PERFORMANCE EVALUATION AND THERMAL EFFICIENCY OPTIMIZATION OF A LOW PRESSURE BOILER

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Abstract

The present research investigates the performance evaluation and thermal efficiency optimization of a low-pressure boiler under continuous operation. A 24-hour dataset comprising steam pressure, steam flow rate, enthalpy, fuel consumption, and equivalent evaporation was analyzed to assess boiler behavior. The results reveal that thermal efficiency ranges from **70.24% to 80.49%**, with an average efficiency of approximately 75%, indicating satisfactory but variable performance. Steam generation was found to be stable within **3250–3700 kg/hr**, while pressure exhibited minimal fluctuations between **7.1 and 7.9 bar**, confirming consistent operating stability. Equivalent evaporation and factor of evaporation were calculated to benchmark performance against standard reference conditions. Efficiency deviations were primarily associated with variations in combustion quality and fuel-air management rather than load instability. The findings emphasize the significance of optimizing burner operation, implementing automated control for pressure and flow, and monitoring feedwater enthalpy to achieve sustained efficiency improvements. This study contributes to enhancing operational strategies for low-pressure boilers, with implications for industrial energy efficiency and cost reduction.

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Chapter 1: Introduction

1.1 Background of the Study

Boilers are integral to industrial operations, providing steam for heating, power generation, and various process applications. Low-pressure boilers are widely used in medium-scale industries due to their operational simplicity, safety, and cost-effectiveness. However, their efficiency is highly dependent on operating conditions, combustion quality, and maintenance practices. Improving boiler performance through systematic evaluation and thermal efficiency optimization not only reduces fuel consumption and costs but also contributes to sustainable energy management. Therefore, the study of boiler performance using real-time operational data is essential to ensure reliable and energy-efficient operation.

1.2 Problem Statement

Low-pressure boilers play a vital role in industrial steam generation, yet they often suffer from efficiency losses due to fluctuating operating conditions and suboptimal fuel-air management. In the studied boiler, thermal efficiency was observed to vary between **70.24% and 80.49%**, indicating inconsistency in performance. Such variations not only increase fuel consumption and operational costs but also reduce overall energy utilization efficiency. The absence of automated control and continuous monitoring further limits the ability to sustain optimal performance. Therefore, a systematic evaluation is necessary to identify the factors contributing to efficiency fluctuations and to develop strategies for performance optimization.

1.3 Objectives of the Study

The objective of this thesis is :

To evaluate the thermal efficiency of a low-pressure boiler based on 24-hour operational data.

1.4 Scope and Limitations

The scope and limitations of this thesis are:

- The research is limited to a single low-pressure boiler operating under industrial conditions.
- Performance evaluation is based on 24-hour operational data including steam pressure, flow, enthalpy, and fuel consumption.
- Thermal efficiency, equivalent evaporation, and factor of evaporation are considered as the primary performance indicators.
- External factors such as ambient conditions, maintenance practices, and long-term operational wear are not deeply analyzed.
- The study emphasizes efficiency optimization strategies, but implementation outcomes are recommended for future research.

1.5 Significance of the Research

The significance of this research can be outlined as follows:

- It provides a systematic performance evaluation of a low-pressure boiler using real operational data.
- It identifies efficiency variations and highlights factors affecting boiler performance.
- It contributes to reducing fuel consumption and operating costs through improved efficiency.
- It establishes equivalent evaporation and factor of evaporation as benchmarks for performance assessment.
- It offers practical strategies for optimizing combustion and fuel-air management.
- It enhances operational reliability by recommending automation and control improvements.
- It supports sustainable industrial practices by promoting energy-efficient boiler operation.
- It creates a reference framework for future research on boiler performance optimization.

Chapter 2: Literature Review

2.1 Boiler Fundamentals and Classification

A boiler is a closed pressure vessel that generates steam by transferring heat produced from fuel combustion or other heat sources to water. The steam generated is utilized in various industrial processes such as power generation, heating, drying, and chemical processing. Boilers form the heart of steam power plants and industrial energy systems, and their design and efficiency directly influence operational performance, fuel consumption, and environmental impact.

Boiler Fundamentals

The working principle of a boiler involves three major steps: (i) fuel combustion in the furnace, (ii) transfer of heat through boiler surfaces to water, and (iii) conversion of water into steam at a desired pressure and temperature. The essential components of a boiler include the furnace, heat exchanger surfaces, steam drum, feedwater system, and control instruments. Efficiency of a boiler is influenced by the quality of combustion, heat transfer rate, fuel characteristics, feedwater temperature, and maintenance of operating conditions.

Boiler Classification

Boilers can be classified on several bases:

1. **Based on Pressure:**
    - **Low-pressure boilers (up to ~15 bar):** Commonly used in heating, textile, food processing, and medium-scale industries where moderate steam output is sufficient.
    - **Medium-pressure boilers (15–80 bar):** Applied in industries requiring higher process steam.
    - **High-pressure boilers (>80 bar):** Used in large-scale power plants for electricity generation.
    - **Supercritical boilers (>220 bar):** Designed for advanced power generation with higher thermal efficiency.

2. **Based on Design and Flow:**
    - **Fire-tube boilers*:*** Hot gases pass through tubes surrounded by water; suitable for small to medium applications (e.g., Cochran, Lancashire boilers).
    - **Water-tube boilers*:*** Water circulates through tubes heated externally by combustion gases; capable of producing high-pressure steam with large capacities (e.g., Babcock & Wilcox, Benson boilers).

3. **Based on Circulation of Water/Steam:**
    - **Natural circulation boilers*:*** Rely on density differences between hot and cold water for circulation.
    - **Forced circulation boilers*:*** Use pumps to circulate water/steam mixture, improving heat transfer and efficiency.
4. **Based on Fuel Type:**
    - Solid fuel (coal, biomass), liquid fuel (oil, diesel), gaseous fuel (natural gas, LPG), and renewable energy sources (biogas, waste heat recovery).
5. **Based on Application:**
    - Power generation, process heating, cogeneration (combined heat and power), and specialized industrial processes.

Relevance to Low-Pressure Boilers

- Low-pressure boilers, the focus of this study, are particularly important for industries where safety, operational simplicity, and moderate steam production are prioritized over extremely high efficiency. While their efficiency is lower than high-pressure systems, they are more cost-effective, easier to maintain, and widely used in textiles, food processing, pharmaceuticals, and small-scale manufacturing. Evaluating and optimizing their performance is therefore essential for energy management and cost reduction in these industries.

2.2 Boiler Mountings

Boiler mountings are the essential fittings and devices that are installed on a boiler to ensure its safe, efficient, and reliable operation. Unlike boiler accessories, which improve efficiency, mountings are mandatory for operation as per boiler regulations and safety standards. Their primary functions include controlling the pressure, regulating steam flow, supplying water, ensuring safety against overpressure, and enabling operators to monitor boiler performance.

The major boiler mountings are:

1) Pressure Gauge

2) Water Level Indicator

3) Fusible Plug

4) Safety Valve

5) Steam Stop Valve

6) Feed Check Valve

7) Blow-off Cock

8) Man and Mud Hole

2.2.1 Bourdon's Pressure Gauge

Function:

1. To record the steam pressure at which the steam is generated in the boiler.
2. A bourdon pressure gauge in its simplest form consists of elliptical elastic tube bent into an arc of a circle.
3. This bent up tube is called as BOURDON'S tube.
4. One end of tube gauge is fixed and connected to the steam space in the boiler. The other end is connected to a sector through a link.

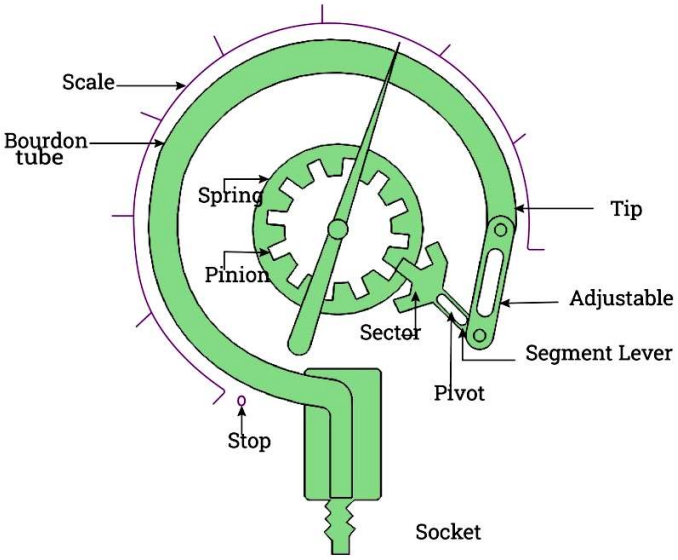


Figure 2.1: Bourdon's Pressure Gauge (Structural Figure)



Figure 2.2: Bourdon's Pressure Gauge in boiler

2.2.2 Water Level Indicator

Function:

1. The function of water level indicator is to indicate the level of water in the boiler constantly.
2. It is also called water gauge.
3. Normally two water level indicators are fitted at the front end of every boiler.

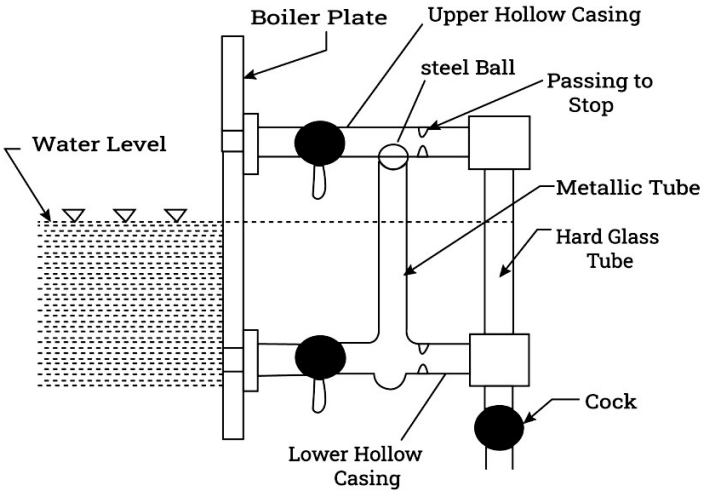


Figure 2.3: Water Level Indicator (Structural Figure)



Figure 2.4: Water Level Indicator in boiler

2.2.3 Fusible Plug

Function:

1. To extinguish fire in the event of water level in the boiler shell falling below certain specified limit.
2. It protects fire tubes from burning when the level of the water in the water shell falls abnormally low and the fire tube or crown plate which is normally submerged in the water, gets exposed to steam space which may not be able to keep it cool.
3. It is installed below boiler's water level.

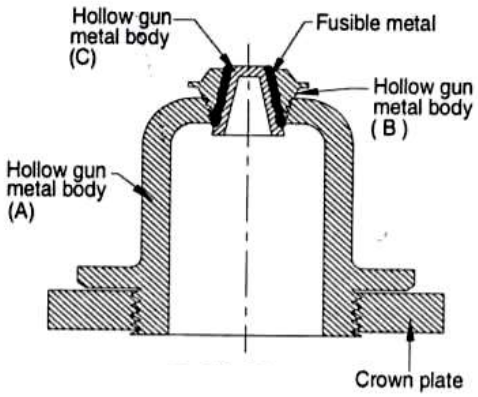


Figure 2.5: Fusible Plug (Structural Figure)

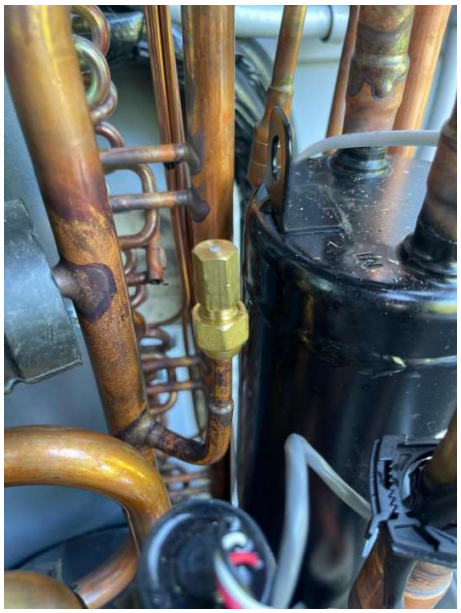


Figure 2.6: Fusible Plug in boiler

2.2.4 Safety Valve

The safety valve is a protective device that automatically releases excess steam when the steam pressure inside the boiler exceeds the maximum allowable working pressure. This prevents the boiler from bursting or getting damaged due to overpressure.

Function:

1. Releases excess steam when boiler pressure rises above the maximum allowable working pressure.
2. Protects the boiler from bursting or severe damage due to excessive pressure.
3. Keeps the boiler pressure within the designed working range for efficient performance.
4. Operates automatically without external control—opens when pressure is high, closes when pressure drops.

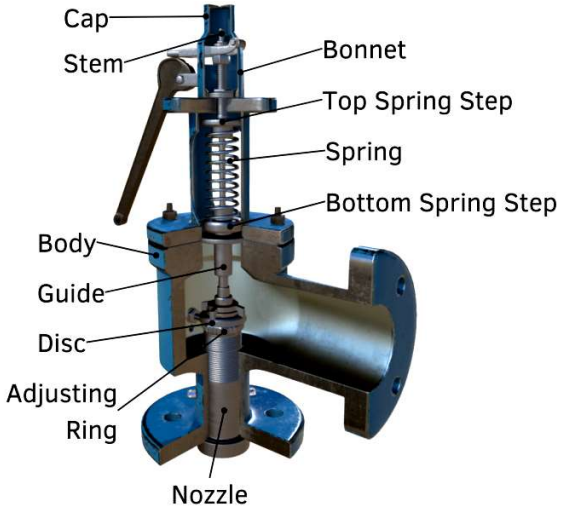


Figure 2.7: Safety Valve (Structural Figure)



Figure 2.8: Safety Valve in Boiler

2.2.5 Steam Stop Valve

This valve is a device that regulates the flow of a fluid (gases, fluidized solids, slurries, or liquids) by opening, closing, or partially obstructing various passageways.

Function:

1. 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.
2. When the band wheel is turned, the spindle which is screwed through the nut is raised or lowered depending upon the sense of rotation of wheel. The passage for flow of steam is set on opening of the valve.

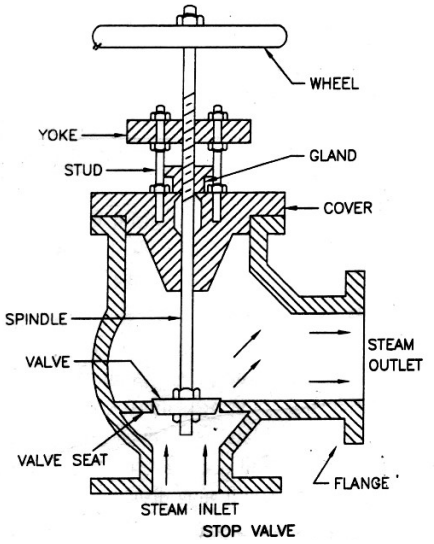


Figure 2.9: Steam Stop Valve (Structural Figure)



Figure 2.10: Steam Stop Valve in Boiler

2.2.6 Feed Check Valve

Function:

The function of a feed check valve is to control the supply of water to the boiler and to prevent the escaping of water from the boiler when the pump pressure is less or pump is stopped.

1) To allow the feed water to pass into the boiler.
2) To prevent the back flow of water from the boiler in the event of the failure of the feed pump.

The feed check valve is fitted in the water space of the boiler slightly below the normal level of the water.

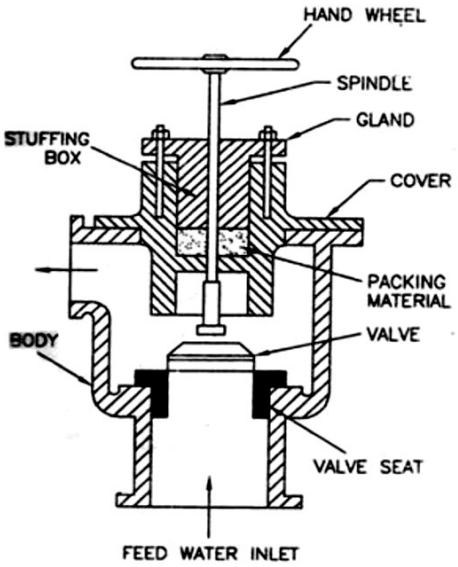


Figure 2.11: Feed Check Valve (Structural Figure)

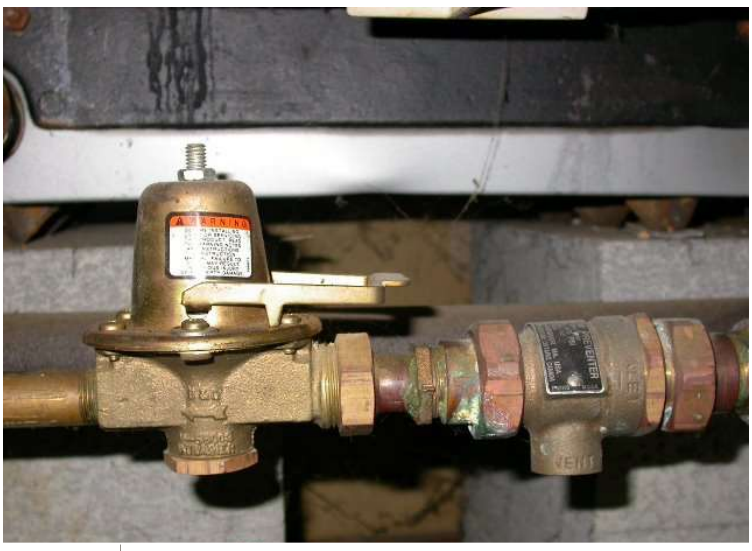


Figure 2.12: Feed Check Valve in Boiler

2.2.7 Blow off Cock

Function:

To drain out the water from the boiler for internal cleaning, inspection, repair or other purposes.

1) It may discharge a portion of water when the boiler is in operation to blow out mud, scale or sediments, periodically.
2) It is' fitted on the boiler shell directly or to a short branch pipe at the lowest part of the water space.

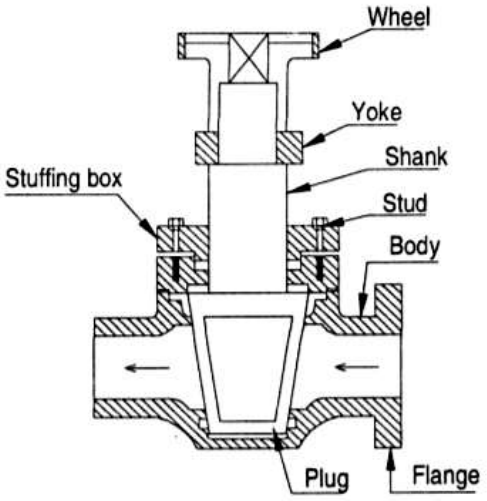


Figure 2.13: Blow off Cock (Structural Figure)



Figure 2.14: Blow off Cock in Boiler

2.2.8 Manhole and Mud Box

Manhole (in Boilers)

1. Provides a sufficiently large opening for a person to enter inside the boiler.
2. Used for cleaning, inspection, and maintenance purposes.
3. Allows safe access to internal parts of the boiler during shutdown.

Mud Box (in Boilers)

1. Acts as a collection chamber at the lowest point of the water space.
2. Collects mud, scale, and other impurities carried by the feedwater.
3. Equipped with a blow-off cock/valve to periodically remove the settled mud and maintain boiler efficiency.

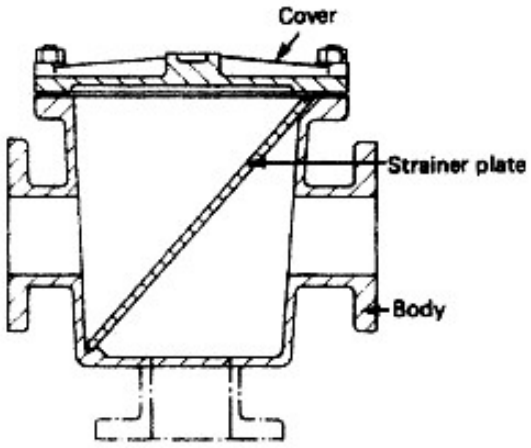


Figure 2.15: Man and Mud Box (Structural Figure)



Figure 2.16: Man and Mud Box in Boiler



Figure 2.17: Fulton FB-C Firetube Steam Boiler

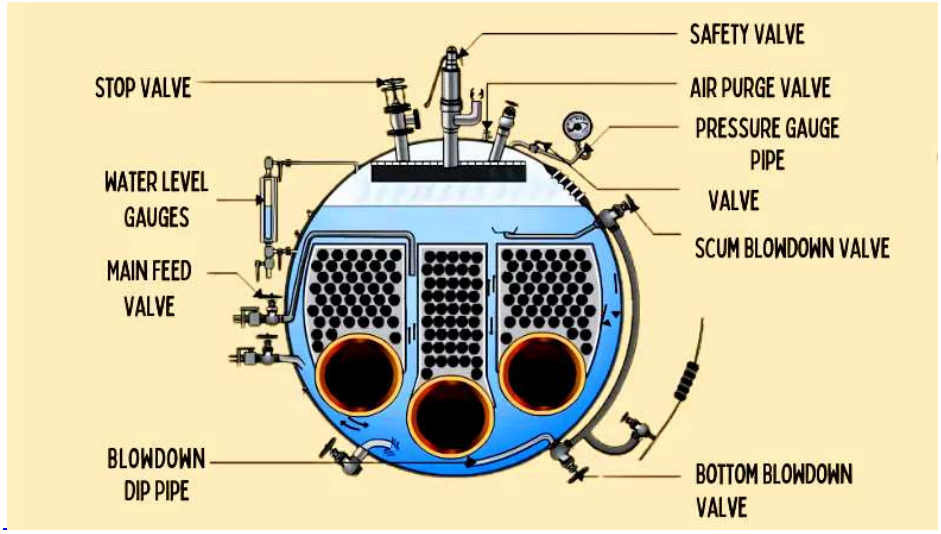


Figure 2.18: Boiler Mountings

Importance of Boiler Mountings

1. Ensures Safe Operation

- Boilers operate under **very high pressure and temperature**.
- Mountings like **safety valves** automatically release excess steam if pressure exceeds the design limit.
- Prevents dangerous accidents such as **boiler explosions**.

2. Maintains Correct Water Level

- **Water Level Indicator** shows the operator the exact water level inside the boiler drum.
- Too **low water level** → overheating of boiler tubes, leading to bursting.
- Too **high water level** → water particles may carry over with steam, damaging turbines.
- Hence, mountings help maintain the **optimum water level**.

3. Pressure Monitoring & Control

- **Pressure Gauge** continuously monitors boiler steam pressure.
- Operators can take corrective actions if pressure rises abnormally.
- Helps maintain boiler operation within **safe and efficient limits**.

4. Safe Startup & Shutdown

- **Stop Valve (Main Steam Stop Valve)** regulates steam flow from the boiler to the steam line.
- Allows controlled startup, load adjustment, or safe shutdown of the boiler without sudden pressure surges.

5. Efficient Combustion & Operation

- **Blow-off Cock/Valve** is used to remove sediments, scale, and impurities from the boiler water.
- This prevents corrosion, overheating, and improves **steam purity**.
- Ensures long life and efficient functioning of the boiler.

6. Prevention of Accidents

- **Fusible Plug** melts at a certain temperature if water level drops too low, extinguishing the fire by releasing steam/water into the furnace.
- This prevents **tube damage and boiler explosion**.

7. Facilitates Regular Maintenance

- Some mountings (like manholes, blow-off valves) make it easier to **inspect, clean, and maintain** the boiler.
- Ensures that the boiler runs reliably for long periods.

2.3 Boiler Accessories

Boiler accessories are auxiliary devices fitted to a boiler to improve its efficiency and overall performance. Unlike mountings, they are not essential for the safe operation of a boiler but are installed to increase steam output, enhance heat utilization, and reduce fuel consumption. By recovering waste heat and improving combustion, accessories make boiler operation more economical and sustainable.

The major boiler accessories include:

1. Air Preheater
2. Economizer
3. Superheater
4. Steam Separator
5. Feed Pump

2.3.1 Air Preheater

An air preheater is a boiler auxiliary and waste heat recovery device in which the air required for combustion is preheated by utilizing the heat of exhaust (flue) gases before they are discharged through the chimney.

Functions of Air Preheater

1. **Preheats Combustion Air** – raises the temperature of incoming air before it enters the furnace.
2. **Enhances Thermal Efficiency** – reduces fuel consumption by utilizing waste heat.
3. **Improves Furnace Performance** – hot air accelerates the ignition of fuel, ensuring complete combustion.
4. **Reduces Flue Gas Loss** – lowers the temperature of flue gases before they leave the boiler.
5. **Facilitates Drying of Coal (in coal-fired boilers)** – helps remove moisture from fuel, improving burning efficiency.

Construction

- A **heat exchanger** placed between the **economizer** (or boiler outlet) and the **chimney**.
- It has **two fluid streams**:
    - **Hot flue gases** (from boiler → chimney).
    - **Cold air** (from atmosphere → furnace).
- Heat is transferred from flue gases to air either **directly** (recuperative type) or through a **regenerative matrix** (rotary type).

Types of Air Preheater

1. **Recuperative Air Preheater**
    - **Tubular Type** – flue gases pass through tubes, air flows outside (or vice versa).
    - **Plate Type** – uses plates with alternating air and flue gas passages.
2. **Regenerative (Rotary) Air Preheater**
    - A rotating **matrix/element** stores heat from flue gases in one part of rotation and transfers it to air in another.
    - Compact, widely used in **large power plants**.

Advantages

- Increases boiler efficiency by **6–10%**.
- Reduces **fuel consumption**.
- Improves **steam generation capacity**.
- Reduces **smoke and unburnt carbon** in ash.
- Helps in achieving **higher furnace temperature** for complete combustion.

Disadvantages / Limitations

- Increases **initial cost** and requires **extra space**.
- Flue gases may cause **corrosion** at low temperatures (especially if SO_2 + moisture → sulfuric acid).
- Maintenance required for **cleaning deposits** (ash, soot, dust).
- In rotary type, **seal leakage** may occur between air and gas compartments.

Typical Position in Boiler System

Boiler → Superheater → Economizer → Air Preheater → Chimney

This sequence ensures **maximum utilization of waste heat**.

Structure of Air Preheater

1. **Casing / Shell**
    - A strong outer body (usually made of steel).
    - Provides housing for tubes/plates/rotary matrix.
    - Designed to withstand hot flue gas temperature and air pressure.
2. **Heating Element / Heat Transfer Surface**
    - The main part where heat exchange occurs.
    - Depending on the type:
        - **Tubular APH** → steel tubes.
        - **Plate APH** → steel plates arranged alternately.
        - **Rotary APH** → a rotating matrix made of corrugated steel sheets.

3. **Air Duct**
    - Pathway for **cold air** from atmosphere → furnace.
    - Air passes through the heating element, absorbs heat, and moves to furnace.
4. **Gas Duct**
    - Channel for **hot flue gases** from boiler → chimney.
    - Flue gases flow across the heating surface and transfer heat to the air.
5. **Rotary Support (for Regenerative type)**
    - A central shaft with bearings supports the **rotating matrix**.
    - Driven by a motor at very low speed (~1–3 rpm).
6. **Seals (for Rotary APH)**
    - Prevent **leakage between hot gas side and cold air side** during rotation.
7. **Soot Blowers / Cleaning Mechanism**
    - Removes deposited soot, ash, and dust from heating surfaces.
    - Uses compressed air or steam jets for cleaning.

Longevity of Air Preheater

Typical Service Life

- **Tubular or Plate type APH → 15–20 years** if maintained properly.
- **Rotary (Regenerative) APH → 10–15 years** depending on operating conditions.
- In **power plants** running continuously (24/7), life may be shorter (8–12 years) due to heavy duty.

Factors Affecting Longevity

1. **Corrosion**
    - Flue gases contain **SO_2, SO_3, CO_2, O_2, and moisture**.
    - When flue gas temperature drops below **dew point (~120–150°C)**, **acid condensation (H_2SO_4)** causes severe corrosion.
    - This is the **most common cause** of APH failure.
2. **Erosion & Abrasion**
    - Dust, ash, and unburnt particles in flue gases **erode tubes/plates** over time.
    - Especially in coal-fired boilers with high fly ash content.
3. **Fouling & Deposits**
    - Ash and soot accumulate on heating surfaces → reduces heat transfer efficiency.
    - Overheating and stress can shorten lifespan.
4. **Operating Temperature**
    - Higher temperatures increase **thermal stress** on materials.
    - If temperatures are maintained above dew point, corrosion risk is reduced.
5. **Material Quality**
    - **Carbon steel** is common, but in critical areas, **alloy steels or enamel coatings** are used for longer life.
6. **Maintenance Practices**
    - Regular **soot blowing, cleaning, inspection, and timely repair** extend APH life.
    - Protective coatings and anti-corrosion paints also help.

Ways to Increase Longevity

- Keep **flue gas exit temperature above acid dew point** (usually >150°C).
- Use **better fuel quality** (less sulfur, less ash).
- Install **efficient soot blowers** to reduce fouling.
- Apply **corrosion-resistant coatings** or use **alloy steels** in high-risk zones.
- Perform **regular inspection and tube replacement** when needed.

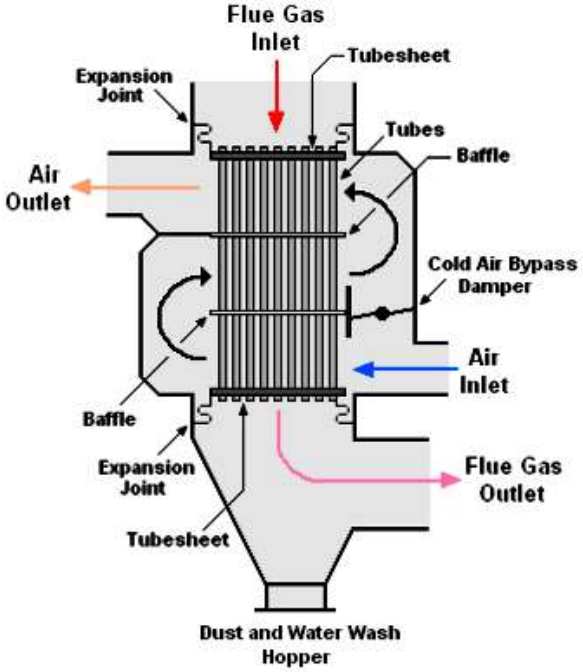


Figure 2.19: Air Preheater (Structural Figure)



Figure 2.20: Air Preheater

2.3.2 Economizer

An economizer is a waste heat recovery device fitted to a boiler. It heats the feedwater entering the boiler by utilizing the residual heat of flue gases leaving the boiler.

Functions of Economizer

1. Preheats feedwater before it enters the boiler drum.
2. Recovers waste heat from flue gases (normally at 250–350°C).
3. Increases boiler efficiency (by 10–12%).
4. Reduces fuel consumption, as less heat is needed to convert water to steam.
5. Reduces thermal stresses inside the boiler (since water enters at a higher temperature, closer to saturation temperature).

Construction

- **Casing / Shell:** Outer steel casing to enclose tubes.
- **Tubes / Coils:** Series of steel tubes through which feedwater flows .
- **Gas Duct:** Path for flue gases from boiler → chimney.
- **Headers:** Distribute feedwater into tubes and collect heated water.
- **Mountings:** Fitted between boiler outlet and chimney, usually after the superheater.

Working Principle

1. **Hot flue gases** (from furnace) flow around economizer tubes.
2. **Cold feedwater** flows inside the tubes.
3. Heat transfers from gases → water (without mixing).
4. Water temperature rises (often by 50–100°C).
5. Heated water enters the boiler drum, requiring less fuel to reach boiling point .

Types of Economizers

1. **Non-condensing Economizer**
   - Flue gas temperature is kept above the dew point to avoid corrosion.
   - Common in coal-fired and oil-fired boilers.
2. **Condensing Economizer**
   - Flue gas is cooled below its dew point, and latent heat of condensation is recovered.
   - More efficient but requires corrosion-resistant materials.
3. **Tubular Economizer**
   - Consists of parallel steel tubes with water inside and hot gases outside.
   - Simple and widely used.
4. **Plate Economizer**
   - Uses thin steel plates instead of tubes.
   - Compact but less common.

Advantages of Economizer

- Increases boiler efficiency by **10–12%**.
- Saves **5–15% of fuel consumption**.
- Reduces flue gas temperature → less heat loss.
- Increases steam generation rate.
- Reduces thermal stress on boiler shell and tubes.

Disadvantages / Limitations

- Increases **initial cost** and requires **extra space**.
- Risk of **corrosion** if flue gas temperature falls below dew point (especially with sulfur in coal/oil).
- Needs **regular cleaning** (soot, ash, scaling deposits).
- Pressure drop in gas flow may require a stronger induced draft fan.

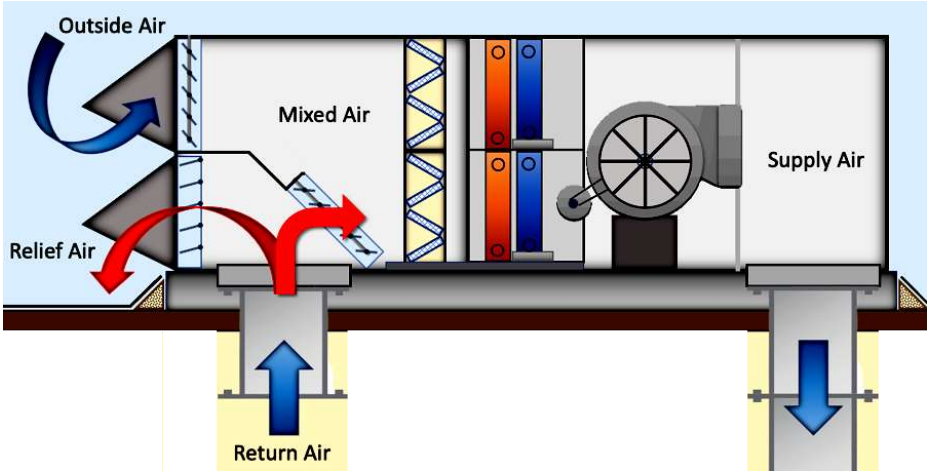


Figure 2.21: Economizer (Structural Figure)



Figure 2.22: Economizer (Factory view)

2.3.3 Super Heater

A **superheater** is a set of **heat exchange tubes** used in boilers to **heat saturated steam** (steam at saturation temperature) into **superheated steam** (steam at a higher temperature, no moisture content) by using the **hot flue gases** from the furnace.

Functions of Superheater

1. **Removes moisture** from saturated steam → provides dry steam.
2. **Increases steam temperature** (20°C to 250°C above saturation temperature).
3. **Improves turbine efficiency** (superheated steam expands more efficiently in turbines).
4. **Prevents turbine blade erosion** (wet steam damages blades).
5. **Reduces specific steam consumption** → less steam needed for same power.
6. **Improves boiler efficiency** by utilizing waste heat of flue gases.

Construction

- **Tubes / Coils** – steel alloy tubes placed in the boiler flue gas path.
- **Headers** – distribute saturated steam to tubes and collect superheated steam.
- **Support structures** – hold tubes firmly in furnace/flue gas region.
- **Control valves / bypasses** – regulate the degree of superheating.

Working Principle

1. Steam generated in the boiler drum is **saturated steam** (still contains moisture).
2. This steam is passed through the **superheater tubes**.
3. **Hot flue gases** from furnace flow across these tubes.
4. Heat transfer occurs → steam absorbs additional sensible heat → becomes **superheated**.
5. Superheated steam is then supplied to **steam turbines or engines** for power generation.

Types of Superheaters

1. **Radiant Superheater**
    - Placed directly in the furnace (absorbs heat from **radiation** of burning fuel).
    - Produces high degree of superheating.
2. **Convective Superheater**
    - Placed in flue gas path (absorbs heat mainly by **convection**).
    - Gives moderate superheating.
3. **Combined (Radiant + Convective) Superheater**
    - Most common in **modern high-pressure boilers**.
    - Ensures stable superheat temperature under varying loads.

Advantages of Superheated Steam

- Higher **thermal efficiency** in power cycles.
- Prevents **condensation** in turbine → protects blades.
- Higher **dryness fraction** → more energy per kg of steam.
- Reduces **specific steam consumption (SSC)**.
- Improves **work output** from Rankine cycle.

Disadvantages / Limitations

- Increases **initial cost** of boiler.
- Needs **temperature control** (to avoid turbine material damage).
- Superheater tubes are exposed to very high temperatures → risk of **overheating, creep, and corrosion**.
- Requires **better maintenance** (soot blowing, cleaning).

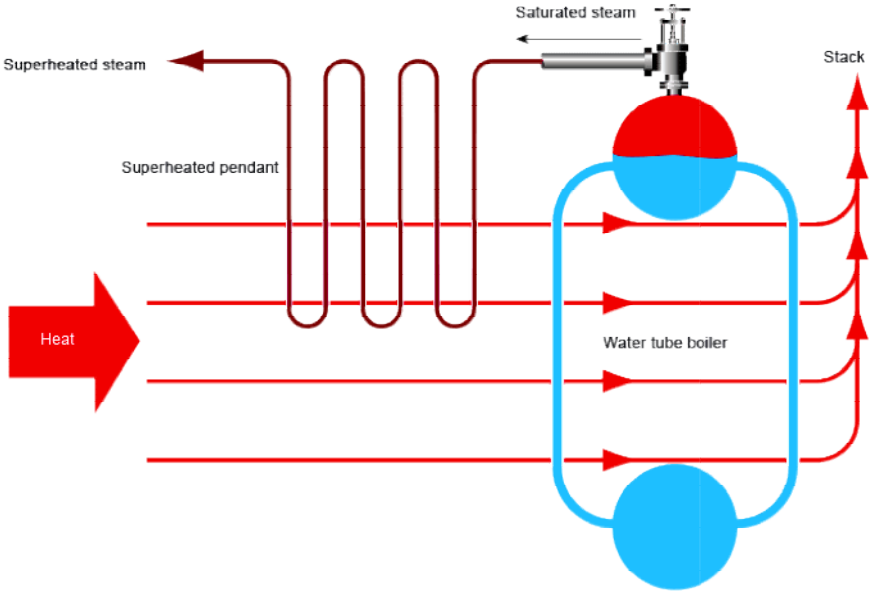


Figure 2.23: A water tube boiler with a superheater (Structural Figure)



Figure 2.24: A water tube boiler with a superheater (Factory View)

2.3.4 Feed Pump

A **boiler feed pump** is a critical piece of equipment in a steam power plant or industrial boiler system. Its main job is to **supply water (feedwater) to the boiler drum or steam generator** at the required pressure and flow. Since the boiler is already under high pressure, the feed pump must deliver water at **a pressure higher than the boiler drum pressure** to ensure continuous flow.

Functions of Boiler Feed Pump

1. **Supply feedwater** continuously to the boiler drum.
2. Maintain the required **boiler water level** to avoid overheating or tube damage.
3. Provide water at a **pressure higher than boiler pressure** to overcome resistance.
4. Ensure **safe and efficient steam generation**.
5. In power plants, it contributes to **thermal efficiency** by using economizers & regenerative heating.

Types of Boiler Feed Pumps

1. **Centrifugal Feed Pumps**
    - Most commonly used in modern high-capacity boilers.
    - Uses an impeller to impart velocity and pressure.
    - Can be multistage (2 to 8 stages or more) for very high pressures (like supercritical boilers).
2. **Positive Displacement Feed Pumps (Reciprocating/Plunger Type)**
    - Used in older or small capacity boilers.
    - Works by displacing a fixed volume of water.
    - High pressure, low flow applications.

Main Components

- **Pump Casing** → Holds water and guides flow.
- **Impeller/Plunger** → Imparts pressure to the water.
- **Suction Pipe** → Draws water from feedwater tank or deaerator.
- **Delivery Pipe** → Sends water to boiler drum.
- **Check Valve** → Prevents backflow from boiler.
- **Mechanical Seal/Gland** → Prevents leakage at shaft.
- **Drive Mechanism** → Motor, steam turbine, or engine.

Working Principle

1. Feed pump takes water from the **deaerator/feedwater tank**.
2. Water enters the pump suction side.
3. Impellers (in centrifugal type) accelerate water, converting velocity to pressure.
4. Pressurized feedwater passes through check valves.
5. Enters **economizer** → heats feedwater using flue gas.
6. Finally, enters **boiler drum/steam generator**.

Typical Pressure & Flow Ranges

- **Industrial boilers**: 10 – 40 bar (1 – 4 MPa)
- **Power plant subcritical boilers**: 150 – 180 bar
- **Supercritical/Ultra-supercritical boilers**: 250 – 350 bar
- Flow capacity depends on boiler load, can range from **tens of m³/h to thousands of m³/h**.

Importance in Boiler Operation

- Without feed pumps, boiler water level would drop, leading to **tube damage** or boiler explosion.
- Feed pump failure is a **critical emergency** in any plant.
- Usually, **two or more pumps** (1 running + 1 standby) are installed for reliability.

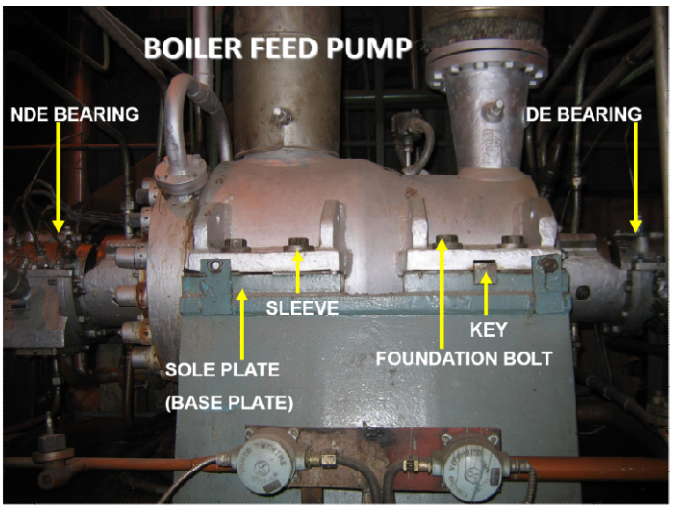


Figure 2.25: Feed pump


Figure 2.26: Feed pump

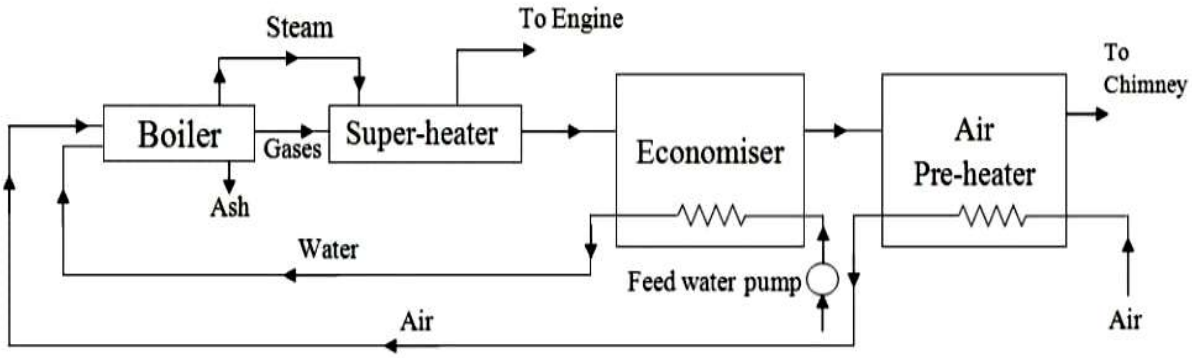


Figure 2.27: Schematic diagram of a boiler plant

- **Feed Pump:** Raises the pressure of the condensed water (condensate) so it can re-enter The boiler.
- **Economizer:** Recovers waste heat from flue gases to preheat the feedwater, improving efficiency.
- **Boiler (Steam Generator):** Adds heat to the high-pressure water, converting it into high-pressure steam.
- **Steam Turbine:** Expands the steam, converting thermal energy into mechanical power (which drives an electrical generator).
- **Condenser:** Cools the low-pressure steam leaving the turbine, converting it back into liquid water.
- **Closed Loop:** The condensed water is pumped back, completing the cycle.

Importance of Boiler Accessories

Boiler accessories are supplementary devices that **enhance the efficiency, reliability, and performance** of steam boilers. While they are not mandatory for the boiler to operate, their presence provides significant benefits:

1. Enhancement of Thermal Efficiency

- Accessories recover and reuse waste heat, reducing heat losses.
- Example:
  - **Economizer** – preheats feedwater using flue gases.
  - **Air Preheater** – warms the air before combustion, ensuring better fuel burning.
- **Impact:** Up to **10–15% increase in efficiency** can be achieved.

2. Fuel Economy

- Reduced fuel consumption since less heat energy is wasted.
- Example: A boiler with an economizer may save **10–12% of coal/fuel** compared to one without.
- This directly lowers **operational costs**.

3. Improvement in Steam Quality

- **Superheater** – converts saturated steam into **superheated steam**.
- **Steam Separator** – removes water droplets, producing **dry steam**.
- **Benefit:** Prevents turbine blade erosion, increases power output, and ensures smooth turbine operation.

4. Increased Power Output

- With higher efficiency and better steam quality, the turbine can deliver **more mechanical power**.
- A well-accessorized boiler system can produce the **same power with less fuel**.

5. Environmental & Sustainable Operation

- Lower fuel usage → reduced emissions of CO_2, SO_2, NO_x.
- Preheating combustion air leads to **cleaner and more complete combustion**.
- Promotes **sustainable energy management**.

6. Operational Flexibility & Productivity

- Accessories allow boilers to **adapt to varying loads** without efficiency loss.
- Example: A **feed pump** ensures continuous circulation of water, keeping the boiler running steadily.

7. Integration with Safety & Reliability

- While mountings (like safety valves, fusible plugs) ensure **safe operation**, accessories ensure **economic and reliable operation**.
- Together they make boilers **both safe and efficient**.

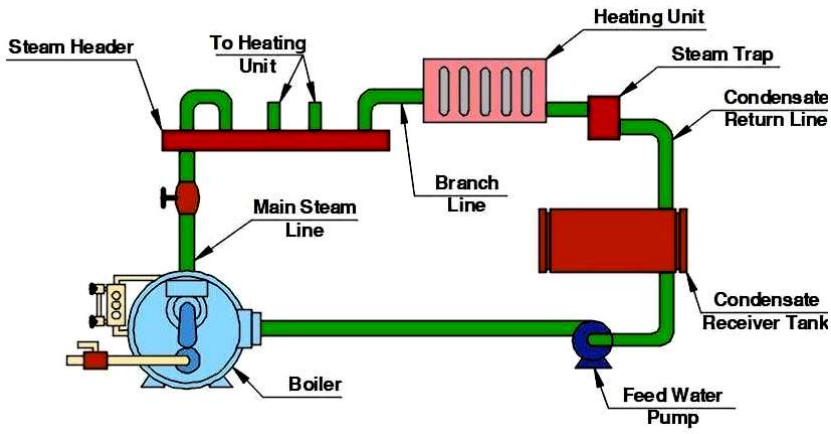


Figure 2.28: Diagram of a steam boiler

2.4 Thermal Efficiency of Boilers

The thermal efficiency of a boiler is a measure of how effectively the chemical energy of the fuel is converted into useful heat energy in the form of steam. It is defined as the ratio of the heat absorbed by the water and steam to the total heat supplied by the fuel. Mathematically, it can be expressed as:

$$\eta = \frac{m_S \times (h - h_O)}{m_f \times cv} \times 100\ \%$$

Where,

- **η** = Boiler thermal efficiency (%)
- **m_s** = Mass of steam generated (kg/hr)
- **m_f** = Mass of fuel consumed (kg/hr)
- **h** = Enthalpy of saturated steam (kJ/kg)
- **h_o** = Enthalpy of feed water (kJ/kg)
- **cv** = Calorific value of fuel (kJ/kg)

2.5 Equivalent Evaporation and Factor of Evaporation

Equivalent Evaporation

Equivalent evaporation is a standardized measure used to compare the performance of different boilers under varying operating conditions. It represents the amount of water evaporated from water at **100 °C** into dry saturated steam at **100 °C and 1 atm pressure**, which corresponds to a latent heat of **2257 kJ/kg (540 kcal/kg)**. This standardization allows fair comparison of boiler efficiency, regardless of operating pressure and temperature.

Equivalent evaporation "from and at 100^0 C",

$$\mathbf{E = \frac{m_S \times (h - h_O)}{2257}}$$

Where,

- **E** = Equivalent evaporation (kg of steam/hr from and at 100 °C)
- **ms** = Mass of steam generated (kg/hr)
- **h** = Enthalpy of steam produced (kJ/kg)
- **h_o** = Enthalpy of feedwater (kJ/kg)
- **2257** = Latent heat of vaporization at 100 °C (kJ/kg)

A higher equivalent evaporation value indicates better boiler performance, as it reflects the effective conversion of fuel energy into steam production.

Factor of Evaporation

The factor of evaporation (F_e) accounts for the difference between the actual enthalpy rise in steam generation and the standard latent heat of vaporization. It is the ratio of the actual heat absorbed per kilogram of steam to the standard latent heat (2257 kJ/kg).

Factor of evaporation,

$$\mathbf{F_e} = \frac{h - h_O}{2257}$$

Where,

- $\mathbf{F_e}$ = Factor of evaporation (dimensionless)

$\mathbf{F_e}$ is always greater than unity for all boilers because the enthalpy difference between feedwater and steam at higher pressures/temperatures is always more than the latent heat at standard atmospheric conditions.

Relevance to Boiler Performance

Both equivalent evaporation and factor of evaporation provide reliable benchmarks for comparing boilers operating under different conditions. They help normalize performance evaluation, making it possible to judge the efficiency of a low-pressure boiler against theoretical or ideal conditions. In this study, these parameters are applied to validate the calculated thermal efficiency and to highlight areas for performance improvement.

2.6 Factors Affecting Boiler Efficiency

The efficiency of a boiler is influenced by several key factors, including:

- **Fuel quality and calorific value**: Impurities, ash, or high moisture content reduce combustion effectiveness and overall efficiency.
- **Fuel–air ratio and combustion completeness**: Excess air results in heat loss through flue gases, while insufficient air causes incomplete combustion and unburnt fuel.
- **Heat losses**: Flue gas losses, radiation, and convection losses lower efficiency if not controlled through proper design, insulation, and maintenance.
- **Load demand variations**: Frequent load changes lead to unstable combustion and reduced boiler efficiency compared to steady rated load operation.
- **Feedwater temperature and quality**: Low feedwater temperature increases fuel consumption, while poor water quality causes scale deposits on heat transfer surfaces.
- **Use of performance-enhancing accessories**: Devices such as economizers and air preheaters improve efficiency by recovering waste heat and reducing fuel usage.

Chapter 3: Methodology

3.1 Research Framework

The research framework of this study is designed to systematically evaluate the performance of a low-pressure boiler through experimental data analysis. The framework integrates **data collection, performance evaluation, and optimization strategies**. Operational data, including steam pressure, steam flow rate, enthalpy, feedwater conditions, and fuel consumption, were collected over a continuous 24-hour period. These data were then processed to calculate **thermal efficiency, equivalent evaporation, and factor of evaporation**, which served as the primary performance indicators. The analysis framework also involved graphical interpretation of efficiency and pressure trends, enabling the identification of performance fluctuations and operational bottlenecks. Based on these findings, optimization strategies were proposed focusing on **combustion control, automation, and heat recovery methods** to improve boiler efficiency and reliability.

3.2 Description of the Boiler System

The boiler under study is a **low-pressure, fire-tube type boiler** designed to generate saturated steam for industrial process applications. It operates within a pressure range of **7–8 bar**, with a steam generation capacity of approximately **3250–3700 kg/hr**, as observed during the study. The boiler uses **diesel fuel** with a calorific value of around **10,900 kcal/kg (≈45,600 kJ/kg)**, supplied through a burner system that regulates fuel injection and combustion.

The boiler consists of a **furnace chamber** where combustion occurs, **fire tubes** that transfer heat to the surrounding water, a **steam drum** for steam collection, and **feedwater systems** for continuous supply. Standard boiler **mountings** such as a safety valve, water level indicator, pressure gauge, and steam stop valve ensure safe operation, while accessories like an **economizer** may be used to improve feedwater temperature and efficiency.

During operation, the boiler maintains relatively stable pressure (7.1–7.9 bar) and efficiency (70–80%), although fluctuations occur depending on fuel-air ratio and load demand. These characteristics make the system suitable for medium-scale industrial processes but also highlight the need for performance optimization through **better control systems and waste heat recovery methods**.

3.3 Data Collection Procedure

The data required for this study were collected systematically as follows:

- **Operational Time Frame**: Data were recorded over a continuous **24-hour cycle** to capture variations in boiler performance under different load conditions.
- **Measured Parameters**: Key operating parameters included **steam pressure (bar), steam flow rate (kg/hr), feedwater temperature (°C), and fuel consumption (kg/hr)**.
- **Enthalpy Values**: The **enthalpy of saturated steam** and **feedwater** were obtained from standard steam tables corresponding to the recorded pressure and temperature.
- **Fuel Properties**: The **calorific value of diesel fuel (≈10,900 kcal/kg)** was used for efficiency calculations.
- **Instrumentation**: Data were obtained using installed instruments such as a **steam flow meter, pressure gauge, temperature sensors, and fuel flow measurement system**.
- **Recording Frequency**: Observations were logged **hourly**, creating a dataset of 24 readings for subsequent analysis.
- **Performance Indicators**: From the collected data, **thermal efficiency, equivalent evaporation, and factor of evaporation** were calculated.
- **Validation**: Data trends were cross-checked using graphical plots (efficiency vs. time, pressure vs. time, etc.) to ensure consistency and reliability.

3.4 Measurement Parameters

For the performance evaluation of the low-pressure boiler, the following parameters were measured and analyzed:

- **Steam Pressure (bar)**
  - Measured using a pressure gauge connected to the steam drum.
  - Indicates the operating pressure of the boiler, which affects efficiency.
- **Steam Flow Rate (kg/hr)**
  - Recorded through a calibrated steam flow meter.
  - Represents the actual steam output of the boiler per unit time.
- **Fuel Consumption (kg/hr)**
  - Measured by tracking the hourly diesel fuel supply.
  - Used to calculate the energy input into the boiler system.
- **Feedwater Temperature (°C)**
  - Measured using temperature sensors installed at the feedwater inlet.
  - Essential for calculating the enthalpy difference between steam and feedwater.
- **Enthalpy of Steam (kJ/kg)**
  - Obtained from standard steam tables based on the measured steam pressure.
  - Represents the heat content of the produced steam.
- **Enthalpy of Feedwater (kJ/kg)**
  - Derived from steam tables corresponding to the feedwater temperature.
  - Used to calculate the net heat absorbed during steam generation.

Chapter 4: Results and Analysis

4.1. Saturated Steam Table

Table 1: Saturated Steam Table (Prepared by the ASME Research and Technology Committee on Water and Steam in Thermal Systems)

Pressure (bar)	Temperature (°C)	Enthalpy (kcal/kg)
7.1	168.07	657.8
7.2	168.73	657.3
7.3	169.38	656.8
7.4	170.03	656.3
7.5	170.68	655.9
7.6	171.32	655.4
7.7	171.96	654.9
7.8	172.60	654.4
7.9	173.24	653.9
8.0	173.87	653.4

For Temperature:

"The temperature increases gradually at each step, which is consistent with the behavior of saturated steam."

- In a saturated steam table, as **pressure increases**, the corresponding **saturation temperature** also increases.
- This is a fundamental property of steam: **higher pressure leads to higher boiling (saturation) temperature**.

For Enthalpy:

"The enthalpy (specifically of saturated steam) slightly decreases with each step, which aligns with the principle that higher pressure results in lower latent heat."

- As **pressure increases**, although the temperature rises, the **enthalpy of vaporization (latent heat)** decreases.
- This is because at higher pressures, steam requires **less additional energy** to change phase from liquid to vapor.
- So, the total **specific enthalpy (kcal/kg)** of saturated steam **gradually decreases** as pressure increases.

Summary:

- **Temperature** ↑ with **Pressure** ↑ → matches steam behavior.
- **Enthalpy** ↓ with **Pressure** ↑ → due to decreasing latent heat at higher pressure.

4.2. 24-Hour Operational Data Presentation

Table 2 : 24-Hour Steam Data of a Boiler (Using Economizer)

Time (Hours)	Steam Pressure (bar)	Steam Flow Meter (kg/hr)		Steam produces at boiler (kg/hr)	Enthalpy of saturated steam, h (kcal/kg)	Thermal Efficiency of Boiler, η (%)
		Initial	Final			
01:00	7.6	0	3340	3340	655.4	72.36 %
02:00	7.4	3340	6,815	3475	656.3	75.40 %
03:00	7.5	6815	10,235	3420	655.9	74.16 %
04:00	7.7	10235	13535	3300	654.9	71.44 %
05:00	7.5	13535	16985	3450	655.9	74.81 %
06:00	7.4	16985	20465	3480	656.3	75.51 %
07:00	7.8	20465	23755	3290	654.4	71.16 %
08:00	7.4	23755	27250	3495	656.3	75.84 %
09:00	7.5	27250	30710	3460	655.9	75.03 %
10:00	7.7	30710	34040	3330	654.9	72.09 %
11:00	7.8	34040	37320	3280	654.4	70.94 %
12:00	7.7	37320	40765	3345	654.9	72.41 %
13:00	7.5	40765	44205	3430	655.9	74.38 %
14:00	7.7	44205	47565	3360	654.9	72.74 %
15:00	7.6	47565	50965	3340	655.4	72.36 %
16:00	7.5	50965	54305	3400	655.9	73.73 %
17:00	7.7	54305	57525	3320	654.9	71.87 %
18:00	7.9	57525	60775	3250	653.9	70.24 %
19:00	7.6	60775	64220	3345	655.4	72.47 %
20:00	7.5	64220	67630	3410	655.9	73.94 %
21:00	7.8	67630	70900	3270	654.4	70.73 %
22:00	7.4	70900	74370	3470	656.3	75.30 %
23:00	7.1	74370	78070	3700	657.8	80.49 %
24:00	7.3	78070	81635	3565	656.8	77.42 %

4.3 Steam Pressure During 24-Hour Operation

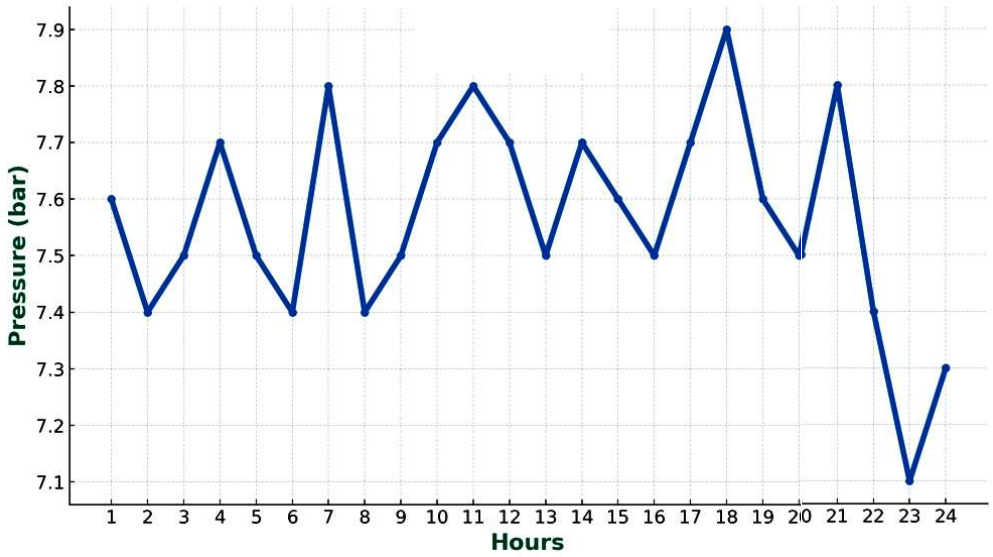


Figure 4.1: Steam Pressure vs Time

- The steam pressure remained generally stable between **7.1 bar and 7.9 bar**, with only minor fluctuations throughout the 24-hour operation.
- The highest pressure was recorded at **18:00 hours (7.9 bar)**, while the lowest occurred at **23:00 hours (7.1 bar)**, indicating effective but slightly variable pressure control.

4.4 Steam Production During 24-Hour Operation

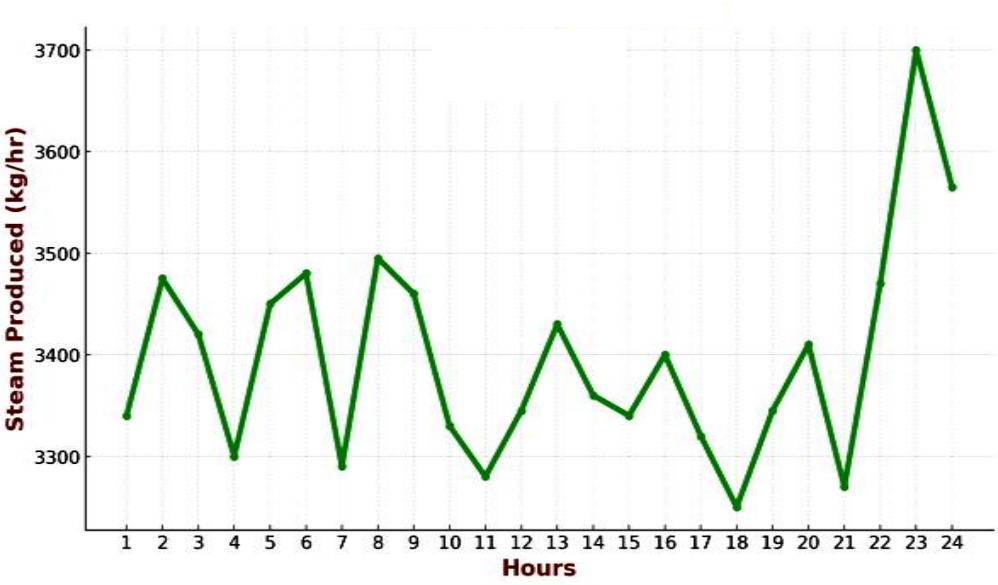


Figure 4.2: Steam Produced vs Time

- The steam generation rate remained fairly consistent within the range of **3250–3500 kg/hr** for most of the 24-hour cycle.

- A significant peak of **3700 kg/hr** was observed at **23:00 hours**, while the lowest production occurred around **18:00 hours (3250 kg/hr)**, indicating minor variations in load demand and fuel-air control.

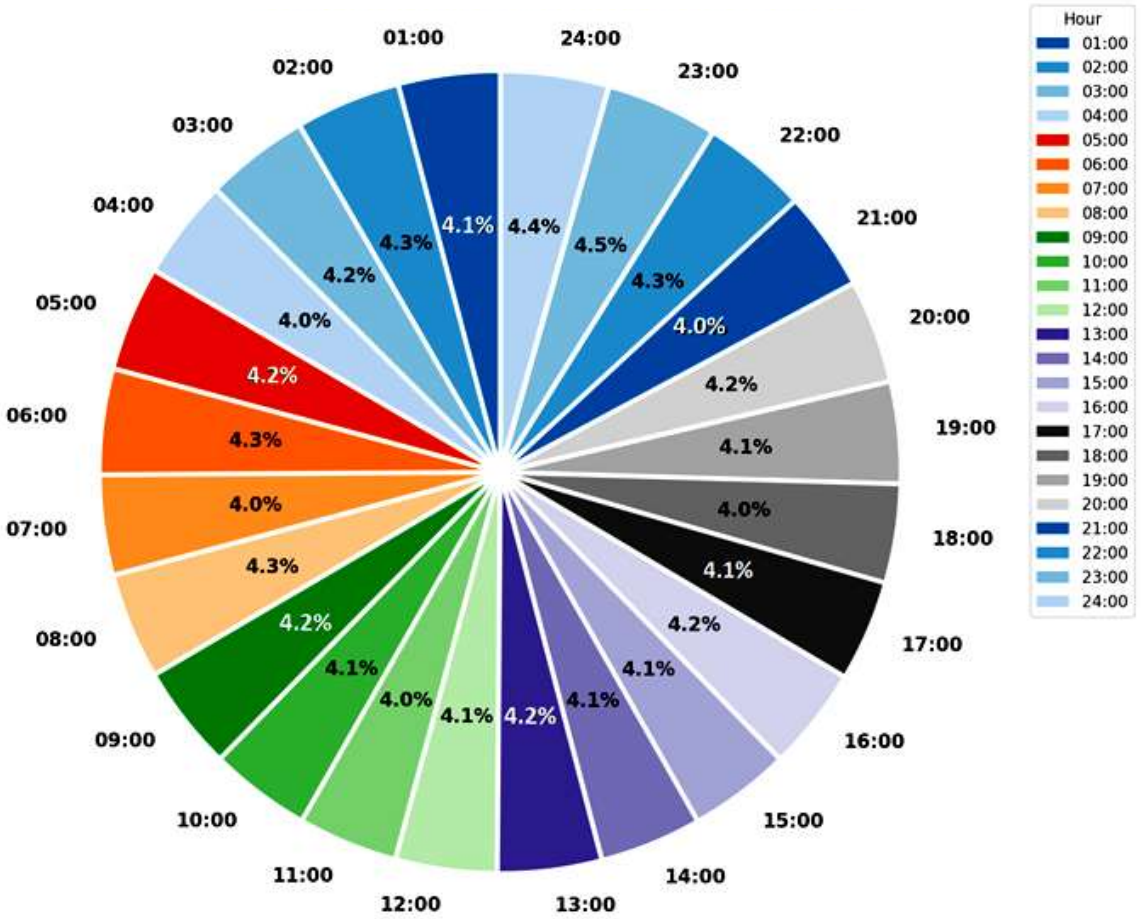


Figure 4.3: Steam Produced per Hour (Pie Chart)

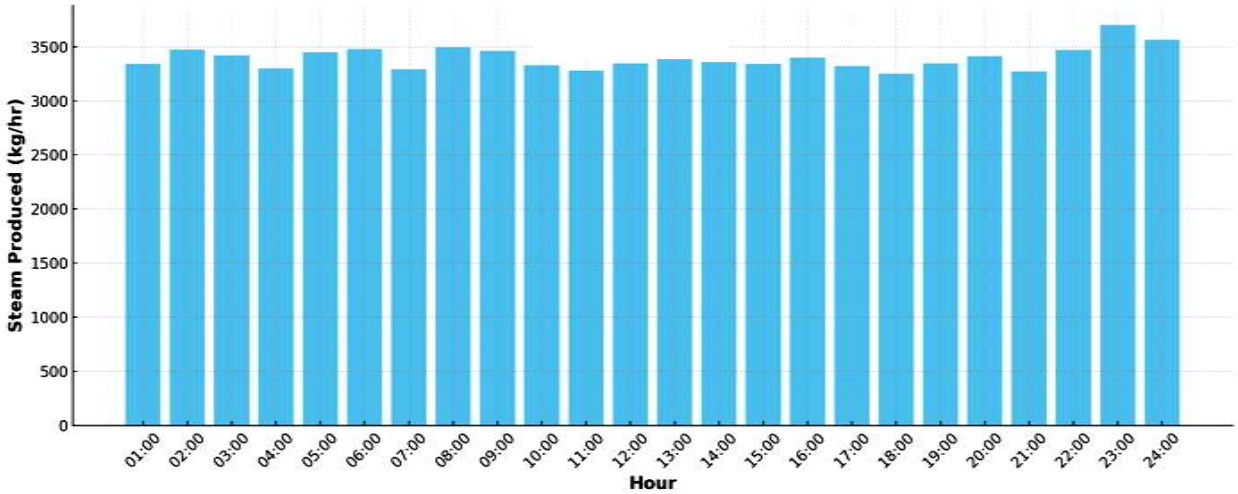


Figure 4.4: Steam Produced per Hour (Bar Chart)

4.5 Enthalpy of the Saturated Steam During 24-Hour Operation

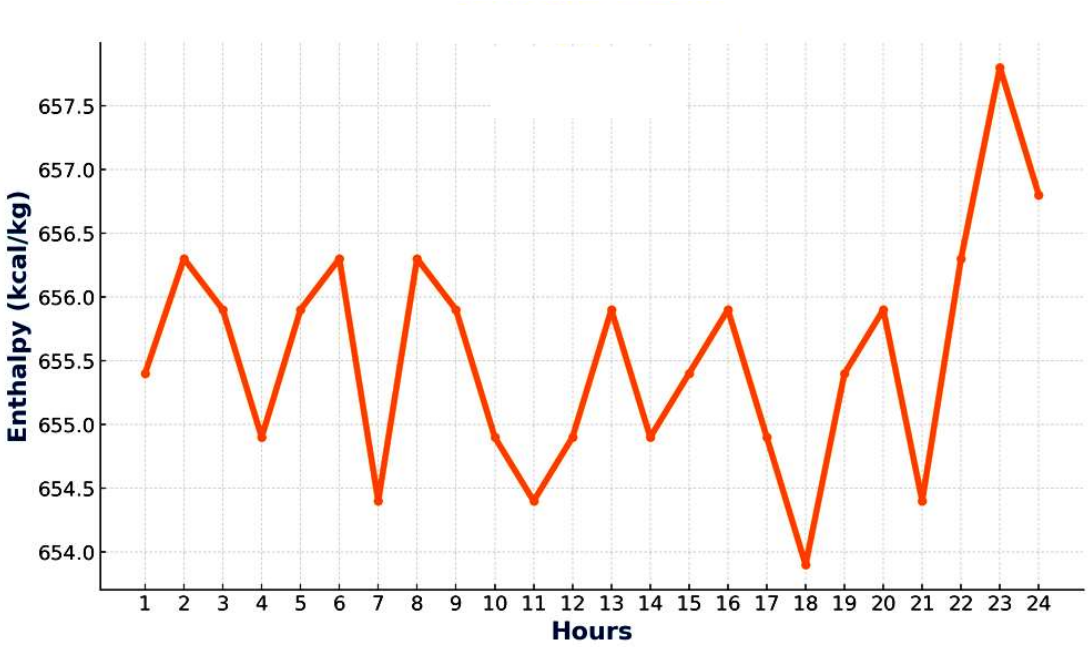


Figure 4.5: Enthalpy vs Time

4.6 Thermal Efficiency Evaluation

For the 1st hour from the above table,

Mass of fuel consumption, m_f = 250 kg/hr

Steam produces at boiler, m_S = 3340 kg/hr

Enthalpy of the saturated steam, h = 655.4 kcal/kg

Enthalpy of the feed water, h_O = 65 kcal/kg

Calorific value of diesel fuel, c = 10900 kcal/kg

Thermal Efficiency of the Boiler for the 1st hour,

$$\eta = \frac{m_S \times (h - h_O)}{m_f \times c} \times 100\ \%$$

$$= \frac{3340 \times (655.4 - 65)}{250 \times 10900} \times 100\ \%$$

$$= 0.7236 \times 100\ \%$$

$$= 72.36\%$$

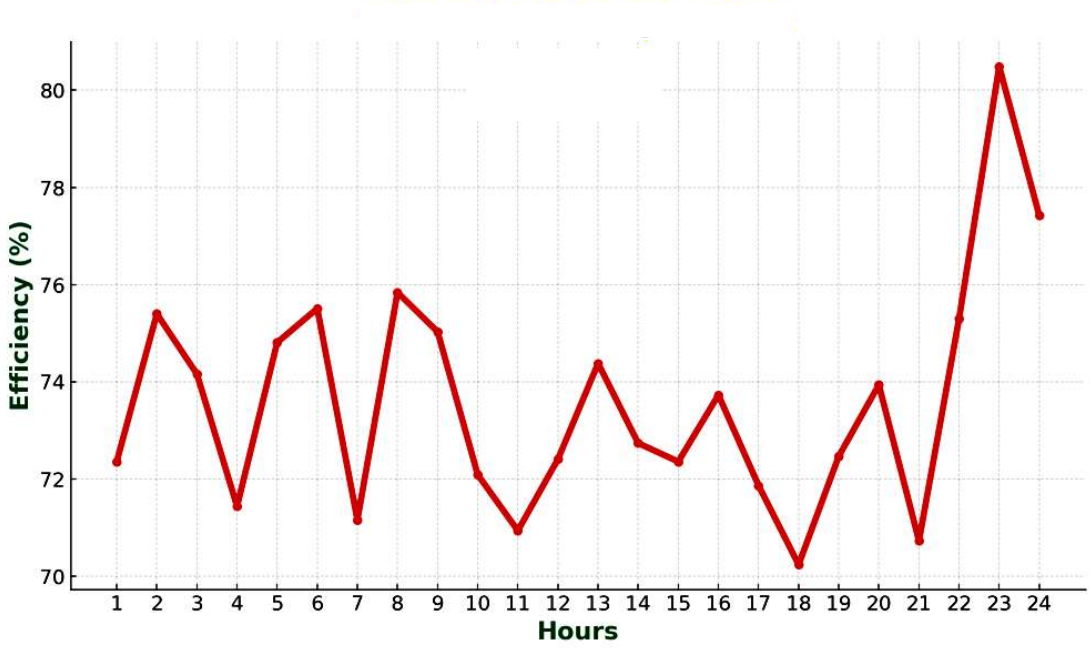


Figure 4.6: Thermal Efficiency vs Time

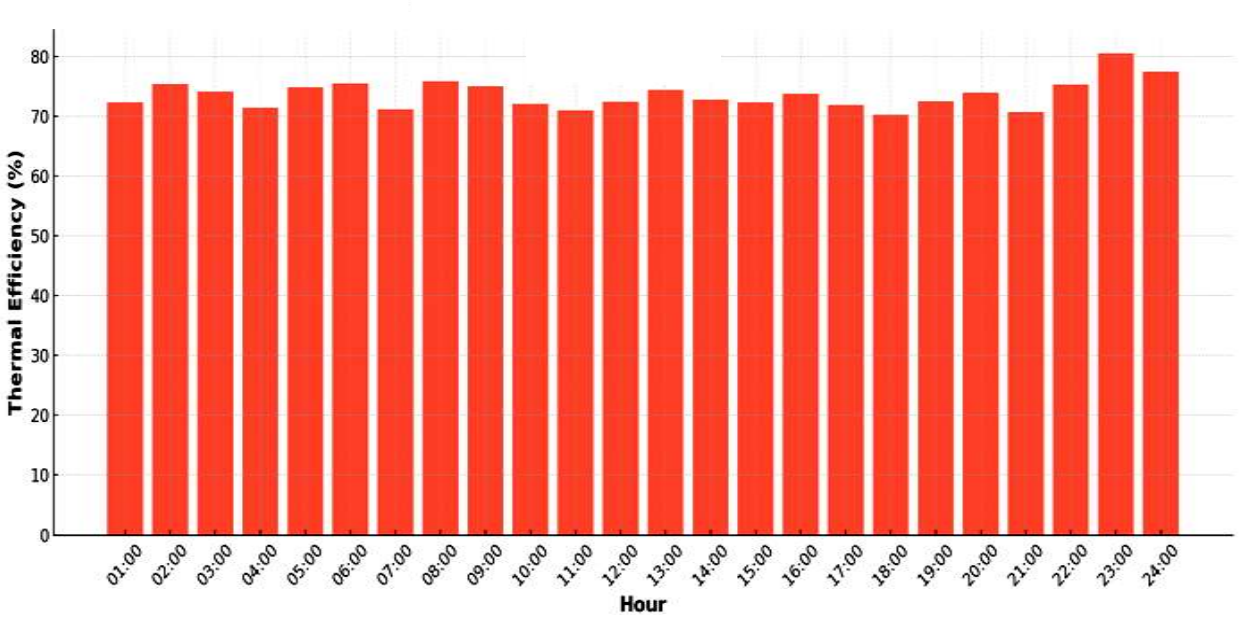


Figure 4.7: Thermal Efficiency per Hour (Bar Chart)

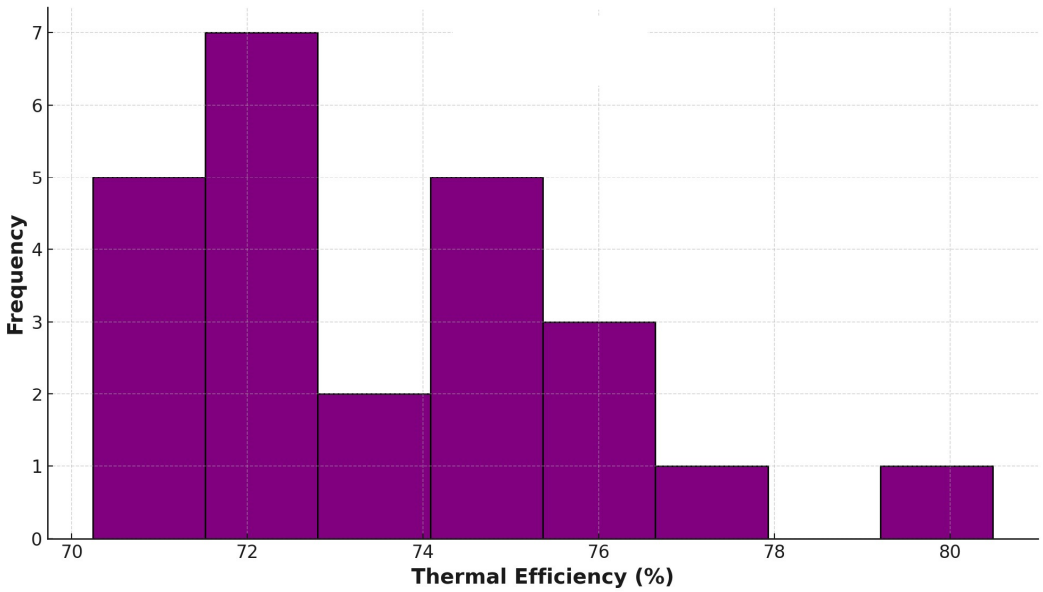


Figure 4.8: Histogram of Thermal Efficiency

4.7 Equivalent Evaporation and Factor of Evaporation Results

Equivalent Evaporation is the amount of water evaporated from feed water at 100°C and formed into dry and saturated steam at 100°C at normal atmospheric pressure; it is, usually, written as "from and at 100°C".

As the water is already at the boiling temperature, it requires only latent heat at 1.013 bar to convert it into steam at the temperature (100°C). The value of this latent heat is taken as **2257 kj/kg**.

For the 1st hour from the above table,

Steam produces at boiler, m_S = 3340 kg/hr

Enthalpy of the saturated steam, h = 655.4 kcal/kg = 655.4×4.186 = 2743.5 kj/kg

Enthalpy of the feed water, h_O = 65 kcal/kg = 65×4.186 = 272.1 kj/kg

Equivalent evaporation:

Equivalent evaporation "from and at 100^0 C", $\mathbf{E} = \frac{m_S \times (h - h_O)}{2257}$

$= \frac{3340 \times (2743.5 - 272.1)}{2257}$

= 3657.3 kg/hr

Factor of evaporation:

Factor of evaporation, $\mathbf{F_e} = \frac{h - h_O}{2257}$

$= \frac{2743.5 - 272.1}{2257}$

= 1.0952

Equivalent Evaporation and Factor of evaporation:

Table 3: Equivalent Evaporation and Factor of evaporation

Time (Hours)	Steam produces at boiler, m_s (kg/hr)	Enthalpy of saturated steam, h (kcal/kg)	Enthalpy of saturated steam, h (kJ/kg)	Thermal Efficiency of Boiler, η (%)	Equivalent evaporation, E (kg/hr)	Factor of evaporation, F_e
01:00	3340	655.4	2743.5	72.36 %	3657.3	1.0952
02:00	3475	656.3	2747.8	75.40 %	3811.7	1.0969
03:00	3420	655.9	2746.1	74.16 %	3748.7	1.0961
04:00	3300	654.9	2741.9	71.44 %	3611.2	1.0943
05:00	3450	655.9	2746.1	74.81 %	3781.5	1.0961
06:00	3480	656.3	2747.8	75.51 %	3817.2	1.0969
07:00	3290	654.4	2739.8	71.16 %	3597	1.0933
08:00	3495	656.3	2747.8	75.84 %	3833.7	1.0969
09:00	3460	655.9	2746.1	75.03 %	3792.5	1.0961
10:00	3330	654.9	2741.9	72.09 %	3644	1.0943
11:00	3280	654.4	2739.8	70.94 %	3586	1.0933
12:00	3345	654.9	2741.9	72.41 %	3660.4	1.0943
13:00	3430	655.9	2746.1	74.38 %	3759.6	1.0961
14:00	3360	654.9	2741.9	72.74 %	3676.8	1.0943
15:00	3340	655.4	2744	72.36 %	3658	1.0952
16:00	3400	655.9	2746.1	73.73 %	3726.7	1.0961
17:00	3320	654.9	2741.9	71.87 %	3633.1	1.0943
18:00	3250	653.9	2737.7	70.24 %	3550.3	1.0924
19:00	3345	655.4	2744	72.47 %	3663.4	1.0952
20:00	3410	655.9	2746.1	73.94 %	3737.7	1.0961
21:00	3270	654.4	2739.8	70.73 %	3575.1	1.0933
22:00	3470	656.3	2747.8	75.30 %	3806.2	1.0969
23:00	3700	657.8	2754.1	80.49 %	4068.9	1.0997
24:00	3565	656.8	2749.9	77.42 %	3913.7	1.0978

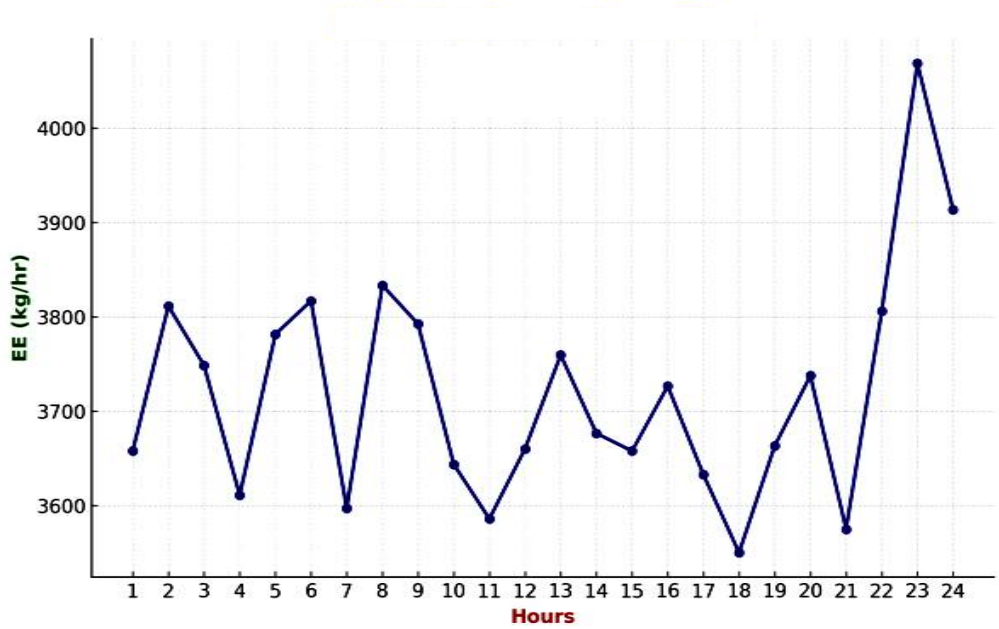


Figure 4.9: Equivalent Evaporation vs Time

The plot illustrates the hourly variation of Equivalent Evaporation (EE) over a 24-hour operational cycle. EE closely follows the steam generation pattern, ranging between **3550 kg/hr and 4070 kg/hr** with an average of approximately **3720 kg/hr**. The highest EE was observed at **23:00 hours**, coinciding with the peak steam output, while the lowest occurred at **18:00 hours**. This trend demonstrates that boiler steam production and equivalent evaporation are strongly correlated, reflecting consistent thermal efficiency under varying load conditions.

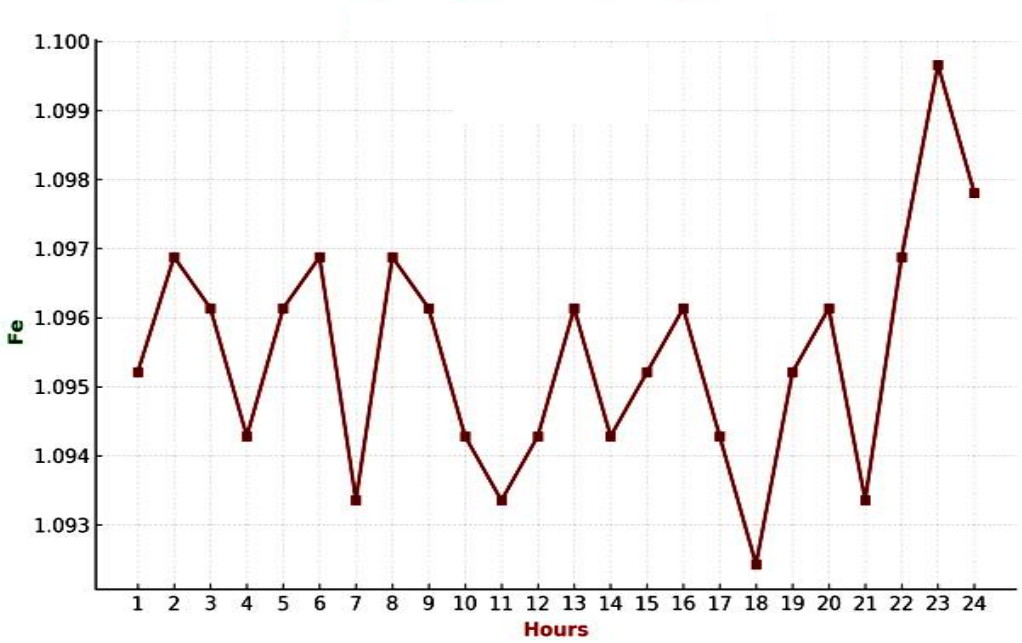


Figure 4.10: Factor of Evaporation vs Time

Chapter 5: Discussion and Decision

5.1 Interpretation of Thermal Efficiency Fluctuations

Observations from the 24-Hour Boiler Data Table

Thermal Efficiency Range

- Thermal efficiency fluctuated between **70.24% and 80.49%**, with the highest performance at **23:00 hours (80.49%)**.
- The overall average efficiency remained within a consistent and acceptable band.

❖ **Decision:**

- The boiler demonstrates satisfactory thermal performance.
- However, efficiency dips noted at **04:00, 11:00, and 18:00 hours** suggest the need to optimize **fuel management and load distribution** during those periods.

5.2 Steam Production Stability

- Steam generation ranged between **3250 kg/hr and 3700 kg/hr**, with peak output at **23:00 hours (3700 kg/hr)** and the lowest at **18:00 hours (3250 kg/hr)**.
- Overall, production stability was maintained across the operational cycle.

❖ **Decision:**

- The system ensures stable steam delivery, but the reduced output during evening hours may impact **demand fulfillment**.
- A review of **load demand patterns** and **control settings** is recommended to avoid mismatches between production and demand.

5.3 Steam Pressure Fluctuations

- Boiler pressure remained within a narrow range of **7.1–7.9 bar**, with the highest pressure at **18:00 hours (7.9 bar)** and the lowest at **23:00 hours (7.1 bar)**.
- These variations were minor and within acceptable limits.

❖ **Decision:**

- Pressure management is stable.
- Installation of **automatic pressure regulators or alarms** could further minimize variance and support higher thermal efficiency.

5.4. Equivalent Evaporation (EE)

- EE ranged between **3550 kg/hr and 4070 kg/hr**, closely following steam generation trends.
- The maximum EE occurred at **23:00 hours**, while the minimum was observed at **18:00 hours**.

❖ **Decision:**

- EE confirms boiler performance stability, with variations mainly reflecting **load demand** rather than efficiency losses.

5.5 Factor of Evaporation (F_e)

- F_e remained relatively stable between **1.092 and 1.100**, indicating that enthalpy changes due to pressure variation were minor.

❖ **Decision:**

- The near-uniform Fe values validate the **consistency of thermodynamic performance**, ensuring that efficiency changes are primarily due to load variation and operational handling.

5.6 Graphical Trends Confirmed

- Graphical analyses of **efficiency, pressure, enthalpy, and steam output** revealed consistent trends with only minor dips during early morning and evening hours.
- These visual insights confirm the numerical findings and highlight areas where targeted improvements can be applied.

❖ **Decision:**

- Continuous monitoring through graphical tools is highly beneficial for identifying efficiency dips.
- Strategies such as **combustion tuning, improved load scheduling, and feedwater preheating** should be applied to further smooth operational performance.

Chapter 6: Efficiency Optimization Techniques

6.1 Energy Losses and Sources of Inefficiency

From the dataset, we know the following:

- **Fuel consumption** = 250 kg/hr
- **Calorific value of diesel** = 10,900 kcal/kg
- **Total heat input** = 250 × 10,900 = **2,725,000 kcal/hr**
- **Steam produced** ≈ 3,250–3,700 kg/hr
- **Useful heat (based on enthalpy difference)** ≈ 2,000,000 kcal/hr (since efficiency ranges from 70–80%).

The total heat input to the boiler was calculated as **2.73×10^6 kcal/hr**, while the useful heat absorbed by steam ranged between **1.92×10^6 and 2.19×10^6 kcal/hr**, corresponding to thermal efficiencies of **70.24% to 80.49%**. Thus, the energy losses account for approximately **20% to 30%** of the total fuel energy. These losses can be classified and quantified as follows:

1. **Stack (Flue Gas) Losses: (12–18%)**
   The largest energy loss arises from hot flue gases leaving the chimney. Based on measured efficiency, stack losses are estimated to account for nearly two-thirds of the total losses. This range corresponds to 330,000–490,000 kcal/hr.

2. **Radiation and Convection Losses: (2–3%)**
   Heat escaping through the boiler casing and external surfaces contributes to about 55,000–82,000 kcal/hr of energy loss. This value is consistent with published standards for industrial boilers of similar capacity.

3. **Blowdown Losses: (1–2%)**
   Regular blowdown to control dissolved solids results in the discharge of hot water and its sensible heat. The estimated heat loss is 27,000–55,000 kcal/hr, depending on blowdown frequency.

4. **Unburned Fuel Losses: (2–3%)**
   Traces of unburned carbon in ash and incomplete combustion of hydrocarbons contribute to another 27,000–55,000 kcal/hr loss.

5. **Moisture and Incomplete Combustion Losses: (3–4%)**
   Moisture in the fuel and incomplete combustion reactions reduce effective heat release, contributing 82,000–110,000 kcal/hr of energy loss.

Summary of Energy Loss Distribution:

Table 4: Energy Loss Distribution

Loss Type	% of Input Energy	Approx. kcal/hr Lost
Stack (Flue Gas) Losses	12 – 18%	330,000–490,000
Radiation & Convection Losses	2 – 3%	55,000–82,000
Blowdown Losses	1 – 2%	27,000–55,000
Unburned Fuel Losses	2 – 3%	27,000–55,000
Moisture/Incomplete Combustion	3 – 4%	82,000–110,000
Total Losses	20 – 30%	530,000–792,000

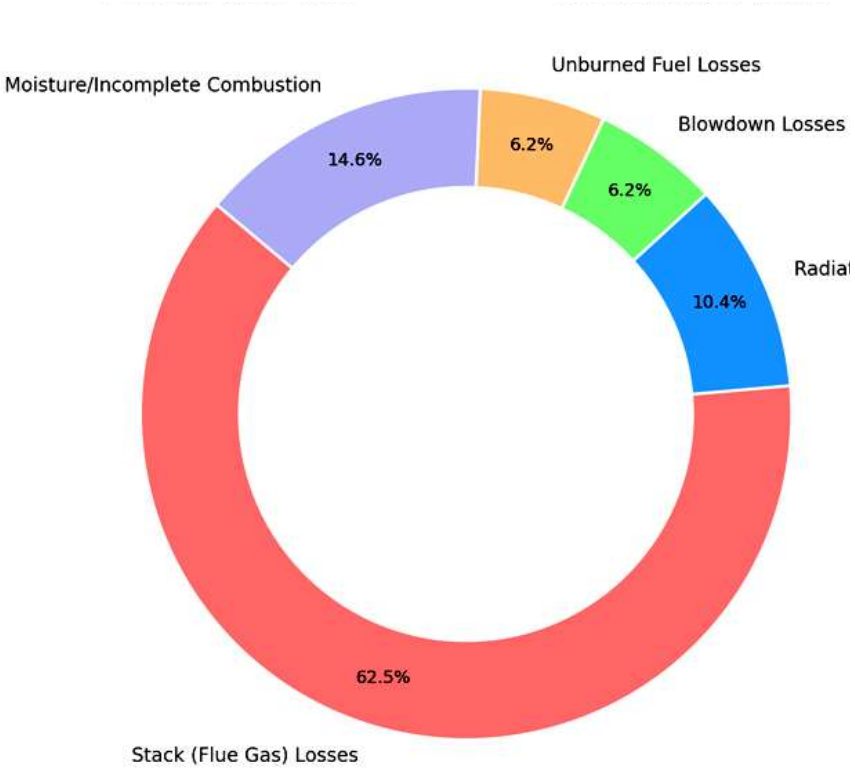


Figure 6.1: Energy Loss Distribution in Low Pressure Boiler

6.2 Efficiency Optimization Techniques

The performance of a boiler is strongly dependent on its ability to minimize energy losses and maximize the effective utilization of fuel energy. This chapter presents various techniques to improve the thermal efficiency of a low-pressure boiler, focusing on combustion improvement, waste heat recovery, reduction of heat losses, and feedwater management. A combined optimization strategy is also proposed.

6.3 Combustion Optimization

Efficient combustion ensures complete utilization of fuel energy, minimizing unburnt fuel losses and excess air losses. The key aspects include:

- **Fuel-air ratio control:** Maintaining the optimal balance between fuel and air prevents both incomplete combustion (due to insufficient air) and heat loss with flue gases (due to excess air).
- **Improved fuel quality:** Using cleaner, drier fuel with higher calorific value enhances combustion stability and reduces particulate emissions.
- **Burner design and maintenance:** Regular cleaning and tuning of burners prevent fouling, carbon deposits, and flame instability.
- **Use of oxygen trim systems:** Automated oxygen control maintains combustion efficiency under varying load conditions.

6.4 Heat Recovery Methods

Recovering waste heat from flue gases and other streams significantly improves boiler efficiency. Common methods include:

- **Economizers:** Installing economizers to preheat feedwater using flue gas heat reduces fuel consumption by lowering the enthalpy difference required during steam generation.
- **Air preheaters:** Preheating combustion air with waste heat enhances combustion temperature and efficiency.
- **Condensing heat exchangers:** Recovering latent heat from water vapor in flue gases increases overall heat utilization.
- **Cascade recovery systems:** Integrating multiple recovery devices (economizer + air preheater) provides higher efficiency gains.

6.5 Reduction of Heat Losses (Radiation, Convection, Blowdown)

Uncontrolled heat losses reduce effective boiler efficiency and must be minimized through design and operational practices:

- **Radiation and convection losses:** Can be minimized by applying high-quality refractory materials, proper insulation, and periodic inspection for leakages.
- **Blowdown losses:** Excessive blowdown wastes heat and water. Implementing controlled blowdown with conductivity-based monitoring reduces unnecessary losses.
- **Steam leakage control:** Ensuring tight sealing of valves, joints, and steam traps avoids continuous energy loss.
- **Preventive maintenance:** Regular inspection and cleaning of heat transfer surfaces reduce fouling and scaling that otherwise cause higher flue gas losses.

6.6 Effect of Feedwater Temperature and Pressuer

The enthalpy difference between feedwater and steam is a crucial factor in boiler efficiency. Optimization of feedwater conditions enhances performance:

- **Higher feedwater temperature:** Preheated feedwater reduces fuel demand by decreasing the heat input required to reach saturation conditions.
- **Deaeration of feedwater:** Removing dissolved oxygen not only prevents corrosion but also slightly increases enthalpy, contributing to efficiency.
- **Feedwater pressure control:** Maintaining stable and optimal feedwater pressure ensures reliable circulation and prevents cavitation in feed pumps.
- **Integration with waste heat sources:** Using process condensate or heat recovery units for feedwater heating further improves thermal efficiency.

6.7 Proposed Optimization Strategy

Based on the identified techniques, a combined optimization strategy is proposed for low-pressure boiler operation:

1. **Adopt intelligent combustion control systems** with automated fuel-air ratio adjustment to ensure optimal combustion under varying loads.
2. **Install economizers and air preheaters** for maximum utilization of flue gas energy.
3. **Improve insulation and refractory maintenance** to minimize radiation and convection losses.
4. **Optimize blowdown practices** by implementing conductivity-based automated blowdown systems.
5. **Preheat feedwater using waste heat recovery units**, ensuring stable temperature and pressure for consistent efficiency.
6. **Introduce periodic performance monitoring** with graphical data analysis to detect efficiency deviations in real time.
7. **Develop operator training programs** to ensure best practices in fuel handling, combustion tuning, and maintenance procedures.

Chapter - 7

Conclusion and Recommendations

7.1 Conclusion

The performance evaluation and thermal efficiency optimization of the low-pressure boiler revealed that the system generally operates within a stable and acceptable range, with thermal efficiencies between **70.24% and 80.49%**. Steam production and pressure management also remained consistent, reflecting a reliable operational profile under most load conditions. However, minor fluctuations in efficiency and output, particularly during specific hours of the day, indicate opportunities for further optimization.

The analysis of **Equivalent Evaporation (EE)** and the **Factor of Evaporation (F_e)** confirmed that variations in efficiency are primarily linked to operational practices rather than thermodynamic inconsistencies, highlighting the importance of improved fuel handling, load management, and feedwater preheating. Graphical trend analyses further validated these findings, showing that while the boiler system is efficient overall, systematic optimization can reduce performance dips and enhance sustainability.

In conclusion, the study emphasizes that significant efficiency improvements can be achieved through targeted measures such as combustion optimization, heat recovery, minimization of heat losses, and better monitoring practices. By implementing the recommended strategies, the boiler can not only achieve higher thermal efficiency and reduced fuel consumption but also contribute to lower operational costs and improved environmental performance. These outcomes align with the broader objectives of energy efficiency, sustainability, and industrial competitiveness.

7.2 Summary of Key Findings

This study evaluated the performance and thermal efficiency optimization of a low-pressure boiler through a comprehensive 24-hour operational analysis. The key findings can be summarized as follows:

1. **Thermal Efficiency Performance:** The boiler exhibited thermal efficiency values ranging from **70.24% to 80.49%**, with the highest recorded efficiency at **23:00 hours**. Despite minor fluctuations, the average efficiency remained consistent and within an acceptable operational range.
2. **Steam Production Stability:** Steam generation varied between **3250 kg/hr and 3700 kg/hr**, with stable operation across most hours. Peak steam output occurred at **23:00 hours**, while the lowest was noted at **18:00 hours**, reflecting minor load-dependent variations.
3. **Pressure Management:** Boiler pressure was maintained within **7.1–7.9 bar**, indicating satisfactory stability. Minor deviations were observed but remained within safe operational limits.
4. **Equivalent Evaporation (EE):** EE values followed steam production trends, ranging from **3550 kg/hr to 4070 kg/hr**, confirming that efficiency variations were closely tied to load conditions.
5. **Factor of Evaporation (F_e):** F_e remained stable between 1.092 and 1.100, validating consistent thermodynamic performance with negligible impact from pressure variations.
6. **Graphical Insights:** Visual analyses of efficiency, steam output, enthalpy, and pressure trends confirmed stable boiler performance, with only minor dips during early morning and evening hours.

Overall, the findings confirm that the boiler system operates efficiently under most conditions but presents opportunities for improvement through targeted optimization strategies such as combustion tuning, heat recovery, and feedwater management.

7.3 Main Reason of Boiler Efficiency Decreases

1. Effect of Low Boiler Feedwater Temperature

- If the feedwater temperature is low, the boiler requires more heat energy to convert water into steam.
- This results in higher fuel consumption. Since more fuel is burned to produce the same amount of steam, the boiler efficiency decreases.

2. Effect of Scale Formation on Boiler Tubes

- When scale deposits form on the inner surface of boiler tubes**,** they act as an insulating layer**.** This obstructs heat transfer from flue gases to water.
- As a result, more fuel is needed to generate the required steam output, leading to higher fuel consumption and lower boiler efficiency**.**

3. Effect of Carbon Deposits inside Boiler Tubes

- If carbon or soot deposits accumulate inside boiler tubes, heat transfer is reduced because the deposits act as a barrier between hot gases and tube walls.
- Consequently, more fuel is consumed to achieve the desired steam generation, causing a reduction in boiler efficiency.

4. Incomplete Combustion of Fuel

- If the fuel does not burn completely (due to insufficient air, poor mixing, or bad fuel quality), part of the energy remains unused.
- This increases fuel consumption and lowers efficiency.

5. Excess Air Supply

- Too much air during combustion carries away heat through the flue gases.
- Although excess air prevents incomplete combustion, too much of it **lowers efficiency** by wasting heat.

6. Poor Quality of Fuel

- Fuel with high **moisture** or **ash content** produces less useful heat.
- More fuel must be burned for the same steam output, decreasing efficiency.

7. Heat Loss through Flue Gases (Stack Losses)

- If flue gas temperature is very high, a large portion of heat escapes with exhaust gases.
- This reduces available heat for steam generation.

8. Heat Loss due to Radiation and Convection

- Heat escaping from the boiler surface to the surrounding atmosphere lowers efficiency.
- Common in old or poorly insulated boilers.

9. Blowdown Losses

- To control water quality and remove dissolved solids, boilers require periodic blowdown.
- Excessive blowdown wastes water and heat, decreasing efficiency.

10. Leakages

- **Steam leakage** from valves, joints, or fittings wastes useful steam.

- **Air leakage** into the furnace reduces combustion temperature, lowering efficiency.

11. Overloading of Boiler

- Operating the boiler beyond its design capacity reduces combustion efficiency.
- Tubes may not transfer enough heat, leading to incomplete steam generation.

12. Poor Maintenance of Burner/Furnace

- Dirty burners, clogged nozzles, or misaligned furnaces reduce proper fuel-air mixing.
- This causes incomplete combustion and efficiency loss.

7.4 Recommendations for Boiler Operation

Based on the analysis of the 24-hour performance evaluation, the following recommendations are proposed to improve the operational efficiency and reliability of the low-pressure boiler:

1. **Combustion Control:** Implement advanced fuel–air ratio monitoring systems (such as oxygen trim controls) to maintain optimal combustion conditions and reduce both unburnt fuel losses and excess air losses.

2. **Heat Recovery Enhancement:** Install or upgrade economizers and air preheaters to recover flue gas heat for feedwater and combustion air preheating, thereby reducing overall fuel consumption.
3. **Minimization of Heat Losses:** Improve boiler insulation, repair refractory linings, and adopt conductivity-based blowdown control to minimize radiation, convection, and blowdown losses.
4. **Feedwater Optimization:** Preheat feedwater using waste heat recovery units and ensure stable pressure and temperature control to reduce the enthalpy difference during steam generation.
5. **Load Management:** Align boiler operation more closely with demand patterns by adjusting load scheduling during low-efficiency periods (e.g., early morning and evening hours) to avoid unnecessary fuel usage.
6. **Monitoring and Automation:** Integrate automated data logging, graphical trend analysis, and alarm systems for real-time performance monitoring and early detection of inefficiencies.
7. **Maintenance and Training:** Conduct routine preventive maintenance to reduce fouling and scaling of heat transfer surfaces, and provide operator training programs to ensure best practices in combustion tuning, blowdown control, and system monitoring.
8. **Sustainability Measures:** Explore opportunities for fuel quality improvement, adoption of renewable or cleaner fuels, and emission reduction strategies to align operations with environmental standards.

7.5 Future Plan and Future Technology

1. Advanced Monitoring and Automation

- Plan: Introduce smart sensors and IoT-based control systems to monitor boiler parameters (temperature, pressure, flue gas composition, water level) in real time.
- Technology:
  - Artificial Intelligence (AI) and Machine Learning (ML) algorithms for predictive maintenance.
  - Automated combustion control to maintain optimum fuel-air ratio.
- Expected Outcome: Reduction in human error, improved efficiency, and minimized downtime.

2. Improved Combustion Techniques

- Plan: Research on alternative combustion methods that ensure complete fuel burning with minimal emissions.
- Technology:
  - Fluidized bed combustion for uniform temperature distribution and higher efficiency.
  - Low NOx burners to reduce harmful emissions.
- Expected Outcome: Higher thermal efficiency with reduced environmental pollution.

3. Integration of Waste Heat Recovery Systems

- Plan: Install advanced economizers, regenerative air preheaters, and heat exchangers to maximize waste heat recovery.
- Technology:
  - Condensing economizers to recover both sensible and latent heat.
  - Organic Rankine Cycle (ORC) systems for low-grade heat recovery.
- Expected Outcome: Significant fuel savings and efficiency improvement of 8–12%.

4. Use of Renewable and Hybrid Fuel Sources

- Plan: Reduce dependency on conventional fossil fuels by blending or switching to renewable fuels.
- Technology:
  - Biomass co-firing with coal or gas.
  - Hydrogen-enriched fuel for cleaner combustion.
- Expected Outcome: Lower CO_2 emissions, sustainable energy use, and compliance with green energy policies.

5. Advanced Boiler Materials and Design

- Plan: Develop lightweight, high-strength, and corrosion-resistant materials for boiler tubes and pressure parts.
- Technology:

    - Nano-coated tubes to resist scaling and fouling.
    - Composite materials to reduce heat losses and extend lifespan.
- Expected Outcome: Better heat transfer, reduced maintenance costs, and longer operational life.

6. Digital Twin Technology

- Plan: Create a digital replica (virtual model) of the boiler system to simulate operating conditions and test optimization strategies.
- Technology:
    - Real-time simulation with AI-integrated digital twins.
- Expected Outcome: Accurate performance prediction, optimized operation, and reduced experimental costs.

7. Carbon Capture and Sustainability Measures

- Plan: Integrate carbon capture technologies with low-pressure boilers to meet environmental regulations.
- Technology:
    - Post-combustion CO_2 capture systems.
    - Use of captured CO_2 in industrial applications (carbon utilization).
- Expected Outcome: Eco-friendly operation, compliance with global emission standards, and contribution to net-zero targets.

The future of low-pressure boilers lies in smart automation, waste heat recovery, renewable integration, advanced materials, and carbon management technologies. By adopting these innovations, boiler performance can be significantly optimized, ensuring higher thermal efficiency, reduced operating costs, and environmentally sustainable operation.

7.6 Future Plan and Future Technology in Bangladesh

1. Modernization of Existing Low-Pressure Boilers

- In many industries in Bangladesh (e.g., textile, garments, food processing, tea estates), old and inefficient fire-tube boilers are still in use.
- Future Plan: Replace or retrofit these boilers with energy-efficient models equipped with economizers, air-preheaters, and automated control systems.
- Benefit: Reduction in fuel cost (coal, gas, furnace oil) and better compliance with energy efficiency standards.

2. Adoption of Renewable Fuels

- Bangladesh imports a significant portion of its fuel. Rising costs and depletion of natural gas reserves demand alternative fuel sources.
- Future Plan: Use biomass (rice husk, jute stick, bagasse, sawdust, etc.) as fuel in low-pressure boilers, since these are widely available in rural and agro-industrial areas.
- Technology: Biomass-fired and hybrid (biomass + natural gas) low-pressure boilers.

- Benefit: Reduced dependency on imported fuels, lower CO_2 emissions, and promotion of local resources.

3. Waste Heat Recovery in Industries

- Many industries in Bangladesh (textile dyeing, cement, steel, sugar) release large amounts of waste heat through exhaust gases.
- Future Plan: Introduce economizers, regenerative air preheaters, and ORC-based systems to utilize waste heat in low-pressure boilers.
- Benefit: Fuel savings of 10–15%, improved national energy security.

4. Digital Monitoring and Automation

- Most small and medium-scale industries still rely on manual boiler operation.
- Future Plan: Introduce IoT-based monitoring, smart sensors, and automated feedwater control to optimize efficiency.
- Technology: Low-cost microcontroller systems designed for SMEs in Bangladesh.
- Benefit: Reduced human error, safer operation, and extended equipment life.

5. Boiler Operator Training and Awareness

- In Bangladesh, many accidents occur due to unskilled operation and lack of maintenance.
- Future Plan: Establish training programs and certification systems for boiler operators under Bangladesh Boiler Act.
- Benefit: Improved safety, reduced accidents, and higher efficiency of boilers.

6. Government Policies and Energy Audits

- Bangladesh Energy Regulatory Commission (BERC) and SREDA are promoting energy efficiency.
- Future Plan:
    - Mandatory energy audits for industries.
    - Subsidies or tax benefits for industries upgrading to high-efficiency low-pressure boilers.
- Benefit: National fuel savings, reduced import burden, and lower greenhouse gas emissions.

7. Future Technologies in Bangladesh Context

- Hybrid Boilers: Use both natural gas and biomass.
- Solar-Assisted Boilers: Preheating feedwater with solar thermal collectors.
- Advanced Materials: Anti-corrosion and anti-scaling coatings to suit Bangladesh's high humidity and water impurities.
- Carbon Capture Integration: Pilot projects in large industries to capture and reuse CO_2.

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