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INTRODUCTION

Scope

This guideline provides guidance in how to design a boiler. This design guideline can assist engineers to understand the basic design of boiler with a suitable size, material and heat of combustion.

The choice of boiler and distributor design is crucial to give the best performance of boiler. Good performance of boiler is influenced by the maximum the heat absorbed and minimum heat loss. The design of boiler may be influenced by factors, including process requirements, economics and safety. All the important parameters use in the guideline are explained in the definition section which help the reader more understand the meaning of the parameters or the term used.

The theory section explains how to calculate sizing and selection of a boiler. This guideline helps the reader to understand about heat balance concept. The application of the boiler theory with the examples will make the engineer understand boiler fundamentals and then be ready to perform the actual design of the boiler.

General Design Consideration

A boiler is any closed vessel in which for any purpose, steam is generated under pressure that is greater than atmospheric pressure. It includes any economizer used to heat to the water fed to the boiler, any super heater used for heating steam, and any pipes and fitting connected to the equipment.

The boiler system comprises of a feed water system, steam system and fuel system. The feed water system provides water to the boiler and regulates it automatically to meet the steam demand. The steam system collects and controls the steam produced in the boiler. Steam is directed through a piping system to the point of use. Steam pressure is regulated using valves and checked with steam pressure gauges. The fuel system includes all equipment used to provide fuel to generate the necessary heat.

There are several different chemical approaches used to treat boilers and their selection and performance depend upon many factors. Some of these include:

1. Feed water characteristics.
2. The type and reliability of external treatment.
3. Boiler type.
4. Boiler pressure and heat flux.
5. Steam load and variations in load.
6. Waterside condition of the boiler and current and long-term goals of the program such as cleaning up scale or maintaining present conditions.
7. Steam purity requirements.
8. Regulatory restrictions such as FDA requirements, other health and safety concerns, or process restrictions.
9. Feed, testing, and control needs or restrictions.
10. Economic considerations.
11. Boiler room layout and number of boilers.

Boilers can be classified by several criteria

1. **Utilization** - is utilized to produce steam for electrical power generation. Normally have large capacity, high steam parameters, and high boiler efficiency. There are two type boilers: industrial boiler and marine boilers.
   a. Industrial Boiler is utilized to produce steam for electrical power generation. Normally have large capacity, high steam parameters, and high boiler efficiency.
   b. Marine Boiler is utilized as a source of motive power for ships. Normally compact general shape, lighter general weight, and mostly fuel oil fired.

2. **Steam / Water Circulation**.
   a. Natural Circulation Boiler – the circulation of the working fluid in the evaporating tube is produced by the difference in density between the steam / water mixture in the risers and water in the down comers.
   b. Forced Multiple Circulation Boilers – the circulation of the working fluid in the evaporating tube is forced by means of a circulating pump included in the circulation circuit.
   c. Once Though Boiler – no drum, the working fluid passes through the evaporating tubes only under the action of the feed water pump.
   d. Combined Circulation Boiler – the system includes a pump, back pressure valve, and a mixer in the circuit. At starting the back pressure valve is opened and the boiler operates as a forced multiple circulation boiler.

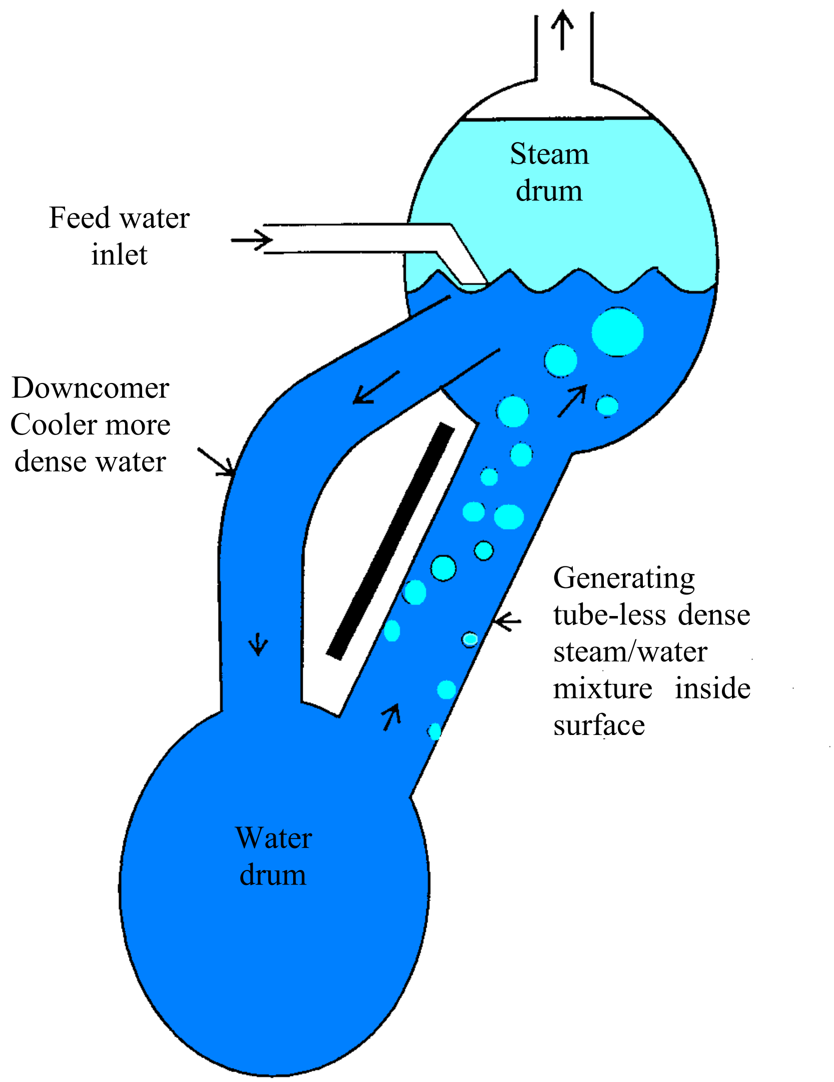


Figure 1: Principle of natural circulation

3. **Pressure**

   a. Low to medium pressure (< 10 Bar) – used as industrial boilers, normally has natural circulation.

   b. High pressure (10 – 14 Bar) – used as utility boilers, normally has natural circulation

   c. Super high pressure boilers (> 17 Bar) – used as utility, can be natural or forced circulation. The prevention of film boiling and high temperature corrosion should be considered.

   d. Supercritical pressure boilers (> 22.1 Bar) – used as utility boiler with large capacity once through or combined circulation. The prevention of film boiling and high temperature corrosion should be considered.

4. **Heat Source**

   a. Solid Fuel Fired Boiler – Typically low cost. The components of fuel and the characteristics of the ash are important factor for boiler design.

   b. Fuel Oil Fired Boiler – Has higher flue gas velocity and smaller furnace volume.

   c. Gas Fired Boiler – Natural Gas is utilized with higher flue gas velocities and smaller furnace volumes.

   d. Waste Heat Boiler - Utilizing waste heat from any industrial process as the heating source.

5. **Tube Layout**

   a. Fired Tube Boiler – Flue of hot gas is flowing inside the tubes. Water is contained inside the shell. Normally for small capacity boilers.

      Fired tube boilers consist of a series of straight tubes that are housed inside a water-filled outer shell. The tubes are arranged so that hot combustion gases flow through the tubes. As the hot gases flow through the tubes, they heat the water surrounding the tubes. The water is confined by the outer shell of boiler. To avoid the need for a thick outer shell fired tube boilers are used for lower pressure applications. Generally, the heat input capacities for fired tube boilers are limited to 50 mbtu per hour or less, but in recent years the size of fired tube boilers has increased.

Fired tube boilers typically have a lower initial cost, are more fuel efficient and are easier to operate, but they are limited generally to capacities of 25000 kg/h and pressures of 17.5 kg/cm^2

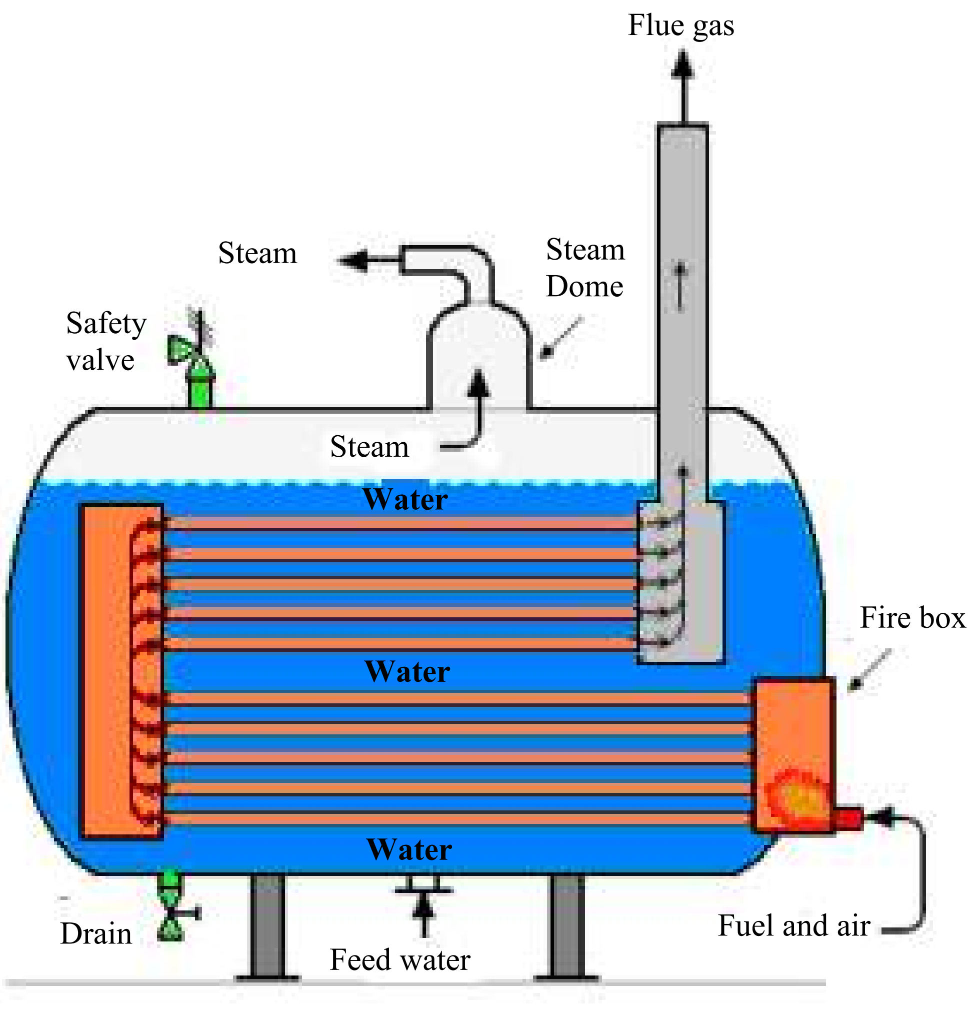


Figure 2: Typical fire tube boiler

b. Water Tube Boiler – Water is flowing inside the tubes. Flue or hot gas is flowing inside the furnace or shell. Normally this is for large capacity boilers.

Water tube boilers are designed to circulate hot combustion gases around the outside of a large number of water filled tubes. The tubes extend between an upper header, called a steam drum, and one or lower headers or drums. Because the pressure is confined inside the tubes, water tube boilers can be fabricated in larger sizes and used for higher-pressure applications.

Typically, the tubes should be greater than 5 mm in diameter and should be space so as to allow plenty of room for a flame path between them. Increasing the number of tubes may not increase the boiler's ability to generate steam. The inner surface of the outer casing is insulated with a ceramic sheet.

Most modern water boiler tube designs are within the capacity range 4,500 – 120,000 kg/h of steam, at very high pressures. Many water tube boilers are of "packaged" construction if oil and /or gas are to be used as fuel. Solid fuel fired water tube designs are available but packaged designs are less common. The features of water tube boilers are:

- Forced, induced and balanced draft provisions help to improve combustion efficiency.
- Less tolerance for water quality calls for water treatment plant.
- Higher thermal efficiency levels are possible

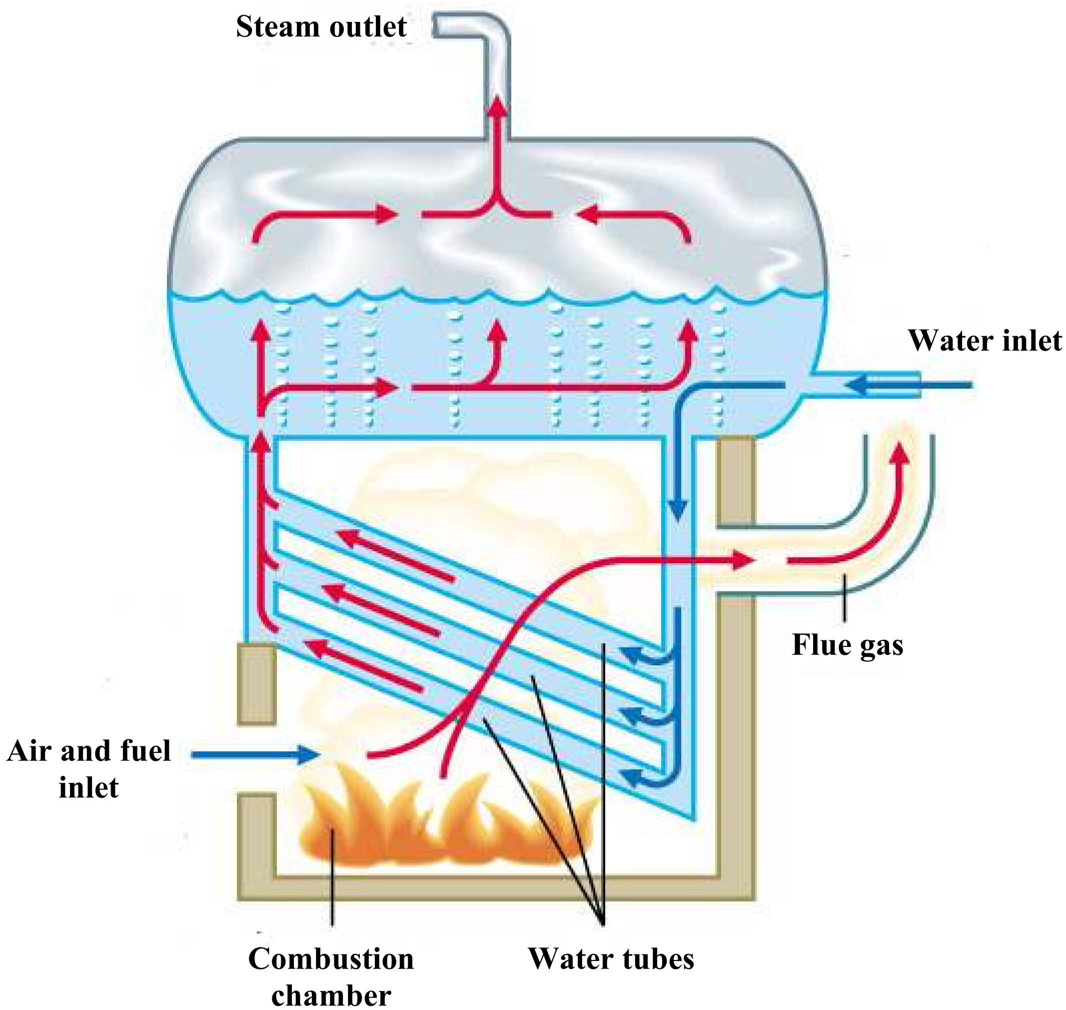


Figure 3: Typical water tube boiler

Table 1: Comparison of fired tube and water tube boiler

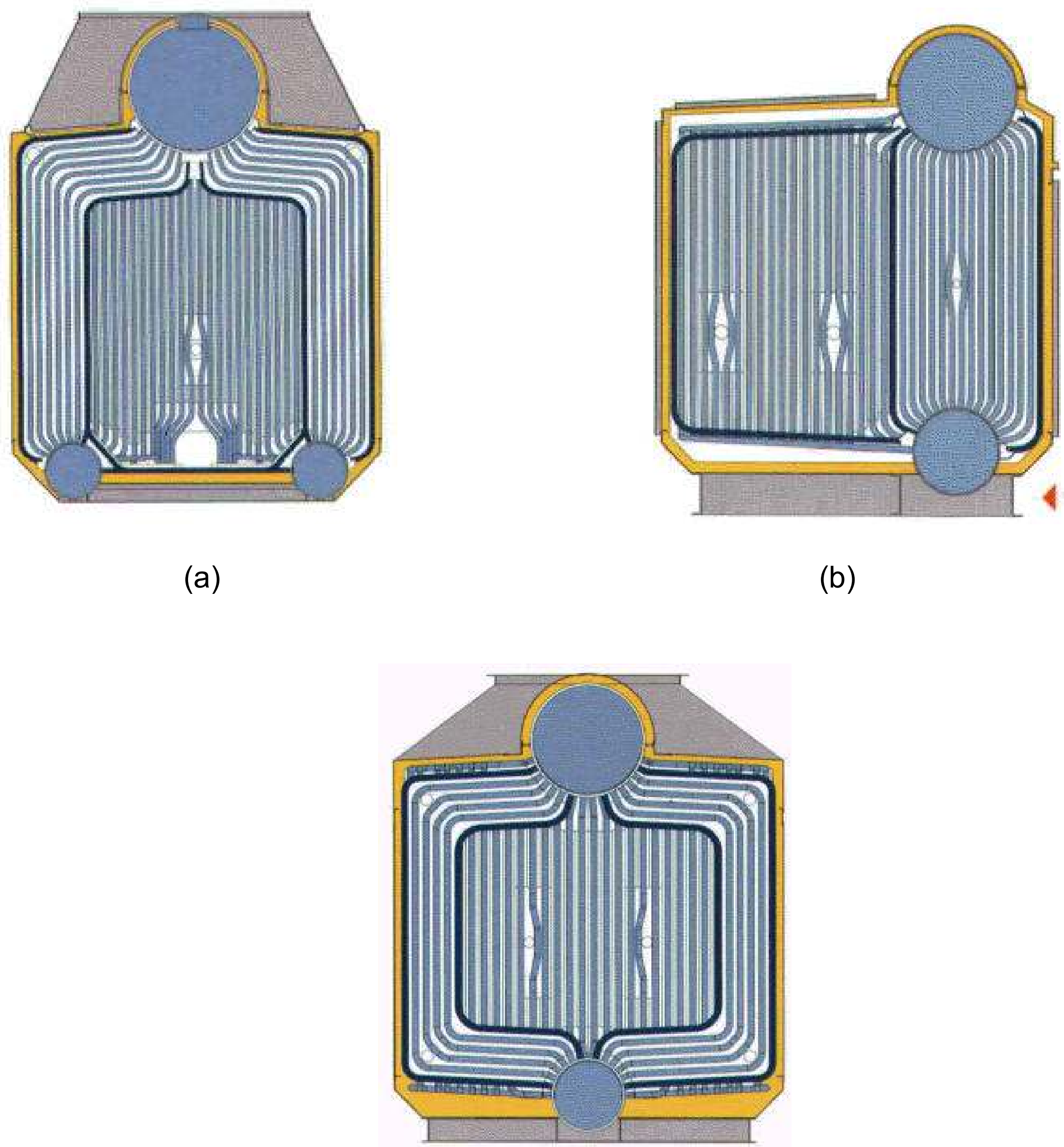
No	Parameter	Fired tube	Water tube
1	Rate of steam generation	Less rapid	More rapid
2	Pressure	< 25 kg/cm2	> 125 kg/cm2
3	Risk of explosion	Less	More
4	Floor space	More	Less
5	Cost	Higher	Less
6	Operating skill	Less	Higher
7	Water treatment	Low	Higher

6. **Boiler Layout.** There are three basic designs: A, D and O type. The names are derived from the general shapes of the tube and drum arrangements. All have steam drums for the separation of the steam from the water, and one or more mud drums for the removal of sludge.

   a. Type A - have two mud drums symmetrically below the steam drum. Drums are each smaller than the single mud drums of the type D or O. Bottom blows should not be undertaken at more than 80% of the rated steam load in these boilers. Bottom blow refers to the required regular blow down from the boiler mud drums to remove sludge and suspended solids.

   b. Type D is the most flexible design. They have a single steam drum and a single mud drum, vertically aligned. The boiler tubes extend to one side of each drum. Generally have more tube surface exposed to the radiant heat than other designs.

   c. Type O - have a single steam drum and a single mud drum. The drums are directly aligned vertically with each other, and have a roughly symmetrical arrangement of riser tubes. Circulation is more easily controlled, and the larger mud drum design renders the boilers less prone to starvation due to flow blockage, although burner alignment and other factors can impact circulation.



(a) (b)

(c)

Figure 4: Classify boiler by its layout: (a). Type A, (b) Type D, and (c) Type O

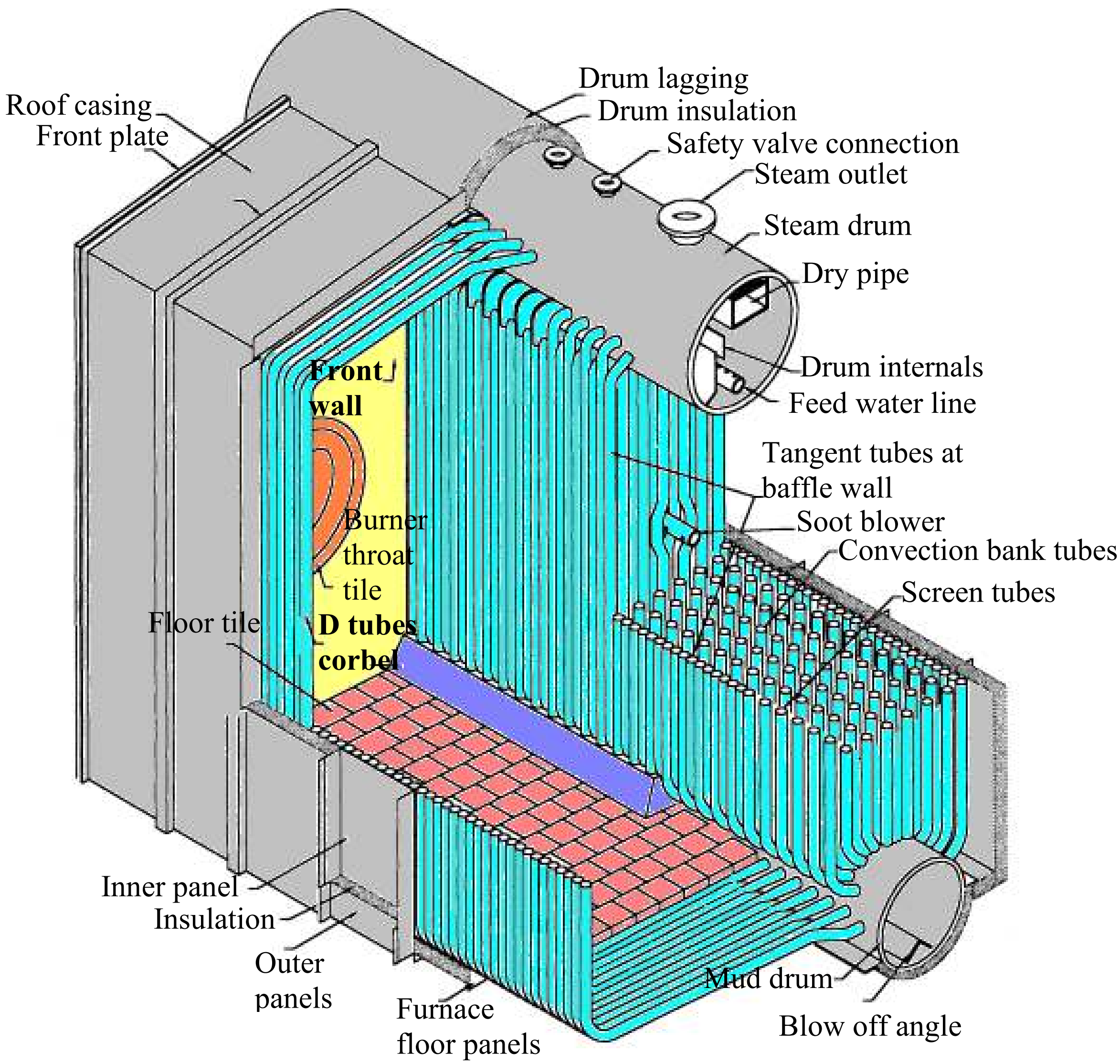


Figure 5: D Type detail

7. **Packaged Boiler.** It comes as a complete package. Once delivered to the site, it requires only the steam, water pipe work, fuel supply and electrical connections to be made for it to become operational. Packaged boilers are generally of shell type with fire tube design so as to achieve high heat transfer rates by both radiation and convection. The features of packaged boilers are:

- Small combustion space and high heat release rate resulting in faster evaporation.
- Large number of small diameter tubes leading to good convective heat transfer.
- Forced or induced draft systems resulting in good combustion efficiency.
- Number of passes resulting in better overall heat transfer.
- Higher thermal efficiency levels compared with other boilers.

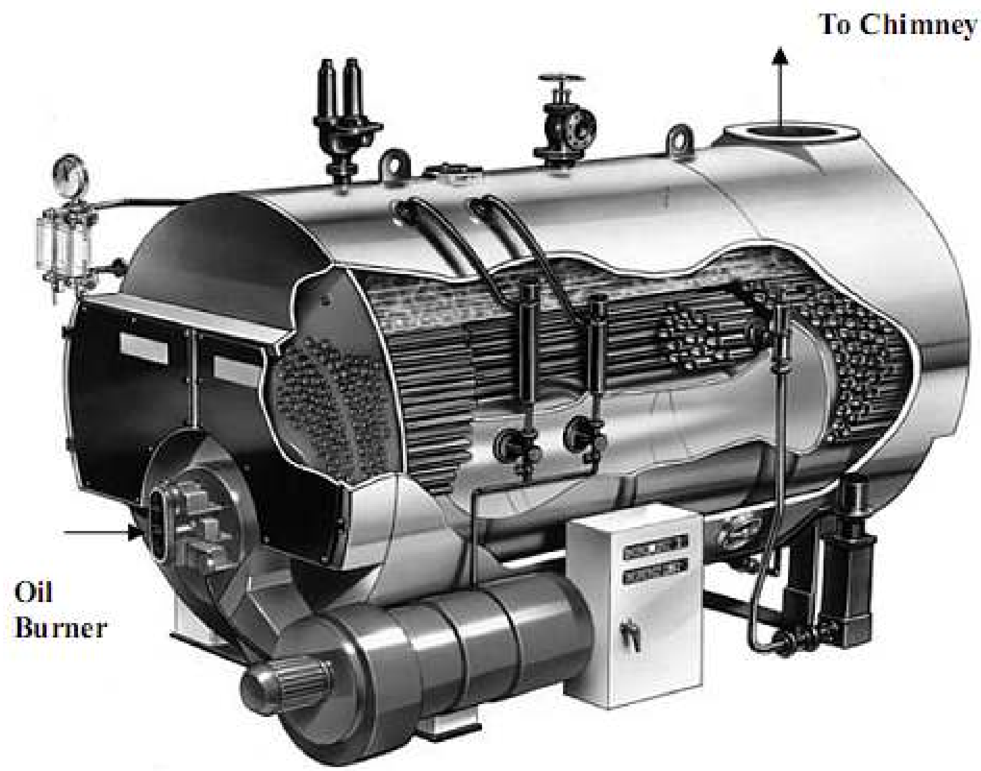


Figure 6: Packaged Boiler

Parts of Boilers

Boilers equipment consists of drums, shell, headers, tubes, baffles and economizer. Below are discuses those parts.

1. Drums, shell and headers

Boiler drums, shells or header are used to collect steam or hot water generated in the boiler and distributes it as necessary within the boiler tubes. These components must be strong enough to contain the steam that is generated and to mechanically hold the boiler tubes as they expand and contract with changes temperature. The shells of fire tubes boilers may be reinforced by the use of stays to hold the boiler heads in place. These components are generally fabricated with welded seams and connections.

2. Boiler Tubes

Boiler tubes carry water, steam, or flue gases through he boiler. Boiler tubes are installed by expanding or welding them into seats in the drums or headers. The expander is slipped into the end of the tube; it consists of a tapered pin which fits into a cage containing small rollers. The pin is turned with a wrench or motor, forcing the rollers out against the tube and simultaneously moving into the tube.

3. Baffles

Baffles are thin walls or partitions installed in water tube boilers to direct the flow of gases over the heating surface in the desired manner. The number and position of baffles have an effect on boiler efficiency. A leaking baffle permits gases to short circuit through the boiler. Heat which should have been absorbed by the water is then dissipated and lost further more tube may be damaged. Baffles maybe made of iron castings, a sheet metal strips, brick, tile, or plastic refractory. Provision must be made to permit movement between baffle and setting walls while still maintaining a gas tight seal.

4. Gage glass, Gage cocks.

Each boiler must have at least one water gage glass. If the operating pressure is 400 psig or greater, two gage glasses are required on the same horizontal line. Each gage glass must have a valve drain, and the gage glass and pipe connections must not be less than ½ inch pipe size. The lowest visible part of the gage glass must be at least 2 inches above the lowest permissible water level, which is defined as the lowest level at which there is no danger of overheating any part of the boiler during operation. For horizontal fire tube boilers the age glass is set to allow at least 3 inches of water over the highest point of the tubes, flues, or crown sheet at its lowest reading. A valve drains to some safe discharge point.

Each boiler must have three or more gage or try cocks located within the visible length of the gage glass. Gage cocks are used to check the accuracy of the boiler water level as indicated by the gage glass. They are opened by hand wheel, chain wheel, or lever, and are closed by hand, a weight, or a spring. The middle cock is usually at the normal water level of the boiler, the other two are spaced equally above and below it. Spacing depends on the size of the boiler.

5. Sootblowers

A sootblower is a device which is designed to blast soot and ash away from the walls of a furnace or similar piece of equipment. Sootblowers operate at set intervals, with a cleaning cycle that can vary in length, depending on the device and the size of the equipment which needs to be cleaned. Soot blowers function to keep combustion particles from sticking to boiler tube banks within the boiler tower.

The basic principle of the soot blower is the cleaning of heating surfaces by multiple impacts of high pressure air, steam or water from opposing nozzle orifices at the end of a translating-rotating tube. A traveling lance with nozzle jets penetrates the narrow openings in the boiler tube banks to blast the tubes clean. The tubes must be kept clean to allow optimum boiler output and efficiency. A common application at oil, coal or multi-fuel source power plants is retractable or rotary soot blowers

The primary elements of the typical soot blower should be: (1) A nozzle-especially selected for each application. (2) A means to convey the nozzle-conveying mechanism includes the lance tube, carriage and drive motor. (3) A means to supply blowing medium into the nozzle-poppet valve, feed tube, packing gland and lance tube. (4) A means to sup-port and contain the lower component -- a canopy type beam with a two-point suspension. (5) Con-trols-integral components protected by the beam to control the blowing cycle and supply power to the drive motor.

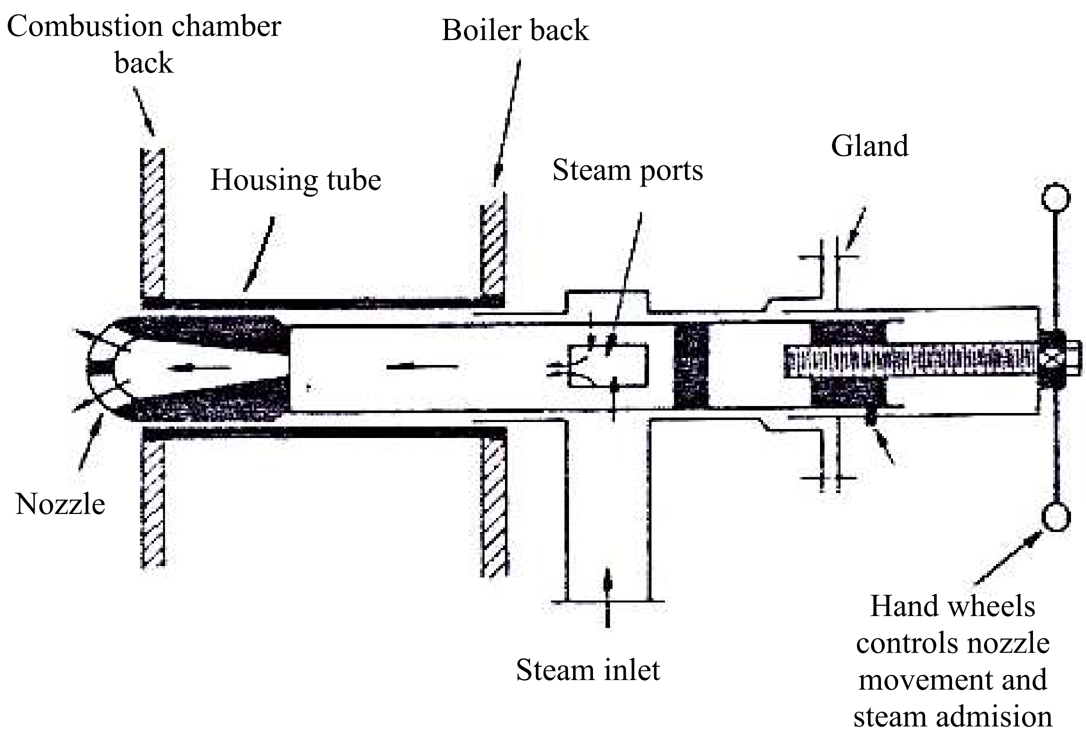


Figure 7: Sootblowers

6. Economizer

Economizers are used to recover heat from the boiler flue gases and thereby increase boiler efficiency. The heat absorbed by economizer is transferred to the boiler feedwater flowing through the inside of the economizer tubes. Continuous tube construction is common. Bare tubes are used for coal fired boilers and fin tubes or extended surface for gas and oil fired units. Extended surface on natural gas fired boiler may use up to 9 fins/in and for heavy oil fired 2 fins/in.

Economizers are usually arranged with gas flow down and water flow up that helps to avoid water hammer. Economizers should be equipped with three valve bypass on the water side to allow bypassing water at low boiler loads and minimize economizers corrosion.

Stacks or chimneys are necessary to discharge the products of combustion at a sufficiently high elevation to prevent nuisance due to low-flying smoke, soot, and ash. A certain amount of draft is also required to conduct the flue gases through the furnace, boiler, tubes, economizers, air heaters, and dust collectors, and the stack can help to produce part of this draft. The height of the stack necessary to:

a. **Stack construction.** Stacks are built of steel plate, masonry, and reinforced concrete. Caged ladders should be installed. All stack guys should be kept clear of walkways and roads and, where subject to hazardous contact, should be properly guarded. Stacks are provided with means of cleaning ash, soot, or water from their base, the means depending mainly of the size of the stack.

b. **Flues and ducts.** Flues are used to interconnect boiler outlets, economizers, air heaters, and stack. Ducts are used to interconnect forced-draft fans, air heaters, and wind boxes or combustion air plenums. Flues and ducts are usually made of steel. Expansion joints are provided to allow for expansion and contraction. All flues or ducts carrying heated air or gases should be insulated to minimize radiation losses. Outside insulation is preferred for its maintainability. Flues and ducts are designed to be as short as possible, free from sharp bends or abrupt changes in cross-sectional area and of adequate cross-sectional area to minimize draft loss at the design flow rates.

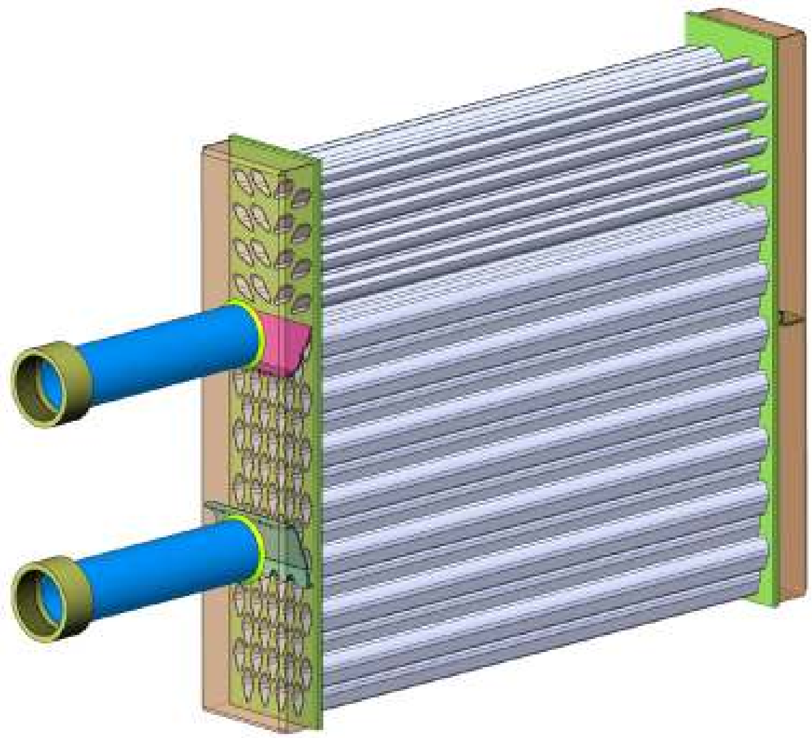


Figure 8: Economizer

A boiler must meet operational safety; generation of clean steam or hot at the desired rate, pressure, and temperature; economy of operation and maintenance; and conformance to applicable codes. To meet these requirements, a boiler must have the following characteristic

1. Adequate water or steam capacity
2. Properly sized steam / water separators for steam boilers
3. Rapid, positive, and regular water circulation
4. Heating surfaces which are easy to clean on both water and gas sides

5. Parts which are accessible for inspection and repair
6. Correct amount land proper arrangement of heating surface
7. A furnace of proper size and shape for efficient combustion and for directing the flow of gases for efficient heat transfer

General rules for boiler (energyefficiencyasia.org)

1. 5% reduction in excess air increases boiler efficiency by 1% (or 1% reduction of residual oxygen in stack gas increases boiler efficiency by 1%).
2. 22 °C reduction in flue gas temperature increases the boiler efficiency by 1%.
3. 6 °C rise in feed water temperature brought about by economizer/condensate recovery corresponds to a 1% savings in boiler fuel consumption.
4. 20 °C increase in combustion air temperature, pre-heated by waste heat recovery, results in a 1% fuel saving.
5. A 3 mm diameter hole in a pipe carrying 7 kg/cm^2 steam would waste 32,650 litres of fuel oil per year.
6. 100 m of bare steam pipe with a diameter of 150 mm carrying saturated steam at 8 kg/cm^2 would waste 25 000 litres furnace oil in a year.
7. 70% of heat losses can be reduced by floating a layer of 45 mm diameter polypropylene (plastic) balls on the surface of a 90 °C hot liquid/condensate.
8. A 0.25 mm thick air film offers the same resistance to heat transfer as a 330 mm thick copper wall.
9. A 3 mm thick soot deposit on a heat transfer surface can cause a 2.5% increase in fuel consumption.
10. A 1 mm thick scale deposit on the waterside could increase fuel consumption by 5 to 8%.

Boilers are equipped with safety devices to minimize the risk of low water and explosion related damage. A typical oil or gas fired boiler safety control system includes the following components:

1. Low water fuel cutoff switch
2. High steam pressure or high water temperature switch
3. Flame scanner
4. Gas supply high pressure switch
5. Gas supply low pressure switch
6. Combustion air flow switch
7. Purge air flow switches
8. Fuel safety shutoff valves with closed-position switches
9. Fuel control valves with low-fire position switch
10. Manual valves , cocks, strainers, and traps
11. Atomizing steam or air switch(es)
12. Atomizing steam or air shutoff and control valves
13. Low oil pressure switch
    High furnace pressure switch (for boiler with induce draft fans)
14. Fan motor switch(es)
15. Control logic

DEFINITIONS

Ash – Incombustible matter in fuel

Baffle – A plate or wall for deflecting gases or liquids

Boiler Horse Power (BHP) – The evaporation of 34 ½ pounds of water per hour from a temperature of 212F into dry saturated steam at the same temperature. Equivalent to 33.472 Btu/h

Burner – A device for the introduction of fuel and air into a furnace at the desired velocities, turbulence and concentration to establish and maintain proper ignition and combustion of the fuel.

Bypass – A passage for a fluid, permitting a portion or all of the fluid to flow around certain heat absorbing surfaces over which it would normally pass.

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.

Coal – Solid hydrocarbon fuel formed by ancient decomposition of woody substance under conditions of heat and pressure.

Combustion – The rapid chemical combination of oxygen with the combustible elements of a fuel resulting in the production of heat.

Continuous Blowdown – The uninterrupted removal of concentrated boiler water from a boiler to control total solids concentration in the remaining water.

Control, Safety – Control (including relays, switches, and other auxiliary equipment used in conjunction therewith to form a safety control system) which are intended to prevent unsafe operation of the controlled equipment.

Corrosion – The wasting away of metals due to chemical action in a boiler usually caused by the presence of oxygen, carbon dioxide, or an acid.

Damper – A device for introducing a variable resistance for regulating the volumetric flow of gas or air.

Drum – A cylindrical shell closed at both ends design to withstand internal pressure.

Drum Head – A plate closing the end of a boiler drum or shell.

Dry Steam - Either saturated or superheated steam containing no moisture

Economizer – A heat recovery device designed to transfer heat of the products of combustion to boiler feed water.

Excess air - The extra air supplied to the burner beyond the air required for complete combustion. Excess air is supplied to the burner because a boiler firing without sufficient air or "fuel rich" is operating in a potentially dangerous condition.

Feed water – Water introduced into a boiler during operation. It includes make-up and return condensate.

Feed water Treatment – The treatment of boiler feed water by the addition of chemicals to prevent the formation of scale or eliminate other objectionable characteristics.

Flue gas temperature - The temperature of the combustion gases as they exit the boiler. The flue gas temperature must be a proven value for the efficiency calculation to be reflective of the true fuel usage of the boiler.

Fuel – A substance containing combustible matter, and used for generating heat.

Gage Pressure – The pressure above atmospheric pressure.

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.

Heat Balance – An accounting of the distribution of the heat input and output.

Lagging – A covering, usually metallic to protect insulating material, on boiler, pipes or ducts.

Leakage – The uncontrolled quantity of fluid which enters or leaves through the enclosure of air or gas passage.

Make-Up – The water added to boiler feed to compensate for that lost through exhaust, blow down, leakage, etc.

Nozzle – A short flanged or welded neck connection on a drum or shell for the outlet or inlet of fluids; also projecting spout for the outlet or inlet of fluids; also a projecting spout through which a fluids flow.

Saturated Steam – Steam at the pressure corresponding to its saturation temperature.

Sediment – Matter in water which is in suspension and can be removed by gravity or mechanical means. Non-Combustible solid matter which settles out at the bottom of an oil tank; a small percentage is present in residual fuel oils.

Soot Blower – A mechanical device for discharging steam or air to clean heat absorbing surfaces.

Stack – A vertical conduit to discharge combustion products to the atmosphere.

Steam – The vapor phase of water substantially unmixed with other gases.

Superheat – To raise the temperature of steam above its saturation temperature, the temperature must be in excess of its saturation temperature.

Superheated Steam – Steam at a higher temperature than its saturation temperature.
Saturated steam: It is the steam, whose temperature is equal to the boiling point corresponding to that pressure.

Stack temperature is a measure of the heat carried away by dry flue gases and the moisture loss. It is a good indicator of boiler efficiency.

Tube – A hollow cylinder for conveying fluids.

Turndown - The ability of the boiler to achieve a wide range (from low to high) of output. The higher the turndown the wider the range of output capabilities.

Wet Steam - Saturated steam which contains moisture

NOMENCLATURE

%B	Percent blow down, %
C	Maximum permissible solid concentration inside the boiler drum, ppm
C_B	Boiler cycle, cycles
C_{FG}	Specific heat of flue gas, kcal/kg°C
C_V	Gross caloric value of fuel, kcal/kg
CO_{2t}	percent CO2 theoretical, %
CO_2	percent CO2, %
E_B	Efficiency of boiler, %
EA	Excess air, %
E_{eco}	Economizer efficiency, %
FW_{makeup}	Feed water makeup, kg/h
G_B	Rate of boiler blow down, kg/h
G_{feco}	Fuel consumption when using economizer, kg/h
G_{fsave}	The saving fuel consumption, kg/h
G_{FW}	Boiler feed water to heat, kg/h
G_s	Steam flow rate produced, kg/h
G_f	Fuel firing rate, kg/h
H	Steam enthalpy, kcal/kg

H_{FW}	Feed water enthalpy, kcal/kg
Q_B	Heat absorbed in boiler, kcal/h
Q_{eco}	Heat absorbed in economizer, kcal/h
$\%Q_{lostFG}$	Precent heat loss to flue gas, %
S	Solid concentration in boiler feed water, ppm
S_B	Boiler size, BHP
T_{air}	Temperature of air supplied to boiler, ^oC
T_{FGeco}	Temperature of flue gas entering economizer, ^oC
T_{FG}	Flue gas temperature, ^oC
T_{FW}	Temperature of feed water inlet to boiler, ^oC
$T_{FW\ eco}$	Temperature of feed water inlet to economizer, ^oC
W_{FG}	Weight of flue gas produced, kg
W_{air}	Weight air supplied, kg

Superscript

T	Temperature, ^oC
G	Rate, kg/h
E	Efficiency, %