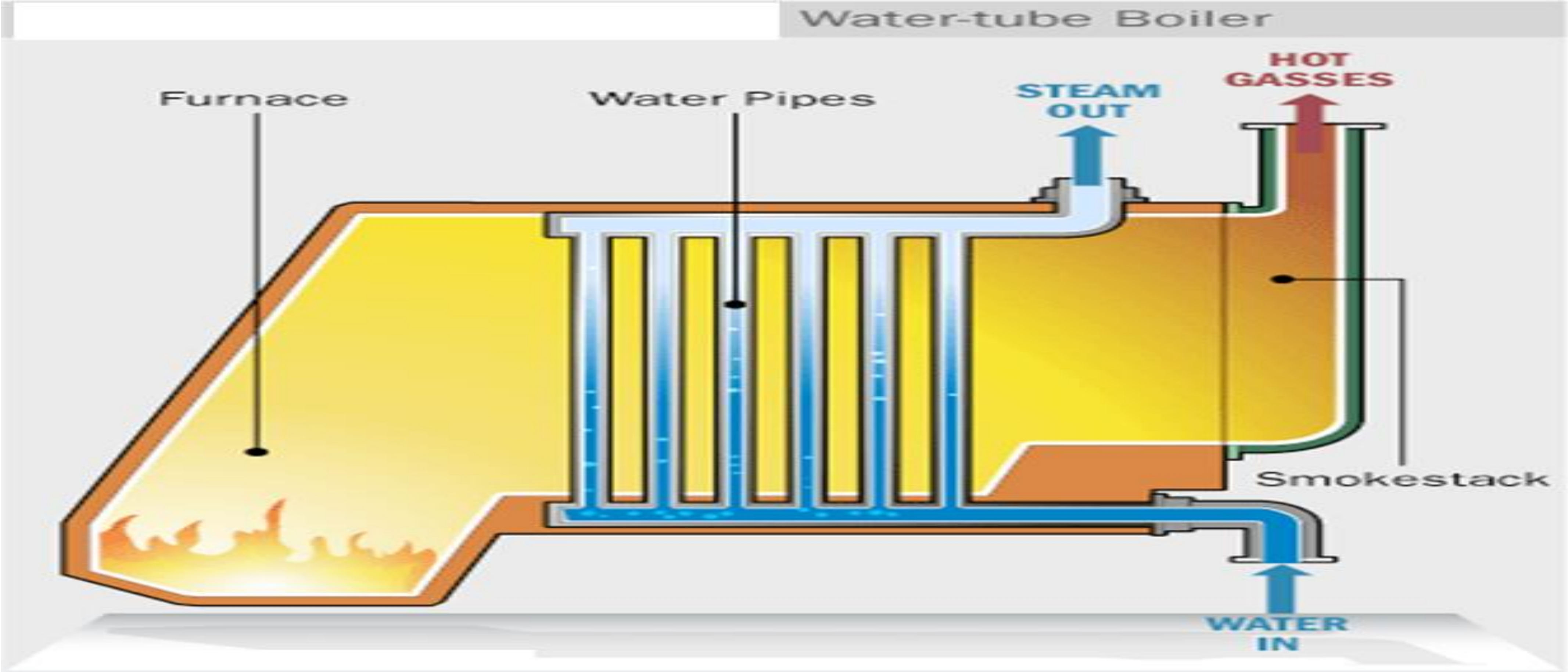
Advantages of Fire Tube Boilers

(*i*) *Low cost*

(*ii*) *Fluctuations of steam demand can be met easily*

(*iii*) *It is compact in size.*

2. Water Tube Boiler



The advent of the water-cooled furnace walls, called *water walls*, eventually led to the integration of furnace, economizer, boiler, superheater, reheater, and air preheater into the modern steam generator. Water cooling is also used for superheater and economizer compartment walls and various other components, such as screens, dividing walls, etc. The use of a large number of feedwater heaters (up to seven or eight) means a smaller economizer, and the high pressure means a smaller boiler surface because the latent heat of vaporization decreases rapidly with pressure. Thus a modern high-pressure steam generator requires more superheating and reheating surface and less boiler surface than older units. Beyond about 1500 psia, the water tubes represent the entire boiler surface and no other tubes, such as those seen in the earlier designs of the previous two sections, are required.

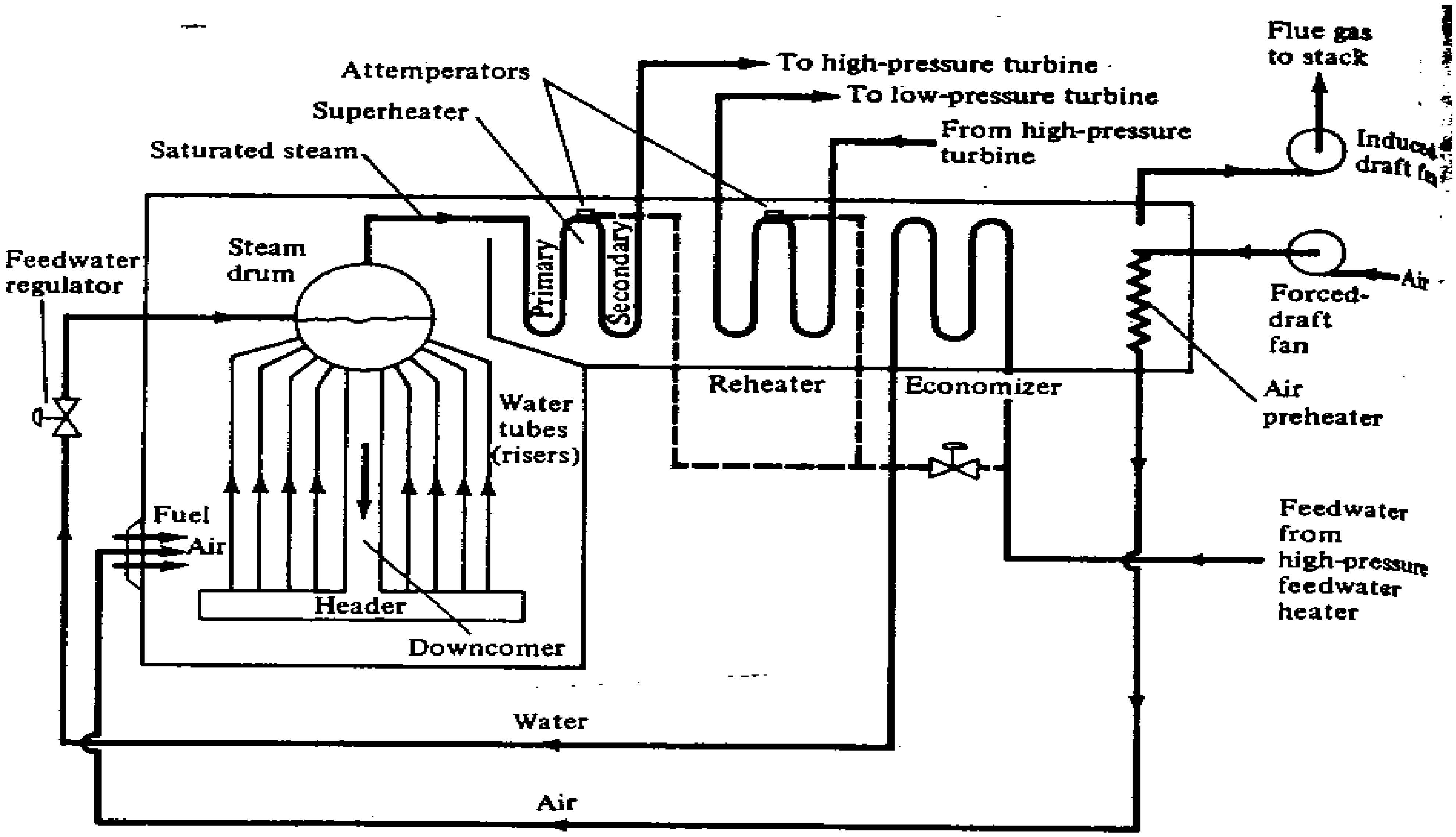


Figure 3-6 Schematic flow diagram of a modern steam generator.

Figure 3-6 shows a schematic flow diagram of a common steam-generator system. Water at 450 to 500°F from the plant high-pressure feedwater heater enters the economizer and leaves saturated or as a two-phase mixture of low quality. It then enters the steam drum at midpoint. Water from the steam drum flows through insulated downcomers, which are situated outside the furnace, to a header. The header connects to the water tubes that line the furnace walls and act as risers. The water in the tubes receives heat from the combustion gases and boils further. The density differential between the water in the downcomer and that in the water tubes helps circulation. Steam is separated from the bubbling water in the drum and goes to the superheater and the high-pressure section of the turbine. The exhaust from that turbine returns to the reheater, after which it goes to the low-pressure section of the turbine.

Atmospheric air from a *forced-draft (FD) fan* is preheated by the flue gases just before they are exhausted to the atmosphere. From there it flows into the furnace, where it mixes with the fuel and burns to some 3000°F. The combustion gases impart portions of some of their energy to the water tubes and then the superheater, reheater, and economizer, and leave the latter at about 600°F. From there they reheat the incoming atmospheric air in the air preheater, leaving it at about 300°F. An *induced draft (ID) fan* draws the flue gases from the system and sends them up the stack. The temperature of about 300°F of the exiting flue gas represents an availability loss to the plant. This, however, is deemed acceptable because (1) the gas temperature should be kept well above the dew point of the water vapor in the gases (equal to the saturation temperature of water at the partial pressure of the water vapor) to prevent condensation which would form acids that would corrode metal components in its path, and (2) the flue gases must have enough buoyancy to rise in a high plume above the stack for proper atmospheric dispersion.

Advantages of Water Tube Boiler

1. Generation of steam is much quicker due to small ratio of water content to steam content. This also helps in reaching the steaming temperature in short time.

2. Its evaporative capacity is considerably larger and the steam pressure range is also high-200 bar.

3. Heating surfaces are more effective as the hot gases travel at right angles to the direction of water flow.

4. The combustion efficiency is higher because complete combustion of fuel is possible as the combustion space is much larger.

5. The thermal stresses in the boiler parts are less as different parts of the boiler remain at uniform temperature due to quick circulation of water.

6. The boiler can be easily transported and erected as its different parts can be separated.

7. Damage due to the bursting of water tube is less serious. Therefore, water tube boilers are sometimes called safety boilers.

8. All parts of the water tube boilers are easily accessible for cleaning, inspecting and repairing.

9. The water tube boiler's furnace area can be easily altered to meet the fuel requirements.

Disadvantages

1. It is less suitable for impure and sedimentary water, as a small deposit of scale may cause the overheating and bursting of tube. Therefore, use of pure feed water is essential.

2. They require careful attention. The maintenance costs are higher.

3. Failure in feed water supply even for short period is liable to make the boiler over-heated.

SUPERHEATERS AND REHEATERS

Superheaters and reheaters in utility steam generators are made of tubes of 2 to 3 in OD (smaller sizes, about half these dimensions, are used in marine service). The smaller diameters have lower pressure stresses and withstand them better. The larger diameters have lower steam-flow pressure drops and are easier to align. Finning on the outside surface of the tubes is avoided because it increases thermal stresses and makes cleaning difficult. Internal ribbing, like that used in boiler water tubes, is unnecessary because no DNB problems arise here. Adequate heat-transfer design is based on gas flow inside the tubes, which has a much lower conductance than nucleate boiling in the boiler tubes. Because the tubes are subjected to high temperatures, pressures, and thermal stresses, their materials of construction must be carefully selected. Below 850°F carbon steel is adequate. Modern superheaters and reheaters operating at about 1000°F, however, are usually made of special high-strength alloy steels chosen for both strength and corrosion resistance . The exact alloy depends upon steam conditions and the types of fuel, especially if it contains undesirable impurities. The allowable stresses for materials drop drastically as the temperature increases.*

* For example, a material called Croloy 2¼, specification number SA213, Grade T22, has maximum allowable design stresses of 13,100, 11,000 and 7,800 psi at 900, 950, and 1000°F, respectively. Carbon steel SA210-A1 has allowable stresses of only 5000 and 3000 psi at 900 and 950°F, respectively.

Departure from nucleate boiling (DNB) : The point at which the heat transfer from a fuel rod rapidly decreases due to the insulating effect of a steam blanket that forms on the rod surface when the temperature continues to increase.

Convection Superheater

Early superheater designs placed them above or behind banks of water tubes to protect them from combustion flames and high temperatures. The main mode of heat transfer between the combustion gases and the superheater tubes, therefore, was convection, and that type of superheater became known as the *convection superheater*. The main distinguishing characteristic is its response to load changes. As demand for steam increases, fuel- and airflow, and hence combustion-gas flow, are increased. The convective heat-transfer coefficients increase both inside and outside the tubes, increasing the overall heat-transfer coefficient between gas and steam faster than the increase in mass-flow rate of the steam alone. (The combustion temperatures do not materially change with load.) Thus the steam receives greater heat transfer per unit mass-flow rate and its temperature increases with load (Fig. 3-10).

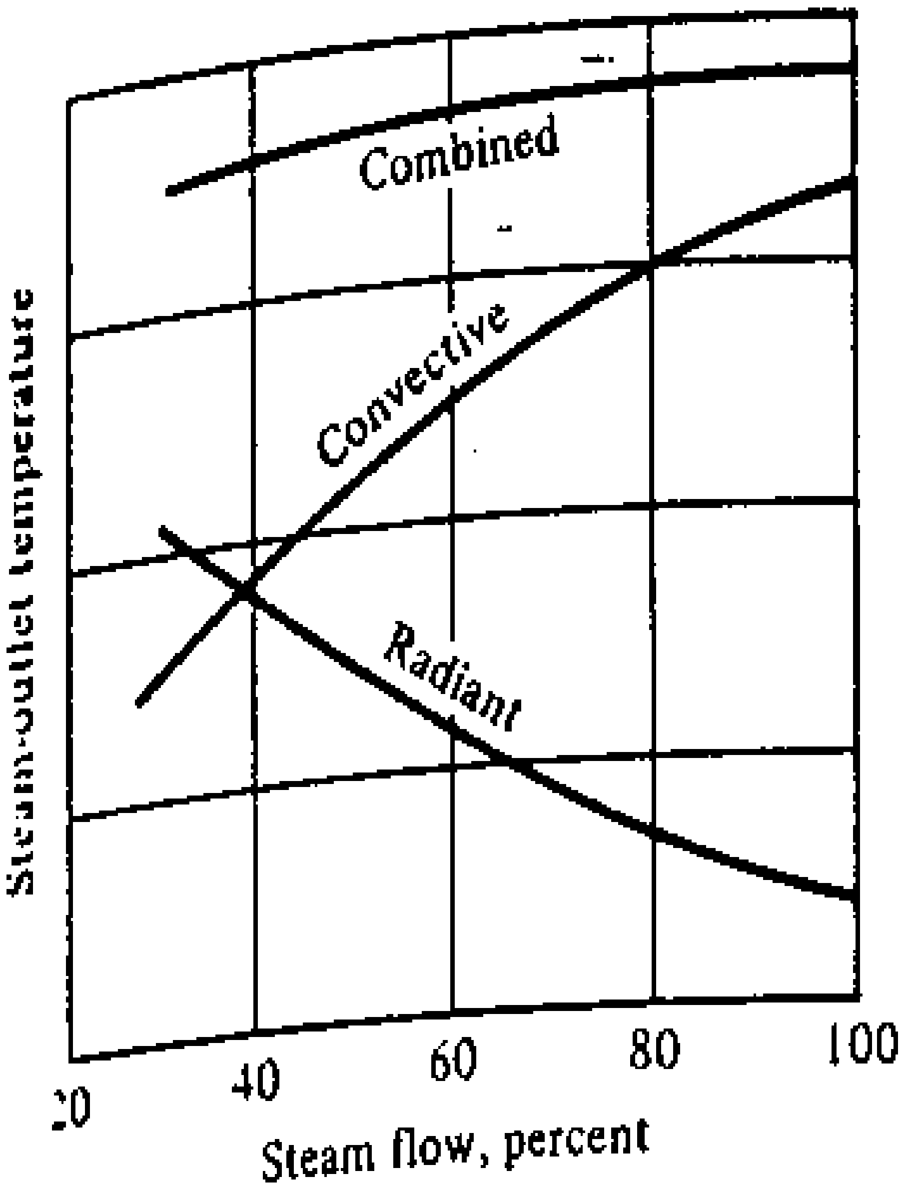


Figure 3-10 Exit-temperature response of convective, radiant, and combined (in-series) superheaters.

Radiant Superheater

Because of the need for greater heat absorption, superheaters were eventually placed nearer higher-temperature, in view of the combustion flames. Steam-flow velocities were increased to increase the overall heat-transfer coefficients, and overall superheater designs were improved to overcome expected higher metal temperatures.

This placement of superheater results in the main heat transfer between the hot gases and flame, and the tube outer walls, to be accomplished by radiation. This design has come to be known as a *radiant superheater*. Radiation heat transfer is proportional to $T_f^4 - T_w^4$, where T_f and T_w are the flame and tube wall absolute temperatures, respectively. Because T_f is much greater than T_w, the heat transfer is essentially proportional to T_f^4. Because T_f is not strongly dependent on load, the heat transfer per unit mass flow of steam decreases as the steam flow increases. Thus an increase in steam flow due to an increased load demand would result in a reduction in exit steam temperature, the opposite effect of a convection superheater (Fig. 3-10).

Design considerations for reheaters are similar to those for superheaters except that, although the steam outlet temperatures are about the same, the overall temperatures are lower and the steam pressures are about 20 to 25 percent of those in the superheaters. The pressure stresses are therefore lower and a lower grade steel alloy is tolerated. In addition, larger tubing with higher stresses may be used, which has the additional beneficial effect of reducing the pressure losses in the reheater.

Convection superheaters alone are used with low-temperature steam generators. Radiant and convection superheaters and reheaters are used for high-temperature service. The radiant units are arranged in flat panels or platen sections with wide spacings of several feet to permit radiation through. These are usually followed downstream by sections on a narrower spacing that permit both radiation and convection. Mechanical construction of the sections are of three kinds: *pendant*, *inverted*, and *horizontal*.

Pendant-type superheaters and reheaters are those that are hung from above (Fig. 3-11*a*). They have the advantage of firm structural support but the disadvantage of flow blockage by condensed steam after a cold shutdown, which necessitates slow restart to purge the water that accumulates in the bottom. *Inverted-type* units, on the other hand, are supported from below (Fig. 3-11*b*). They have proper drainage of the condensed steam but lack the structural rigidity of the pendant type, especially in high-speed gas flow. The inverted type is not commonly used. *Horizontal-type* units (Fig. 3-11*c*) are usually supported horizontally in the vertical gas ducts parallel to the main furnace and receive the hot gases after a U-turn at the top. They do not view the flame directly and hence are mainly of the convection type. They have both proper drainage and good structural rigidity. Figure 3-12 shows a typical arrangement of superheaters and reheaters. Superheaters and reheaters are often split into primary and secondary units for control purposes.

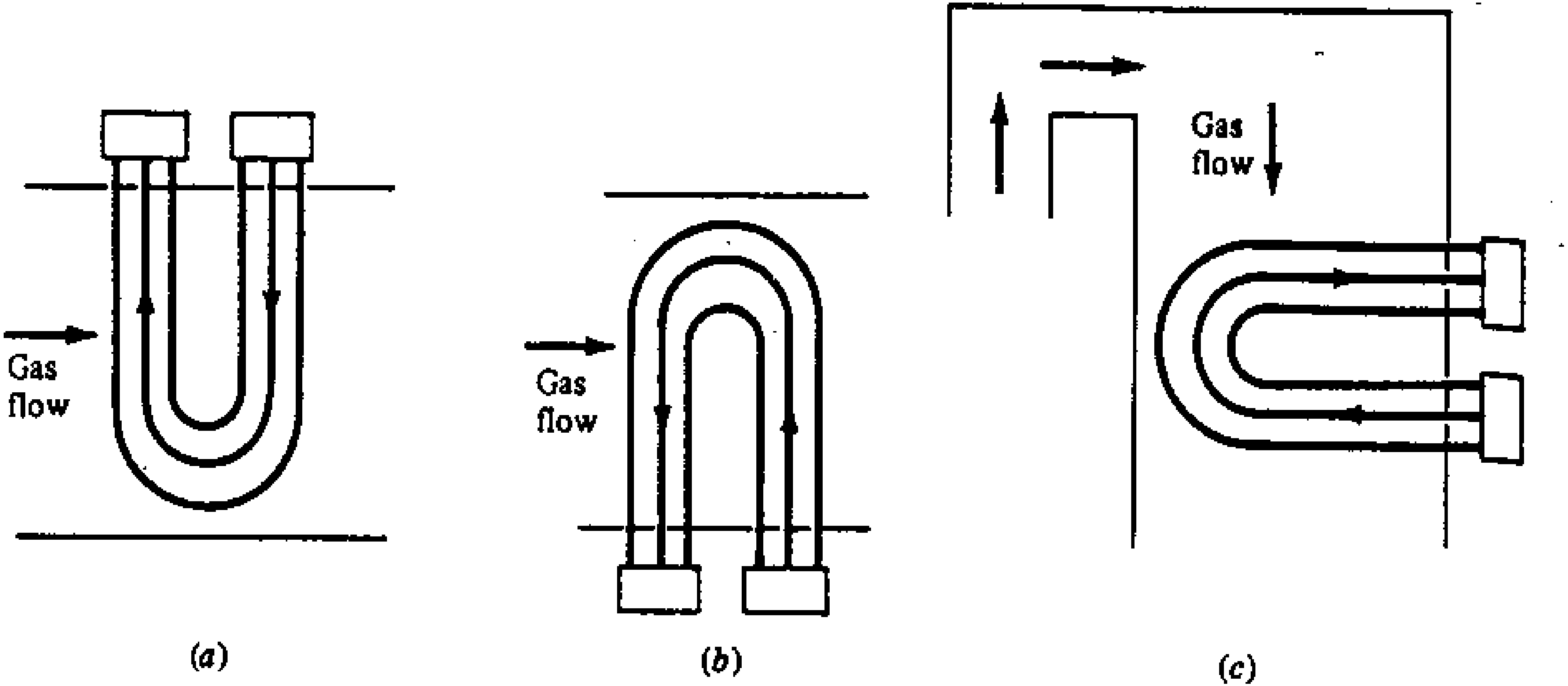


Figure 3-11 Schematic diagram showing (*a*) pendant, (*b*) inverted, and (*c*) horizontal superheaters and reheaters.

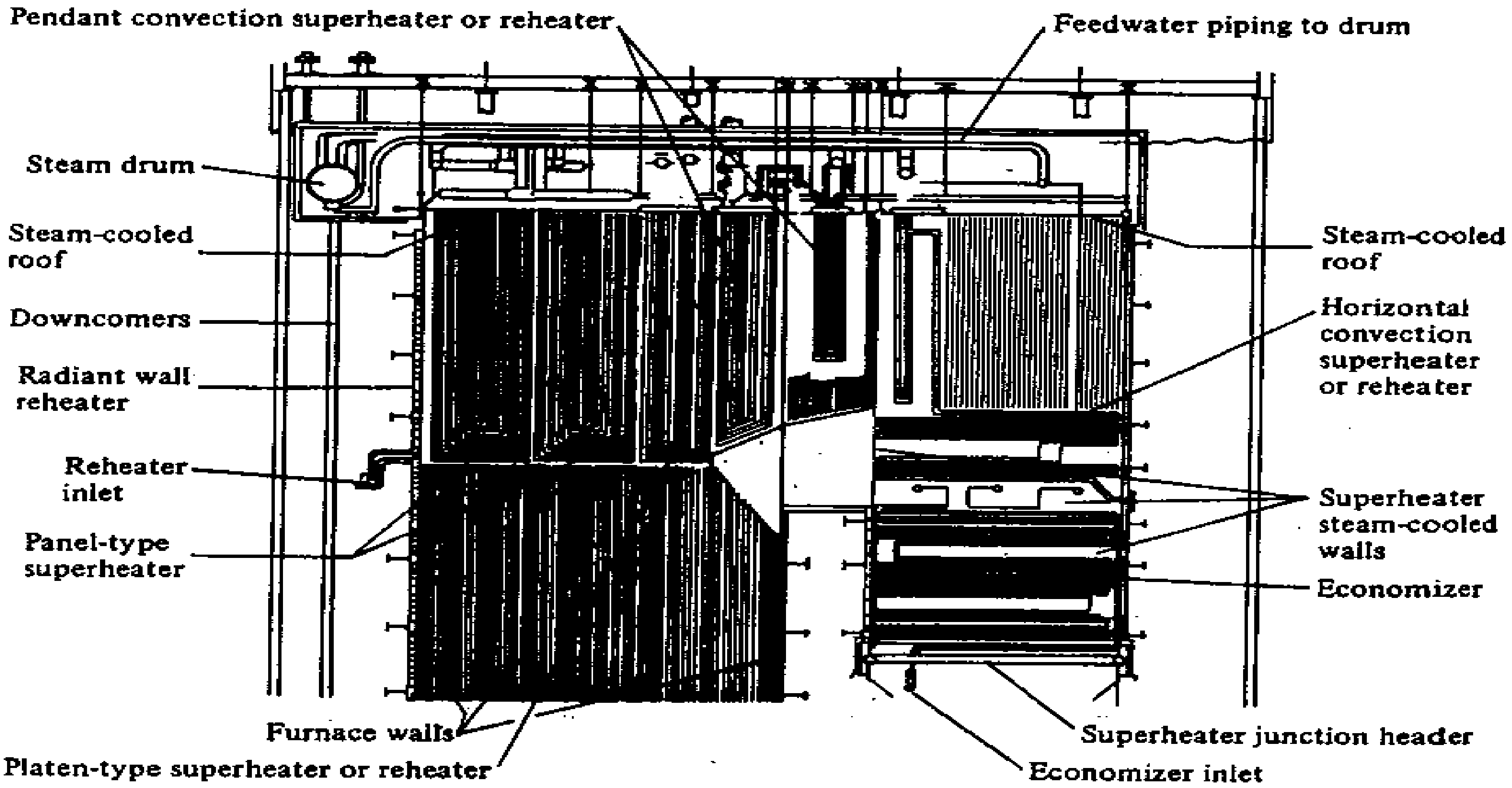


Figure 3-12 Superheater (SH), reheater (RH), economizer, and air preheater arrangements in a drum-type steam generator with cyclone furnace. (*Courtesy Babcock and Wilcox.*)

ECONOMIZERS

The *economizer* (EC) is the heat exchanger that raises the temperature of the water leaving the highest-pressure feedwater heater to the saturation temperature corresponding to the boiler pressure. This is done by gases leaving the last superheater or reheater. These gases, at high enough temperatures to transfer heat to the superheater-reheaters, enter the economizer at 700 to 1000°F. Part of their energy is used to heat the feedwater. The term "economizer" historically was used because the discharge of such high-temperature gases would have caused a large loss in availability and efficiency and hence loss in economy of operation.

Economizers were introduced before feedwater heating, which meant very low inlet water temperatures to the economizers and consequently low tube outer wall temperatures, below the dew point of the flue gases. This caused condensation and corrosion because of the presence of SO_2 and SO_3 in the gases. The moisture also aided in the collection of ash, thus fouling the tube outer surfaces that reduced heat transfer. Economizers were made of cast iron and had mechanical scrapers for cleaning. Early in its use, steel suffered from corrosive attack of the insides of the tubes by oxygen freed from the feedwater as its temperature rose in the economizer.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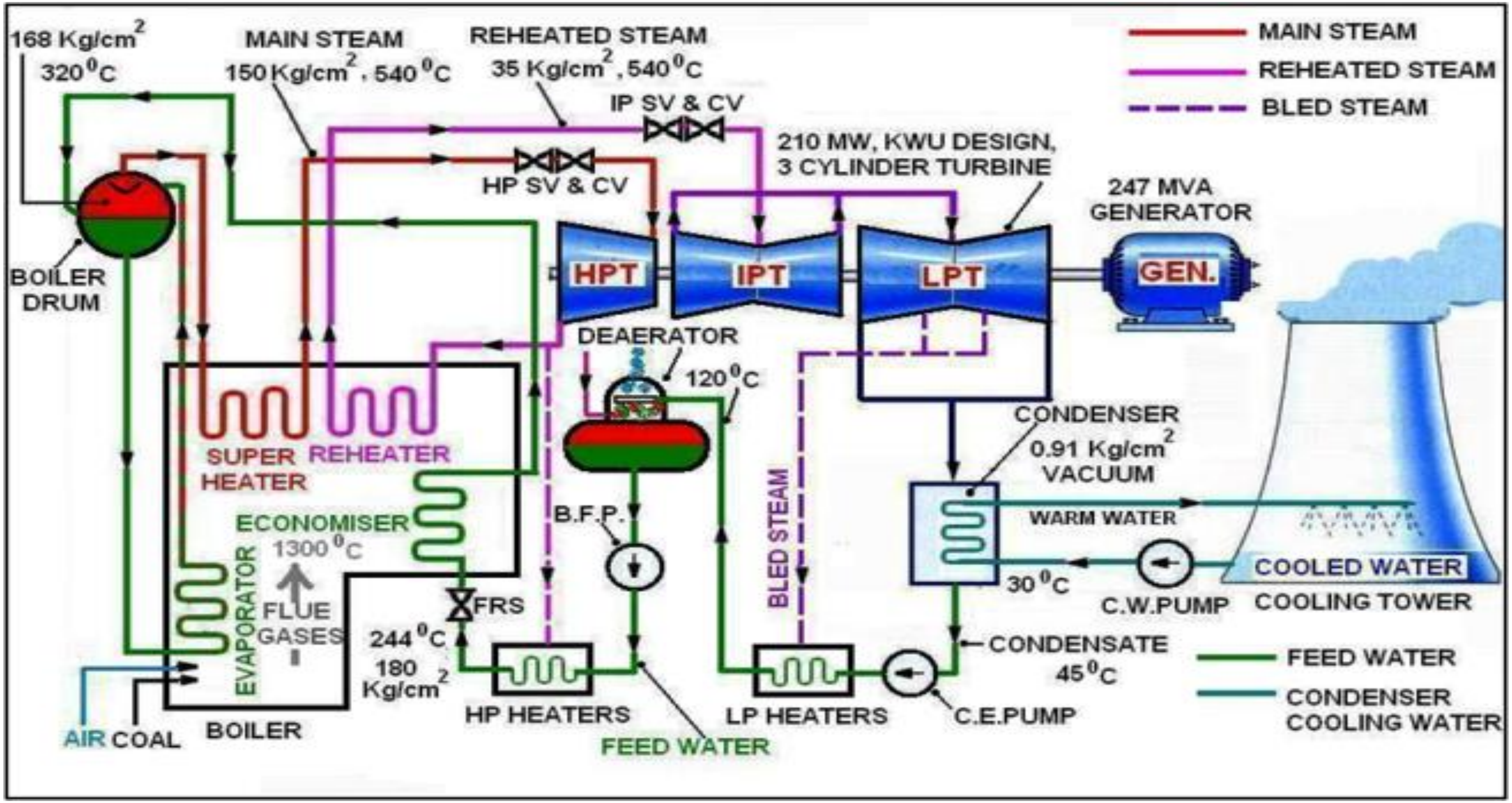
Modern steam generators receive heated feedwater and their economizers operate above the dew point of the gases, thus eliminating external corrosion and fouling. Chemical cleaning of internal surfaces is also used . Also, much of the feedwater oxygen is removed in the deaerating feedwater heater at or above 212°F, which reduces internal corrosion. This is also aided by maintaining the water in the economizer at a pH of 8 to 9. These advances permitted the use of steel, which in turn is suitable for the high pressures encountered in modern economizers.

Modern economizers are designed to allow some boiling of the feedwater in the outlet sections, up to 20 percent quality at full power, less at part loads.

Economizer tubes are commonly 1.75 to 2.75 in OD and are made in vertical sections of continuous tubes, between inlet to outlet headers, with each section formed into several horizontal paths connected by 180° vertical bends for proper draining. Sections are placed side by side on 1.75- to 2-in minimum spacings (edge to edge). The exact spacing depends upon the type of fuel and ash characteristics, which are smaller the cleaner the fuel, such as natural gas. When high-ash fuels are used, the water-soluble ashes accumulating on the economizer are dissolved and washed off during plant shutdown. In that case the economizer is usually located above a hopper, which receives the dissolved deposits. Steam or air-jet cleaning is also used in addition to washing.

Economizers have been built with plain or extended surface tubes. Extended surface tubes with fins or studs on their outer surface have higher heat-transfer characteristics and thus require smaller space. On balance, they have lower capital cost. They are, however, more suited to clean-burning gaseous fuels and situations in which no air preheaters are used, such as in combined steam-gas-turbine cycles.

Economizers are generally placed between the last superheater-reheater and the air preheater. In some cases, a low-temperature economizer is placed after the air preheater. Such an economizer is called a *stack cooler* and acts as a low-pressure feedwater heater except that the heating medium is the flue gas instead of steam bled from the turbine.



168 Kg/cm2
320 0C
MAIN STEAM
150 Kg/cm2, 540 0C
REHEATED STEAM
35 Kg/cm2, 540 0C
IP SV & CV
HP SV & CV
210 MW, KWU DESIGN,
3 CYLINDER TURBINE
247 MVA
GENERATOR
MAIN STEAM
REHEATED STEAM
BLED STEAM
BOILER
DRUM
HPT
IPT
LPT
GEN.
DEAERATOR
120 0C
SUPER
HEATER
REHEATER
CONDENSER
0.91 Kg/cm2
VACUUM
ECONOMISER
1300 0C
B.F.P.
BLED STEAM
WARM WATER
COOLED WATER
EVAPORATOR
FLUE
GASES
FRS
244 0C
180
Kg/cm2
30 0C
C.W.PUMP
COOLING TOWER
CONDENSATE
45 0C
FEED WATER
CONDENSER
COOLING WATER
AIR
COAL
BOILER
HP HEATERS
LP HEATERS
C.E.PUMP
FEED WATER

Air Pre-heater

Super heater and economizers generally cannot fully extract the heat from flue gases. Therefore, pre-heater are employed which recover some of the heat in the escaping gases. The function of an air pre-heater is to extract heat from the flue gases and give it to the air being supplied to furnace for coal combustion. This raises the furnace temperature and increases the thermal efficiency of the plant.

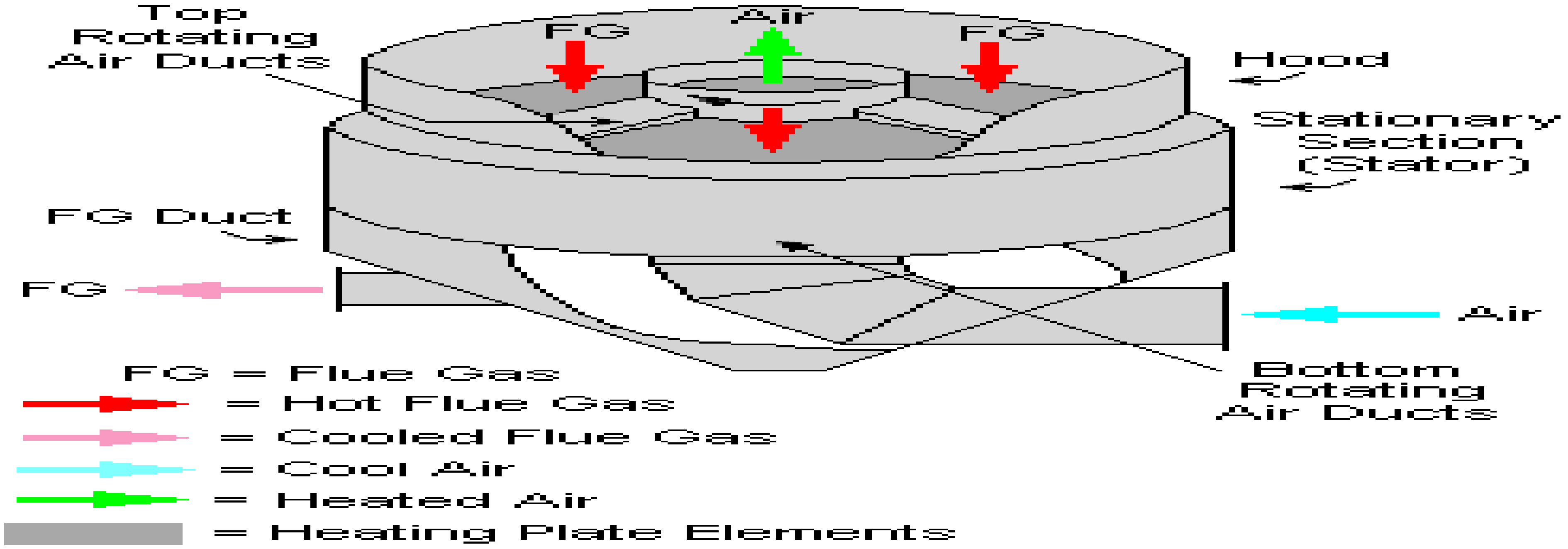
Classification

Depending upon the method of transfer of heat from flue gases to air, air pre-heaters are divided into the following two classes.

- Recuperative Type
- Regenerative Type

- **Recuperative Type**

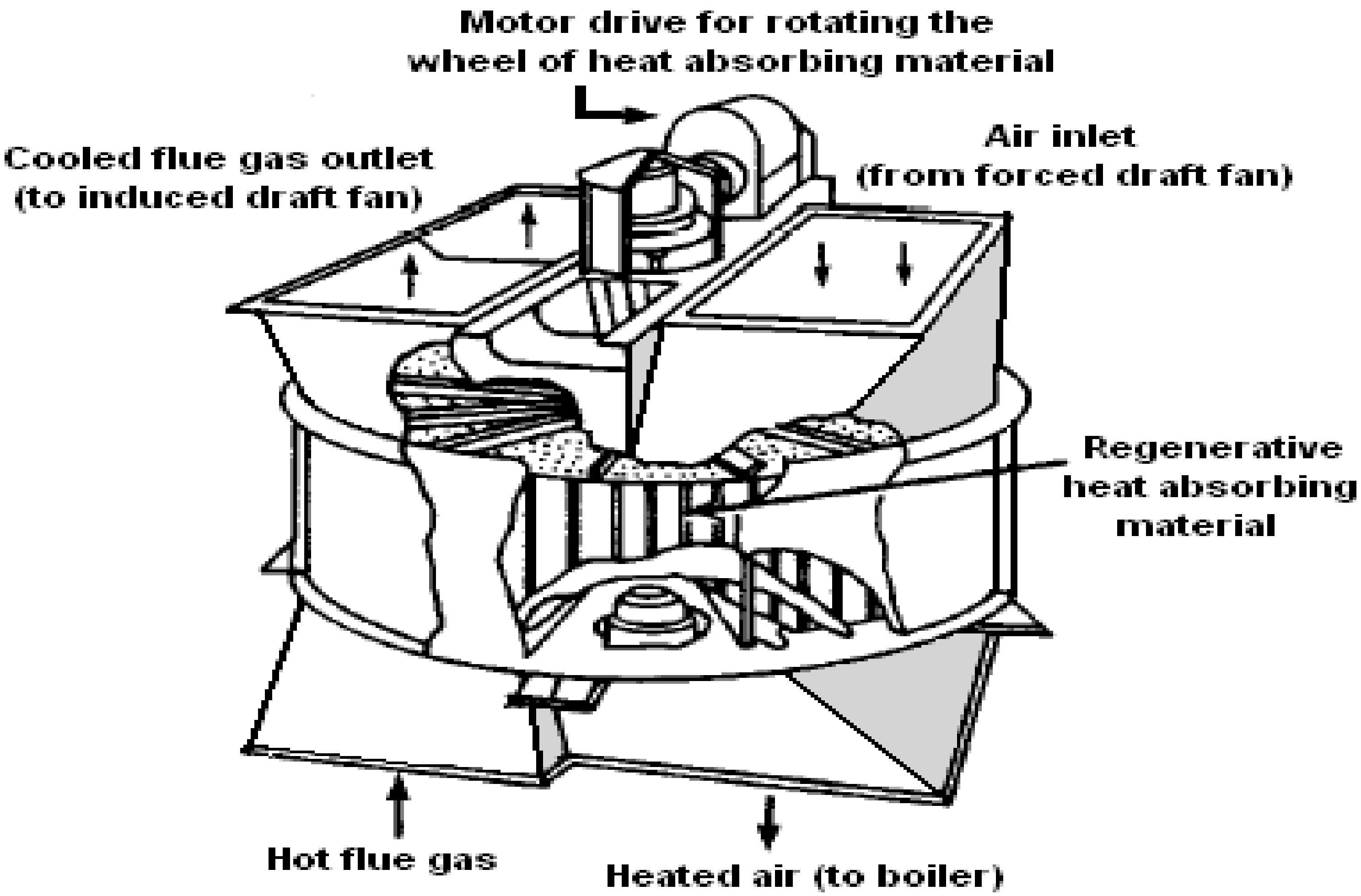
The recuperative type air heater consists of a group of steel tubes. The flue gases are passed through the tubes while the air flows externally to the tubes. Thus heat of flue gases is transferred to air.



Typical Stationary Plate Air Preheater

- **Regenerative Type**

The regenerative type air pre-heater consists of slowly moving drum made of corrugated metal plates. The flue gases flow continuously on one side of the drum and air on the other side. This action permits the transference of heat of flue gases to the air being supplied to the furnace for combustion.


Motor drive for rotating the
wheel of heat absorbing material
Cooled flue gas outlet
(to induced draft fan)
Air inlet
(from forced draft fan)
Regenerative
heat absorbing
material
Hot flue gas
Heated air (to boiler)

Air pre heater in TPS Muzaffargarh

No	Description	Specification
1	Type of air pre heater	Regenerative type
2	Speed of moving drum	2RPM
3	Pressure	1250 Pascal
4	Flue gases inlet temperature	330 C
5	Flue gases outlet temperature	160 C
6	Natural air inlet temperature	70 C
7	Natural air outlet temperature	260 C
8	Manufacturer	Techno Pron (USSR)