Power Plant Engineering

Lecture 5

Steam Generators (Boilers)

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Lecture learning outcomes:

At the end of this lecture, you will be able to:

i. Explain the basic principles of boiler operation and classify boilers based on design, fuel type, and application.

ii. Identify and describe the different types of boilers and their industrial and power generation applications.

iii. Distinguish between boiler mountings and accessories and explain their functions in ensuring efficient and safe boiler operation.

iv. Evaluate boiler performance and efficiency using key performance indicators and methods of improving thermal efficiency.

v. Analyze the concept of boiler draught, differentiate its types, and discuss their roles in combustion and heat transfer.

vi. Demonstrate understanding of boiler operation, maintenance, and safety practices to ensure reliable and hazard-free performance.

Content

1. Introduction and Classification of Boilers
2. Types of Boilers and their Applications
3. Boiler Mountings and Accessories
4. Boiler Performance and Efficiency
5. Boiler Draught and its Types
6. Boiler Operation, Maintenance, and Safety

Summary

References

1. Introduction and Classification of Boilers

- A boiler is a closed vessel in which water is heated to produce steam using heat energy from fuel combustion [1].
- The steam produced may be supplied
  - ✓At high pressure to steam engine or turbines for power generation.
  - ✓At low pressure for industrial process work in sugar factories, breweries, textiles etc…

  Example:- in the textiles for sizing and bleaching.
  - ✓For producing hot water which can be used for heating a building in cold weather and for hot water supply.

1. Introduction and Classification of Boilers

Cont…

- The primary requirements of steam generators or boilers are:
  - ✓The water must be contained safely,
  - ✓The steam must be safely delivered in desired condition as regards to its pressure, temperature, quality, and required rate
- In general, the functions of a Boiler are to:
  - ✓Convert water into steam at desired pressure and temperature
  - ✓Transfer heat efficiently from fuel to water
  - ✓Provide safe and controlled steam generation

1. Introduction and Classification of Boilers

Cont…

- Essential Components of a Boiler
  - Shell: The main outer cylindrical body of a boiler.
  - Furnace: Where fuel is burned to generate heat
  - Burner: The device that mixes and ignites the fuel and air.
  - Water space: Holds water to be converted into steam
  - Steam space: Collects the generated steam
  - Grate: Supports the burning fuel
  - Chimney: Releases combustion gases
  - Feedwater System: Pumps and controls to supply water to the boiler.

1. Introduction and Classification of Boilers

Cont…

Classification of Boilers

- Boilers can be classified based on several key design and operational features.

1. Based on tube content
2. Based on fuel Used
3. Method of firing
4. Axis of the shell
5. Pressure of steam
6. Number of tubes
7. Method of water circulation

2. Types of Boilers and Their Applications

- Understanding the types of boilers helps in selecting the right system for industrial, commercial, or domestic use [2].
- Boilers are classified based on design, fuel type, pressure, and application.

1. Based on Tube Content

a. Fire-tube (smoke-tube) Boiler

- The flame and hot gasses produced by combustion of fuel pass through the tubes which are surrounded by water.
- Heat is conducted through the walls of the tubes from the hot gasses to the surrounded water.

Examples: Simple vertical boiler, Cochran boiler, Lancashire boilers, Cornish boiler, Scotch marine boiler, Locomotive boiler.

2. Types of Boilers and Their Applications

Cont…

Fire-Tube Boiler

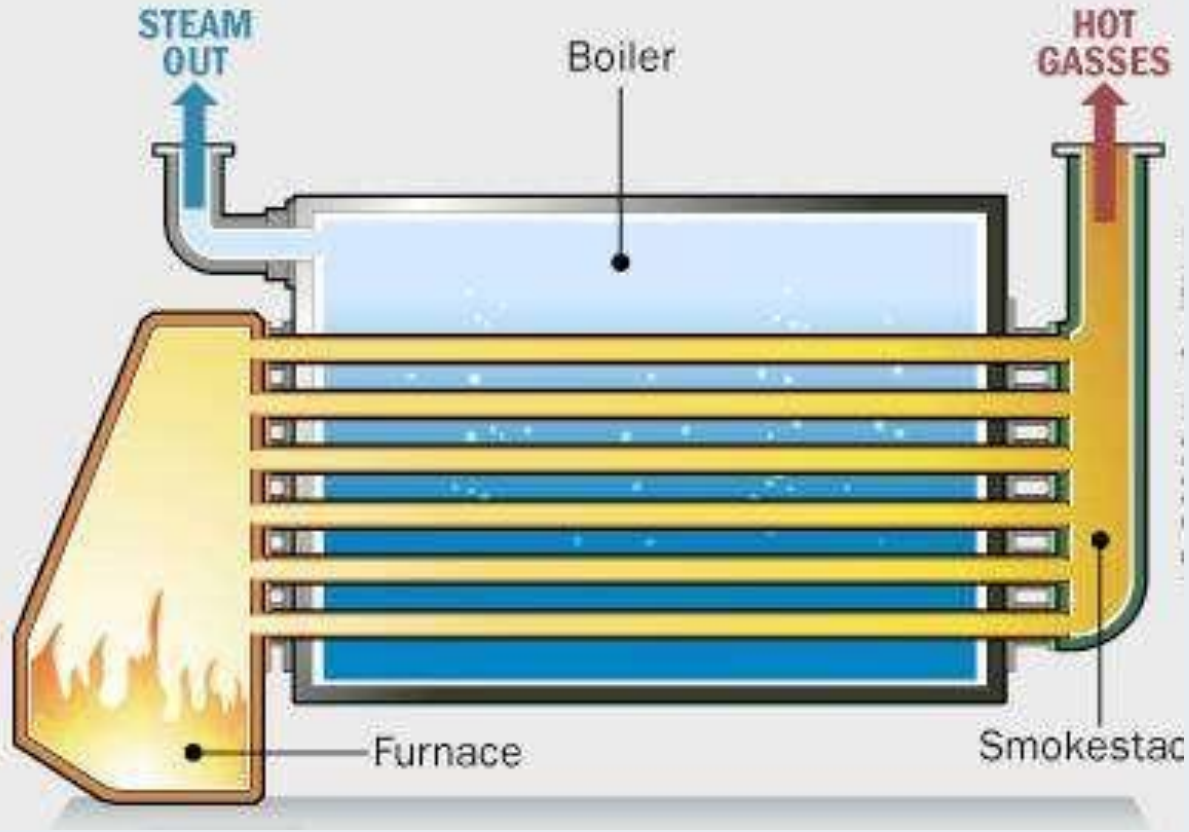


Figure 1: Fire Tube Boiler, Fauzan, M. Faizal., Hamzah, M. H., & Navaretsnasinggam, A. (2009)
url:https://www.researchgate.net/publication/263878729/figure/fig1/AS:392425462878209@1470572929372/Fire-tube-boilers.png

2. Types of Boilers and Their Applications

Cont…

b. Water-Tube Boilers

- The water is contained inside the tubes which are surrounded by the flames and hot gasses from the outside.

Example: Babcock and Wilcox boiler, Sterling boiler , Yarrow boiler, La-Mont boiler.

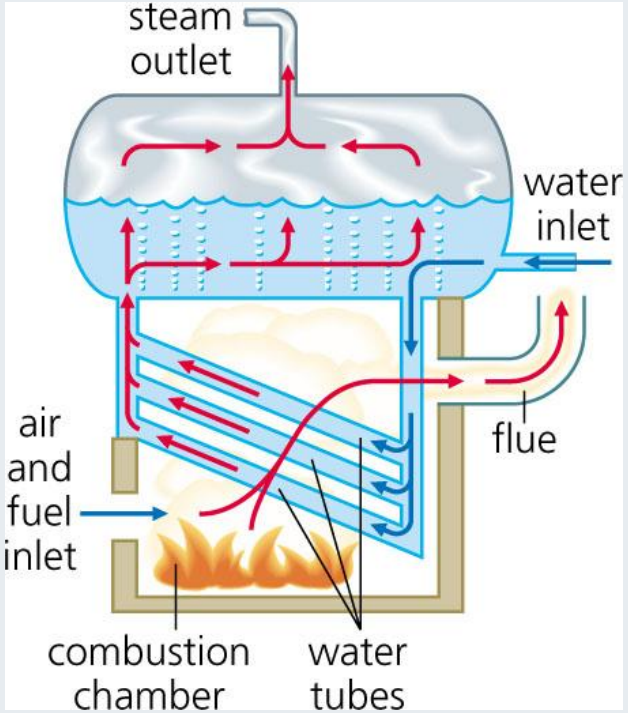


Figure 2: Water Tube Boiler, Types of boilers, Fire tube, water tube and combination. Sivaranjith. (2019) url:https://4.bp.blogspot.com/-q7B44_q6zM8/TwoR8rcGGZI/AAAAAAAAAC8/FV0BNdbvRi4/s1600/schematic+water+tube+boiler+design.jpg

2. Types of Boilers and Their Applications

Cont…

2. Based on Fuel Used

- Coal-fired
- Oil-fired
- Gas-fired
- Electric boilers
- Biomass boilers

3. Method of Firing

a. Internally fired boiler

- ✓ The furnace is located inside the boiler shell.
- ✓ Most fire-tube boilers are internally fired.

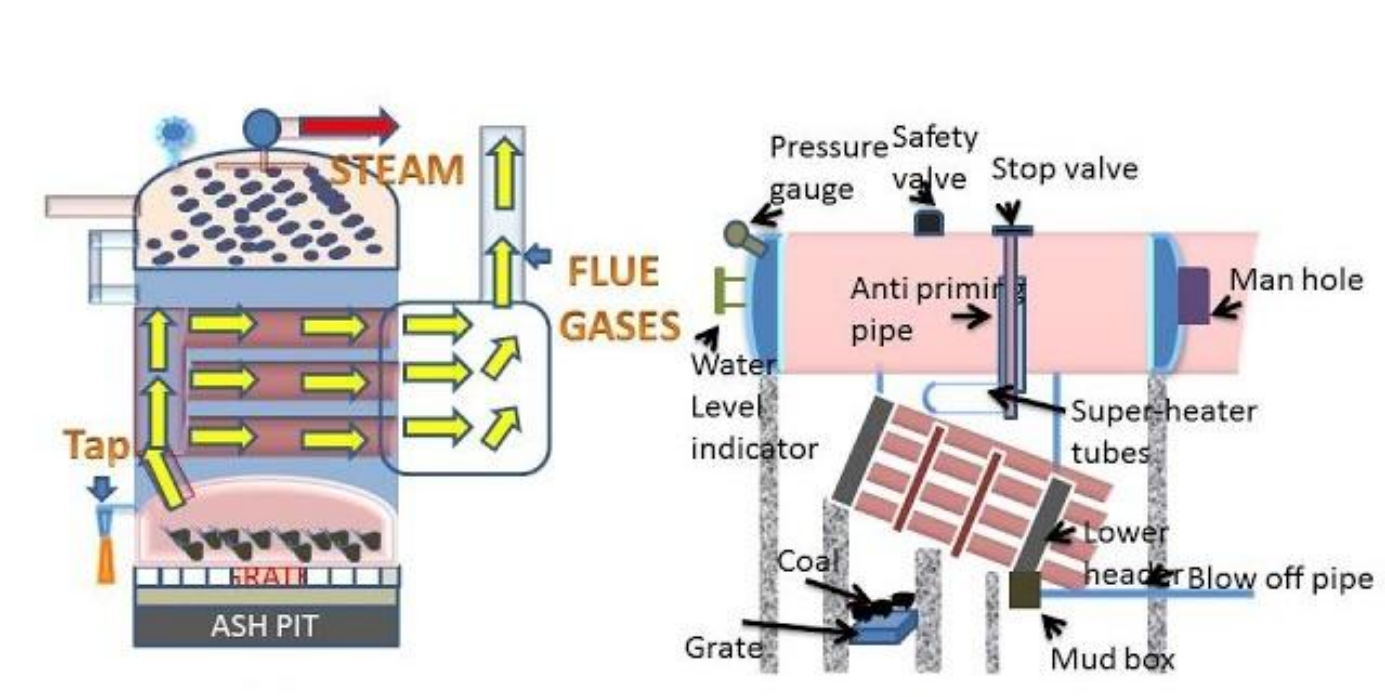
b. Externally fired boiler

- ✓ The furnace is located outside the boiler shell.
- ✓ The furnace is arranged underneath in a brickwork setting.

2. Types of Boilers and Their Applications

Cont…

- Internally and Externally Fired Boilers



(a) (b)

Figure 3: Internally (a) and Externally (b) Fired Boilers, Attique Arshad. (2021). Power Plant.
url: https://i.ytimg.com/vi/oLlw0fFVtsA/sddefault.jpg

2. Types of Boilers and Their Applications

Cont…

4. Axis of the Shell

a. Vertical shell boiler- If the axis of the boiler is vertical

   Example: Cochran boiler.

b. Horizontal shell boiler- If the axis of the boiler is horizontal, most common type,

   Example: Lancashire, Locomotive.

c. Inclined shell boiler- If the axis of the boiler is inclined

5. Pressure of Steam

a. Low-pressure boilers: Operating pressure ≤ 25 bar.

b. High-pressure boilers: Operating pressure > 25 bar.

   Example: Modern water tube boilers.

2. Types of Boilers and Their Applications

Cont…

6. Number of Tubes

a. Single tube boiler - there is only one fire tube or water tube.

b. Multi-tubular boiler - there are two or more fire tubes or water tubes.

7. Method of Water Circulation

a. Natural circulation

✓Water circulates due to density difference between hot water (less dense) and cold water (more dense).

✓Used in most conventional boilers.

2. Types of Boilers and Their Applications

Cont…

a. Forced circulation

✓A pump is used to circulate water through the tubes.

✓Essential for high-pressure and certain specific designs.

8. Mobility

a. Stationary boilers: Permanently installed in power plants or industries.

b. Portable/mobile boilers: Mounted on wheels or vehicles (e.g., locomotive boilers).

2. Types of Boilers and Their Applications

Cont…

Selection Criteria for a Boiler

- Choosing the right boiler depends on:

✓Steam requirement: The required pressure, temperature, and quantity (kg/hr).

✓Available floor space: Fire tube boilers are more compact for smaller capacities.

✓Fuel availability: Coal, oil, gas, or biomass.

✓Operating cost: Fire tube has lower initial cost; water tube has better long-term efficiency.

✓Efficiency: Higher efficiency reduces fuel costs.

✓Safety and reliability: Critical for high-pressure applications.

3. Boiler Mountings and Accessories

- Boilers require various fittings to ensure safe, efficient, and controlled operation. These are categorized into [3]:
  - ✓ Mountings: Essential for the safe operation of the boiler.
  - ✓ Accessories: Improve efficiency and performance.

a. Boiler Mountings

- The devices mounted on a boiler for its safe operation and to control the process are called boiler mountings.
- They are compulsory fittings without which a boiler cannot be operated.
- According to boiler regulations, every boiler must be equipped with the following mountings:

3. Boiler Mountings and Accessories

Cont…

1. Safety Valve

- To automatically blow off the steam when the pressure inside the boiler exceeds a predetermined safe limit.
- It is the most critical safety device.
- Safety valves are mounted directly on the boiler shell, typically in pairs.

2. Water Level Indicator

- Shows the water level inside the boiler drum.
- It is crucial to prevent the boiler from running dry, which can lead to overheating and catastrophic failure.

3. Boiler Mountings and Accessories Cont…

3. Pressure Gauge

- Measures steam pressure inside the boiler.
- Typically calibrated in bar or psi (usually a Bourdon tube pressure gauge).

4. Steam Stop Valve

- Controls the supply of steam from the boiler to the main steam line.
- Mounted at the highest point of the boiler shell.
- It is a non-return valve, meaning steam flows only from the boiler to the main steam line.

5. Feed Check Valve

- Controls the supply of feed water into the boiler and,
- Prevents backflow from the boiler to the feed pump.

3. Boiler Mountings and Accessories Cont…

6. Blow-Off Cock

- Used to remove sediments, impurities, and water during maintenance.
- Connected to the bottom of the boiler shell.

7. Fusible Plug

- A safety device that melts at a fixed temperature.
- Prevents boiler explosion in case of low water level by extinguishing fire.

8. Manhole / Mudhole

- Provides access for inspection, cleaning, and maintenance.

3. Boiler Mountings and Accessories

Cont…

Boiler Mountings

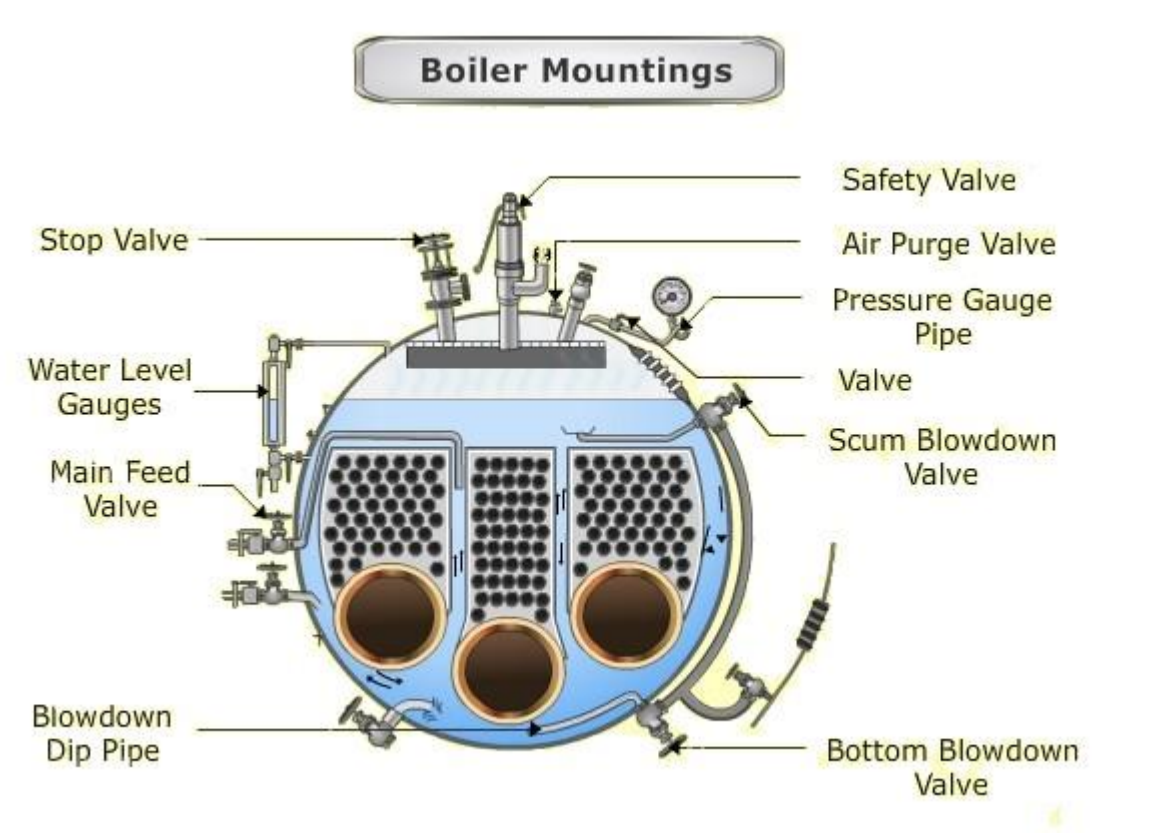


Figure 4: Boiler Mountings, Metta, N. K. (2020, September 9). Essential list of mountings on the marine boiler.
url: https://blogger.googleusercontent.com/img/a/AVvXsEjS2rWphGohcXzJVpztMvndujok0nYfzE2irBJPx1GQlk519hkYVU6XT4M-Y8EXl5A7GXS9j_TFDDa091xATPbPmJNxybaMY38AhwAz-m6dTz24M7U1OnuOVBUjXWzIbPHeMnymaSkeHXCyZavJ3tRdoxZkcUp9jF

3. Boiler Mountings and Accessories Cont…

b. Boiler Accessories

- Accessories are installed to improve the plant's overall efficiency and are typically located in the path of the flue gases [4].
- They are not essential for boiler operation but help save fuel and increase output.

1. Economizer

- It is a heat exchanger, placed in the flue gas path, consisting of a series of vertical cast iron or steel pipes through which feed water passes.
- Hot flue gases flow around these pipes, transferring heat to the water.
- Pre-heats the feed water before it enters the boiler by using the waste heat from the flue gases, increases efficiency and saves fuel.

3. Boiler Mountings and Accessories

Cont…

Economizer

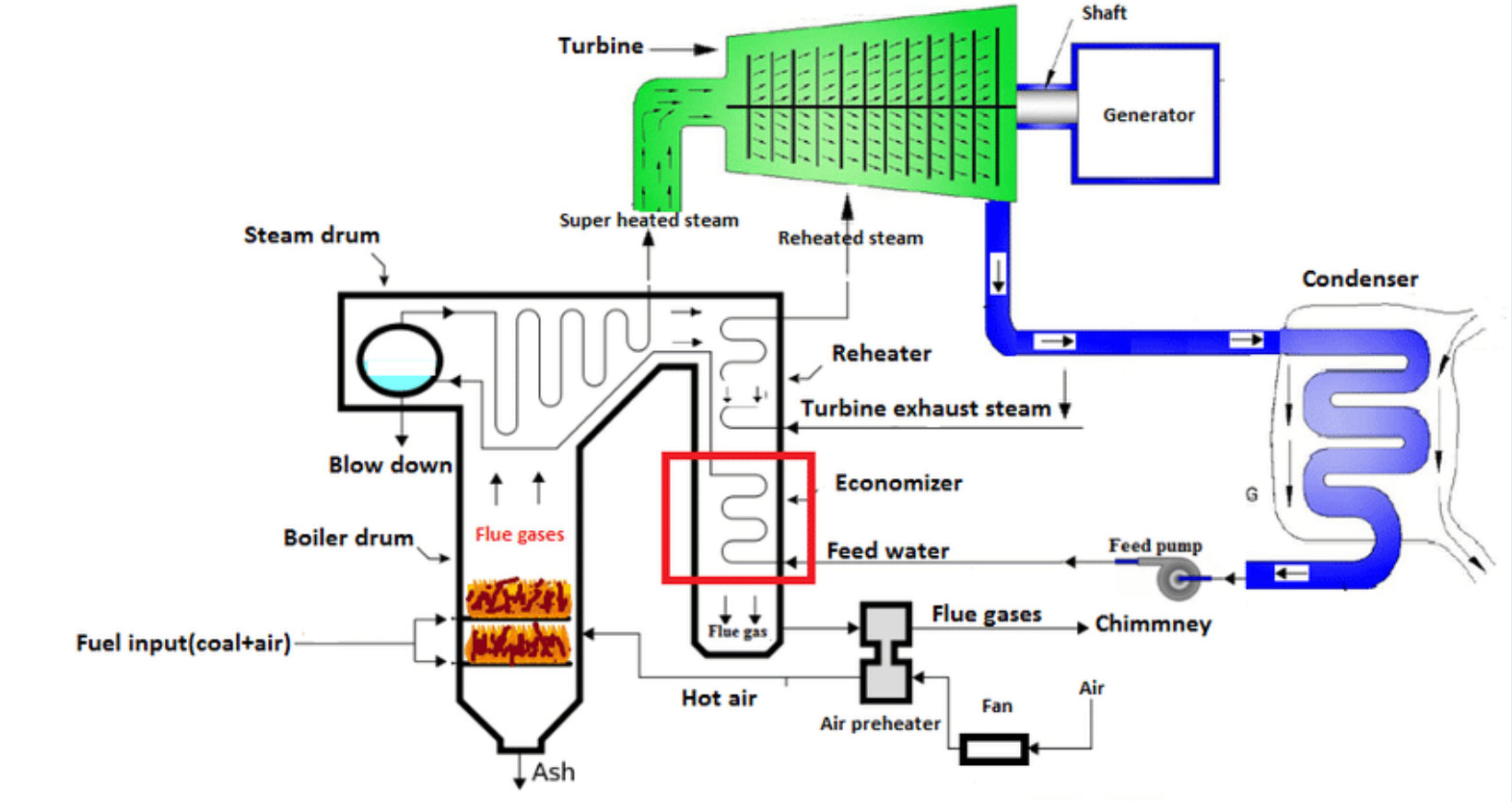


Figure 5: Economizer, Chunchula, R. B., Perumal, K., & Rajamohan, G. (2017). *Computational investigation of fluid flow*
url:https://www.researchgate.net/publication/318289043/figure/fig1/AS:513931779076096@1499542292557/Economizer-in-a-coal-fired-Boiler-adapted-from-7-Fig-1-shows-the-location-of.png

3. Boiler Mountings and Accessories

Cont…

2. Air Pre-heater

- Pre-heats the combustion air supplied to the furnace using the residual heat from the flue gases leaving the economizer.
- Placed after the economizer in the flue gas path.
- Enhances combustion and overall efficiency.

3. Superheater

- Increases the temperature of the steam generated in the boiler above its saturation point.
- The resulting steam is called superheated steam.
- Increases the thermal efficiency of the plant and reduces steam consumption.
- Prevents condensation of steam in the turbines and steam pipes

3. Boiler Mountings and Accessories Cont…

4. Feed Pump

- To pump feed water into the boiler against the high boiler pressure.
- Feed water pressures are, generally set 20% more than the boiler pressure.

5. Steam Injector

- Uses steam pressure to inject feed water into the boiler.
- Useful in small boilers without feed pumps.

6. Steam Separator (steam purifier)

- Removes water droplets from steam, providing dry steam.

7. Steam Trap

- Discharges condensate automatically without losing steam.

4. Boiler Performance and Efficiency

- Boiler performance and efficiency are critical parameters that determine how effectively a boiler converts fuel energy into usable steam.
- Understanding these metrics helps optimize fuel usage, reduce operational costs, and ensure environmental compliance.
- Boiler efficiency is the ratio of useful heat output to the total energy supplied by the fuel.
- If the heat input is expressed as the higher heating value (HHV)

of the fuel per kg of fuel, then the output heat is the heat

absorbed by the water and steam per kg of fuel burnt.

4. Boiler Performance and Efficiency Cont…

Methods of Determining Boiler Efficiency

- There are two principal methods for determining boiler efficiency.

1. The Direct Method (Input-Output Method)

   - This method involves a direct measurement of the energy gained by the water and the energy contained in the fuel.
   - The advantages of this method are:
     - ✓Simple and requires few measurements.
     - ✓Quick evaluation of boiler performance.

4. Boiler Performance and Efficiency Cont…

Boiler efficiency can be determined,

$$\eta = \frac{m_s\,(h_2 - h_1)}{m_f\ x\ CV} X\ 100$$

$Where$:

$m_s = mass\ of\ steam\ generated\ per\ kg\ of\ fuel$

$h_2 = enthalpy\ of\ steam\ (\mathrm{kJ}/kg)$

$h_1 = enthalpy\ of\ feed\ water(\mathrm{kJ}/kg)$

$m_f = mass\ of\ fuel$

$CV = calorific\ value\ of\ fuel$

4. Boiler Performance and Efficiency Cont…

Example:

A boiler generates 5000 kg/hr of steam at 10 bar (saturated). The feedwater temperature is 50^oC. The boiler used 450 kg/hr of coal with a calorific value of 30,000 kJ/kg. Calculate the direct efficiency.

Solution: From steam Tables:

- Enthalpy of saturated steam at 10 bar, $h = 2778.1\ kJ/kg$
- Enthalpy of feedwater at $50^oC, h_f \approx 209.3\ kJ/kg$

- Heat output,

$$Q = \dot{m}_s(h - h_f) = 5000\ \text{x}\ (2778.1 - 209.3) = 12{,}844{,}000\ kJ/hr$$

- Heat input, $\dot{m}_f x\ CV = 450x30{,}000 = 13{,}500{,}000\ kJ/hr$
- Efficiency, $\eta_{direct} = \left(\frac{12{,}844{,}000}{13{,}500{,}000}\right)\text{x}100 = \mathbf{95.14\%}$

4. Boiler Performance and Efficiency Cont…

2. The Indirect Method (Heat Loss Method)

- This method calculates efficiency by identifying and quantifying all the individual heat losses from the boiler system.
- The efficiency is then calculated by subtracting the total losses from 100%.

$$\eta_{indirect} = 100\% - [Total\ Percentage\ Heat\ Losses]$$

$$\eta_{indirect} = 100\% - [L_1 + L_2 + L_3 + L_4 + L_5 + L_6]$$

- This is the more informative and widely used method in detailed energy audits.

4. Boiler Performance and Efficiency Cont…

Major Heat Losses in a Boiler

- Heat loss due to dry flue gas

✓This is the largest loss in a well-operated boiler.

✓It is the heat carried away by the hot dry products of combustion (CO_2, N_2, O_2, SO_2) exiting the chimney.

$$Heat\ lost\ to\ dry\ flue\ gases\ per\ kg\ of\ fuel = \dot{m}_f c_p (T_f - T_b)$$

$Where$:

$\dot{m}_f = mass\ of\ flue\ gases\ per\ kg\ of\ fuel$

$c_p = mean\ specific\ heat\ of\ dry\ flue\ gases$

$T_f = temperature\ of\ flue\ leaving\ chimney$

$T_b = mean\ temperature\ of\ boiler\ room$

4. Boiler Performance and Efficiency Cont…

- Heat loss due to moisture in fuel & steam formation

✓The moisture present in the fuel must be heated and evaporated, consuming a portion of the heat input.

✓The atmospheric air used for combustion contains moisture.

✓This moisture is heated and superheated in the furnace, consuming energy.

$$The\ heat\ lost\ in\ the\ moisture\ present\ in\ the\ fuel\ is = \dot{m}_w(h_{sup} - h_b)$$

$Where$:

$\dot{m}_w = mass\ of\ moisture\ per\ kg\ of\ fuel$

$h_{sup} = specific\ enthalpy\ of\ steam\ at\ the\ flue\ gas\ temperature\ and\ pressure$

$h_b = mean\ specific\ enthalpy\ of\ moisture\ at\ boiler\ room\ temperature$

4. Boiler Performance and Efficiency Cont…

- Heat loss due to unburnt fuel (in ash)

✓A portion of the combustible carbon is lost with the ash (fly ash and bottom ash) without being burnt.

$$The\ heat\ lost\ due\ to\ unburnt\ carbon\ per\ kg\ of\ fuel = m_1 x\ HHV_c$$

$$Where:$$

$$m_1 = mass\ of\ carbon\ in\ ash\ pit\ kg\ of\ fuel$$

$$HHV_c = higher\ heating\ value\ of\ carbon$$

- Heat loss due to radiation & convection

✓Heat lost from the hot boiler shell and components to the surrounding atmosphere by radiation and convection.

4. Boiler Performance and Efficiency Cont…

- Heat loss due to incomplete combustion (CO formation)

✓This occurs when the carbon in the fuel is not fully converted to CO_2, but instead partially forms Carbon Monoxide (CO).

$$Heat\ lost\ due\ to\ incomplete\ combustion = m_2 x\ HHV_{c2}$$

$Where$:

$m_2 = mass\ of\ carbonmonoxide\ in\ flue\ gas\ per\ kg\ of\ fuel$

$HHV_c = higher\ heating\ value\ of\ carbonmonoxide$

4. Boiler Performance and Efficiency Cont…

Factors Affecting Boiler Efficiency

1. Evaporation Ratio

- The ratio of the mass of steam generated to the mass of fuel consumed.

$$Evaporation\ Ratio = \frac{Mass\ of\ Steam\ Generated\ (kg)}{Mass\ of\ Fuel\ Consumed\ (kg)}$$

- A higher ratio indicates better performance.

Example: A typical value for a coal-fired boiler is 5-6 (i.e., 5-6 kg of steam per kg of coal).

2. Excess Air Level

- There is an optimum excess air level that minimizes the sum of losses from unburnt carbon and dry flue gas.

4. Boiler Performance and Efficiency Cont…

3. Fuel-Related Factors
   - Calorific value of fuel, moisture content in fuel, ash content, fuel size and quality

4. Combustion Factors
   - Air-fuel ratio, combustion temperature, furnace design

5. Heat Losses
   - Flue gas losses, radiation and convection losses, unburnt fuel

6. Operational Factors
   - Boiler load, blowdown losses, maintenance and cleaning

7. Use of Boiler Accessories
   - Economizers, air preheaters, superheaters

5. Boiler Draught and Its Types

- Boiler draught refers to the difference in pressure that causes the flow of air into the furnace and the removal of flue gases through the chimney [5].
- In a simpler terms, draught is the difference in pressure between the atmosphere and the gas inside the furnace or flue.
- It is essential for:
  - ✓Supplying adequate amount of air for combustion
  - ✓Removing combustion products from the combustion chamber
  - ✓Maintaining continuous fuel burning
- Without proper draught, combustion would be inefficient or even impossible.

5. Boiler Draught and Its Types Cont…

Types of Boiler Draught

- Boiler draught is broadly classified into two main categories, distinguished by the method used to generate the pressure difference.

a. Natural Draught

- The pressure difference is created naturally due to the density difference between the hot flue gases inside the chimney and the colder, denser ambient air outside.
- Natural draught utilizes a chimney.
- The draught produced is proportional to the height of the chimney (H) and the difference in density (temperature) between the outside air and the hot gases.

5. Boiler Draught and Its Types Cont…

b. Artificial Draught

- When the draught required is more than what can be produced by a natural draught chimney, artificial draught is used.
- It is classified into two main types.
  i. Mechanical Draught
  ii. Steam Jet Draught

1. Mechanical Draught

- This system uses mechanical fans (centrifugal or axial) to create the pressure difference.

5. Boiler Draught and Its Types Cont…

- Mechanical draught is the most common system in modern power plants.
- The subtypes of mechanical draught includes:
  - ✓Forced Draught (FD) System - is installed at the inlet of the boiler, forcing fresh air into the furnace. Pressure inside furnace > atmospheric.
  - ✓Induced Draught (ID) - is installed at the outlet of the boiler, between the air pre-heater and the chimney. It sucks the flue gases out of the boiler. Pressure inside furnace < atmospheric.
  - ✓Balanced Draught - this is the most efficient and widely used system in modern boilers. It uses a combination of both FD and ID fans. Maintains furnace pressure nearly atmospheric.

5. Boiler Draught and Its Types Cont…

2. Steam Jet Draught

- High-velocity steam jet is passed through a nozzle to create suction.
- Used in locomotive and marine boilers.

There are two types of steam jet draught

✓Forced Steam Jet Draught - A jet of high-pressure steam is directed into the air entering the furnace from a steam nozzle.

- The momentum of the steam entrains the air and forces it into the furnace.

✓Induced Steam Jet Draught - A jet of high-pressure steam is directed into the flue gas duct towards the chimney.

- The steam jet sucks the flue gases from the furnace and throws them up the chimney.

6. Boiler Operation, Maintenance, and Safety

- The safe and efficient operation of boilers requires proper handling, routine maintenance, and adherence to safety protocols.

Boiler Operation

a. Startup Procedure

- ✓Pre-checks: Inspect water level, fuel supply, and mountings.
- ✓Purge Furnace: Remove residual gases.
- ✓Ignition: Start burners or fuel feed.
- ✓Pressure Build-up: Gradually increase pressure to operating level.
- ✓Steam Flow: Open steam stop valve to supply steam.

6. Boiler Operation, Maintenance, and Safety Cont…

b. Normal Operation

- ✓Maintain proper water level (neither too high nor too low).
- ✓Regulate fuel and air supply for efficient combustion.
- ✓Monitor steam pressure and temperature.
- ✓Regularly check safety valves, gauges, and control systems.

c. Shutdown Procedure

- ✓Reduce fuel and steam flow slowly.
- ✓Shut steam and feed water valves.
- ✓Use blow-off cock if needed.
- ✓Check for leaks, deposits, and wear.

6. Boiler Operation, Maintenance, and Safety Cont…

Boiler Maintenance

- Proper maintenance ensures efficiency, safety, and long service life.

Types of Boiler Maintenance

1. Preventive Maintenance
   - ✓Routine inspection and servicing.
   - ✓Cleaning of tubes, filters, and burners.
   - ✓Checking for leaks and wear.
2. Corrective Maintenance
   - ✓Repairs after a fault occurs
   - Example: tube replacement, pump repair

6. Boiler Operation, Maintenance, and Safety

3. Predictive Maintenance

✓Using sensors and monitoring systems to predict failures.

✓Vibration analysis, temperature monitoring, and water quality analysis.

Boiler Safety

- Since boilers operate under high pressure, safety measures are critical.

Safety Devices

✓Safety Valve → Prevents excessive pressure.

✓Fusible Plug → Protects against low water level overheating.

✓Water Level Indicator → Prevents dry running.

✓Pressure Gauge → Monitors internal steam pressure.

✓Blow-off Cock → Removes sediments safely.

Summary

- Boilers are closed vessels that generate steam by heating water, and they are classified by design, fuel type, and circulation method.
- Fire-tube and water-tube boilers are the main types, each suited for specific industrial and domestic uses based on pressure and capacity.
- Boiler mountings ensure safety and operation control, while accessories improve efficiency by enhancing heat utilization and fuel economy.
- Boiler performance and efficiency depend on factors like heat losses, combustion quality, and maintenance, which can be optimized through regular inspection and performance analysis.
- Boiler draught systems regulate air and gas flow for proper combustion, and safe operation and maintenance practices are vital to prevent accidents and ensure long-term reliability.

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Thank you !