Power Plant Engineering

Lecture 6

Combustion Mechanism, Combustion Equipment and Firing Methods

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Lecture learning outcomes:

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

i. Explain the basic principles and processes involved in fuel bed combustion and its operational characteristics.

ii. Identify and compare different types of mechanical stokers and their roles in efficient solid fuel combustion.

iii. Describe the working principle, equipment, and advantages of pulverized coal firing systems.

iv. Discuss the components and functioning of fuel-oil firing systems and their combustion control methods.

v. Illustrate the operation and design features of gas firing systems, including burner types and flame control.

vi. Evaluate the advantages, applications, and performance aspects of combined gas and fuel-oil firing systems in modern boilers.

Content

1. Fuel Bed Combustion

- Fuel bed combustion refers to the burning of solid fuels (typically coal, biomass, or waste) on a grate or bed where air is supplied from beneath [1].
- In this method, solid fuel rests on a grate (fuel bed), and air is supplied from beneath to support combustion.
- It is commonly used in small to medium-sized boilers, furnaces, and domestic heating systems.
- The grate serves two critical functions:
  - ✓Support: It physically holds the bed of solid fuel.
  - ✓Air Distribution: It allows for the controlled introduction of underfire air (or primary air) directly through the bed.

1. Fuel Bed Combustion

Advantages of Fuel Bed Combustion

- Simple and economical system.
- Can burn low-grade solid fuels (coal, biomass).
- Easy operation and maintenance.

Limitations of Fuel Bed Combustion

- Inefficient for large-scale boilers (limited air penetration).
- Poor control of combustion process.
- High unburnt carbon loss in ash.
- Low thermal efficiency compared to modern methods (e.g., pulverized coal firing).

1. Fuel Bed Combustion

Cont…

Combustion Stages in a Fuel Bed

When solid fuel burns on a grate, different layers (zones) are formed:

1. Drying Zone

- Located at the top of the fuel bed.
- Moisture is evaporated from the fuel due to heat from below.
- Occurs at temperatures below 100°C.

2. Devolatilization (Pyrolysis)

- Located below the drying zone
- Volatile compounds are released.
- Produces combustible gases and char.

1. Fuel Bed Combustion

Cont…

3. Oxidation Zone (Combustion Zone)
   - Oxygen from primary air reacts with fixed carbon and volatile gases.
   - Produces CO_2, CO, H_2O, and heat.
4. Reduction Zone
   - Located below the oxidation zone.
   - Insufficient oxygen leads to partial combustion, producing CO and H_2.
   - These gases burn in the upper layers with secondary air.

1. Fuel Bed Combustion

Cont…

Equipment Used in Fuel Bed Combustion

- Grates – stationary, travelling, or vibrating.
- Stokers – devices to feed coal mechanically (e.g., chain-grate, spreader stoker).
- Ash pit – collects ash falling from grate.
- Forced draught fan – supplies air through fuel bed.
- Secondary air ports – allow additional air for complete combustion of volatiles.

2. Mechanical Stokers

- Mechanical stokers are automated systems used to feed solid fuel (typically coal or biomass) into a furnace or boiler in a controlled and continuous manner [2].

Its primary functions are to:

- Feed fuel: Transport fuel from a storage hopper to the furnace at a controlled rate.
- Support and distribute: Maintain a uniform fuel bed on a grate.
- Supply air: Provide and distribute underfire air (primary air) through the grate and fuel bed.
- Remove residue: Continuously or intermittently discharge ash for disposal.

2. Mechanical Stokers **Cont…**

- Mechanical stokers ensure a more consistent and efficient combustion process, better response to load changes, and reduced labor costs.
- They are the workhorses for small to medium-sized industrial boilers using coal, biomass, and waste-derived fuels.

Advantages of Stoker Firing

- Efficient fuel utilization
- Uniform fuel feeding
- Reduced labor requirement
- Better control of combustion
- High boiler efficiency
- Reliable for medium capacities

2. Mechanical Stokers

Cont…

Disadvantages of Stoker Firing

- Limited capacity
- Mechanical complexity
- High initial cost
- Maintenance problems
- Lower efficiency at high loads
- High space requirement

2. Mechanical Stokers

Types of Mechanical Stokers

- Mechanical stokers are primarily classified by the direction in which fuel is fed onto the grate relative to the direction of air flow.
- This classification is fundamental, as it dictates the combustion dynamics and the stoker's application.

The three main types are:

1. Overfeed stokers
2. Underfeed stokers
3. Crossfeed stokers

2. Mechanical Stokers Cont…

1. Overfeed (top-feed) stokers

- Fuel is fed onto the top of the fuel bed.
- The fuel and air move in a counter-current fashion: fuel moves downward onto the grate, while air moves upward through it.
- Fresh fuel is added on top while older fuel burns below.

The common types of overfeed stokers are:

i. Chain-Grate or Travelling Grate Stoker

- This is the most common type of overfeed stoker for industrial applications.
- Endless chain (like a conveyor) forms the grate surface.
- Fuel is fed at the front, carried along the moving grate, and burnt during travel.

2. Mechanical Stokers Cont…

i. Chain-Grate or Travelling Grate Stoker

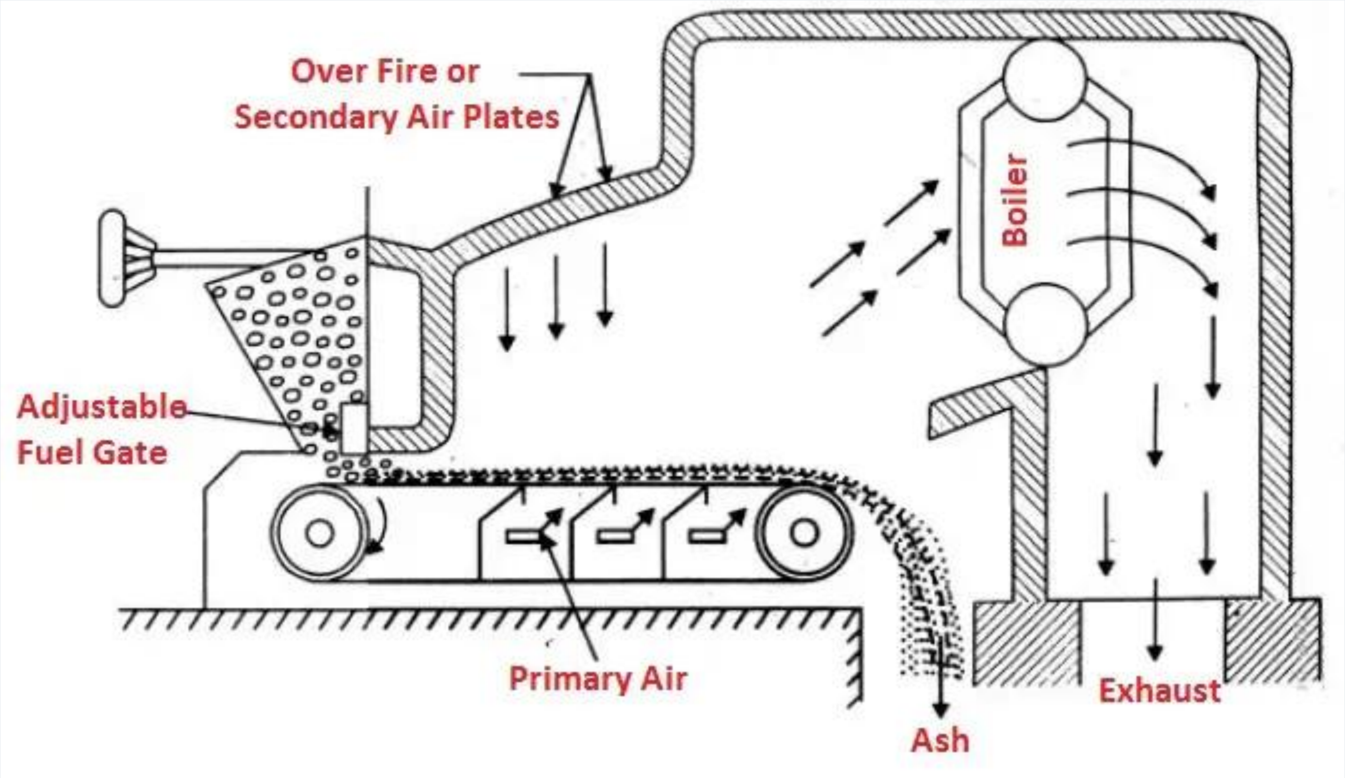

Figure 1: Travelling Gate Stoker, Saif, M. (2020). Coal Handling Plant in Thermal Power Generation.
url:https://www.theengineerspost.com/wp-content/uploads/2019/10/Chain-grate-Stoker-1.jpg

2. Mechanical Stokers Cont…

- Chain-grate stokers are suitable for medium-size boilers.

ii. Spreader Stoker

- Fuel is thrown (spread) onto the grate by mechanical distributors.
- Small particles burn in suspension, while larger particles fall and burn on the grate.
- Ensures rapid ignition and good efficiency.
- Widely used in large industrial boilers.

2. Mechanical Stokers Cont…

ii. Spreader Stoker

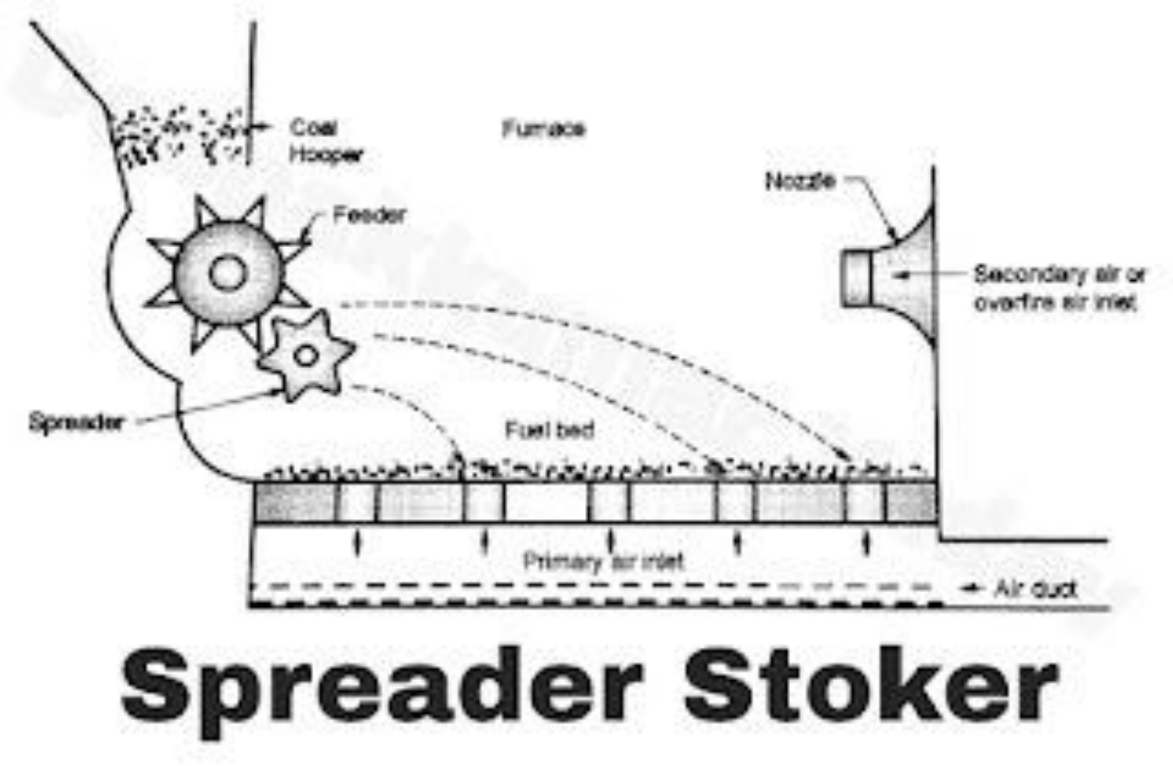

Figure 2: Spreader Stoker, Deepak Kumar Yadav, Overfeed Stokers and Its Types.
url:https://blogger.googleusercontent.com/img/b/R29vZ2xl/AVvXsEhHu8wvU99dZ2K2H_pqc9APOoYQ6edB_LlPrD9QJj9u9HLHjHc0pC5PkkIRVZzOR7ScTaXX7_otie3y3t88skE37UiQNfZXO2cMaEMxUIpG1v65uUI_EKvJQ8yhsD8RWIiEQJZmrEZEnCFC/s320/Spreader+Stoker.jpg

2. Mechanical Stokers Cont…

2. Underfeed Stokers

- Fuel is supplied from below the bed, and air also passes upward.
- Fresh fuel meets high temperature, igniting quickly.
- Suitable for mechanical stokers and uniform fuel sizes.

The common types of underfeed stokers are:

i. Single-Ram and Multiple-Ram Stokers
   - Rams push fresh coal upward from below into the combustion zone.
   - Provides uniform distribution of fuel.

ii. Screw-Feed Stoker
   - A rotating screw pushes coal upward from a hopper into the furnace.
   - Best suited for small to medium boilers with uniform coal size.

2. Mechanical Stokers Cont…

2. Underfeed Stokers

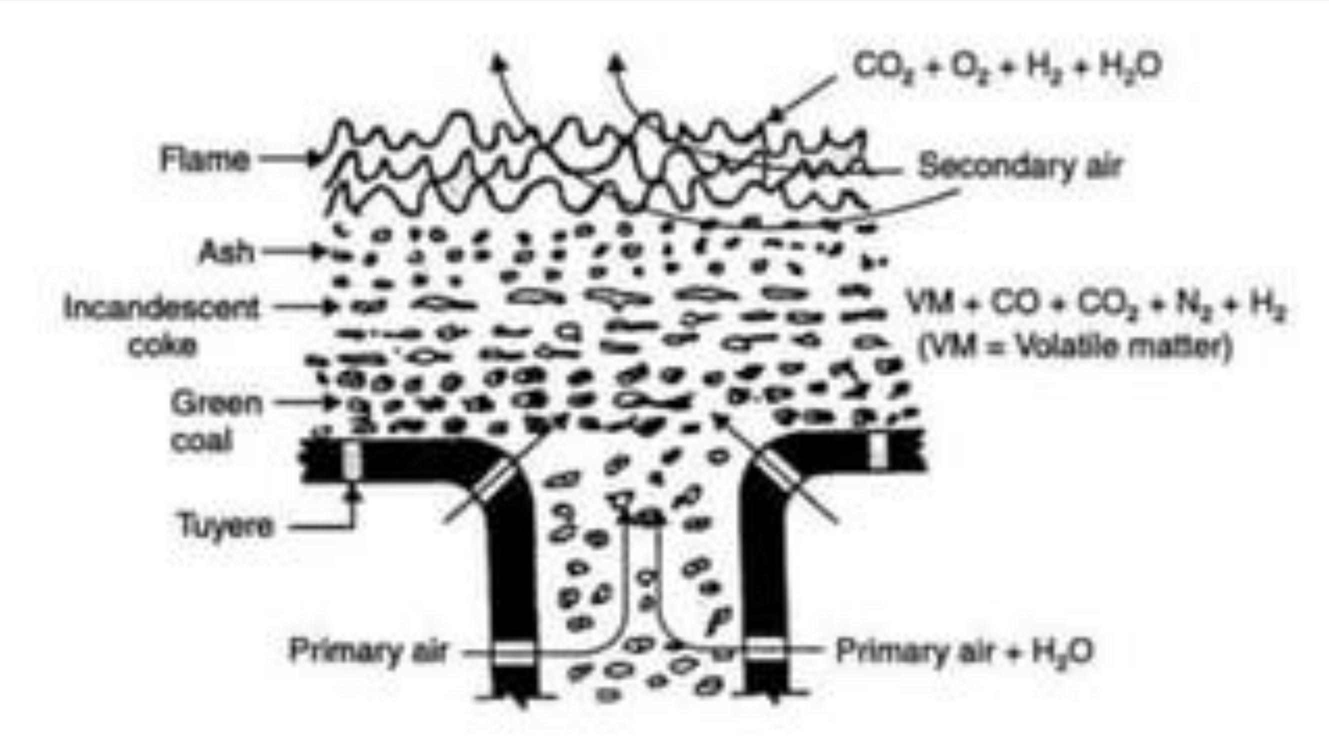

Figure 3: Underfeed Stoker, Saif, M. (2020). Coal Handling Plant in Thermal Power Generation Station.
url:https://image.slidesharecdn.com/mechanicalstokers-220122103539/85/Mechanical-stokers-5-320.jpg

2. Mechanical Stokers Cont…

3. Cross-feed (Side-feed) Combustion

- Fuel is pushed across the grate from one side to the other.
- Air comes from beneath.
- Used in travelling grate stokers.

- In general, the selection of a stoker is a balancing act between:
  - ✓Fuel characteristics
  - ✓Desired capacity
  - ✓Efficiency targets
  - ✓Emissions regulations

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3. Pulverized Coal Firing

- Pulverized coal firing is a method of burning coal after grinding it into a fine powder.
- Coal is ground into a very fine powder and blown with air into the furnace, where it burns in suspension, similar to a gas or oil flame.
- The finely ground coal is mixed with preheated air and blown into the furnace through burners.
- Pulverized coal firing is the dominant technology for large-scale electricity generation worldwide [3].
- It is the most widely used firing method in modern thermal power plants because of its high efficiency and ability to burn a wide range of coal qualities.

3. Pulverized Coal Firing Cont…

- The innovation is that finer particles have larger surface area, better mixing with air, rapid ignition, and nearly complete combustion leading to higher efficiency and greater power output from a single unit.

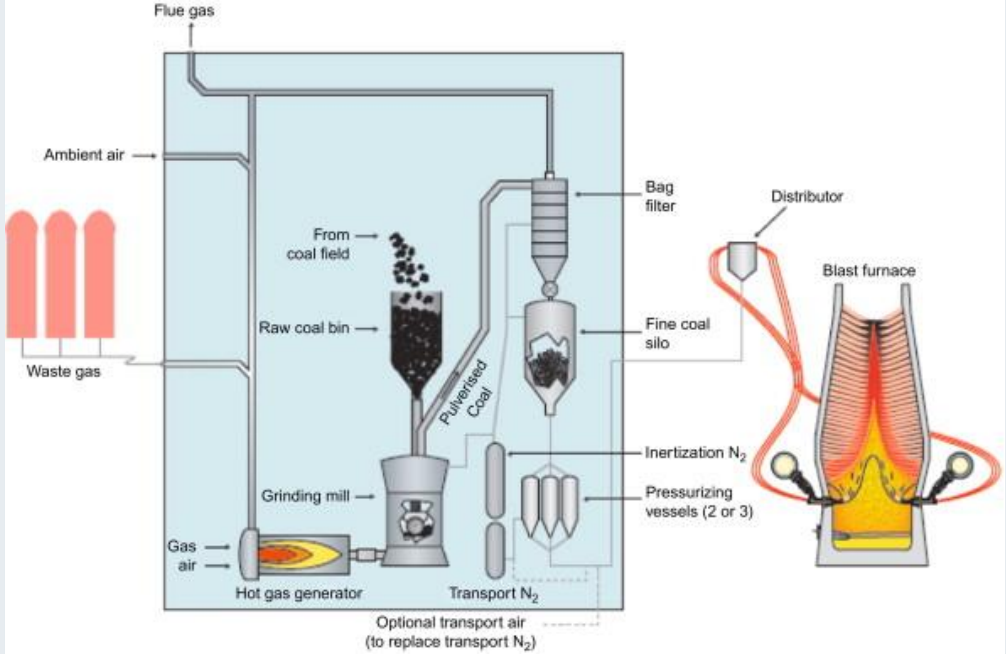

Figure 4: Pulverized Coal Firing, Moodley, S., Naidoo, N., & Mohammadi, A. H. (2019). Coal Combustion Process. url:https://ars.els-cdn.com/content/image/3-s2.0-B9780080969886000171-f1_1-15-9780080969886.jpg

3. Pulverized Coal Firing

Cont…

Advantages of Pulverized Coal Firing

- High combustion efficiency (up to 98%)[3].
- High boiler efficiency and steam generation rates.
- Rapid response to load changes
- Uniform heat distribution
- Suitable for low-grade coal
- Reduced unburned carbon in ash
- Reduced requirement of manual labor (automatic feeding).

3. Pulverized Coal Firing

Cont…

Disadvantages of Pulverized Coal Firing

- High capital cost for pulverizer, burners, fans.
- Requires skilled operation and maintenance.
- Produces fly ash, requiring dust collection equipment (electrostatic precipitators, bag filters).
- Higher risk of explosion and fire hazards due to fine coal dust.
- Not economical for small-scale plants.

3. Pulverized Coal Firing

Major Components of Pulverized Coal System

The system consists of the following main parts:

- Coal pulverizer (mill): Crushes coal into fine powder (typically crushed to ~20 mm).
- Primary air fan: Carries the powdered coal from mill to the furnace.
- Burners: Inject coal-air mixture into furnace for combustion.
- Secondary air supply: Provides additional oxygen for complete combustion.
- Furnace: Where the coal-air mixture is burned.
- Ash Handling System: Removes the ash produced.

3. Pulverized Coal Firing

Cont…

Methods of Pulverized Coal Firing

There are two main systems:

A. Unit System (Direct System)

- In this system, each boiler has its own pulverizing mill, and pulverized coal is directly fed from the mill to the furnace.
- The primary air fan is integrated with the mill.
- The processes are Coal → Pulverizer → Burner → Furnace
- Simple and flexible, used in small plants.

3. Pulverized Coal Firing

Cont…

Unit System

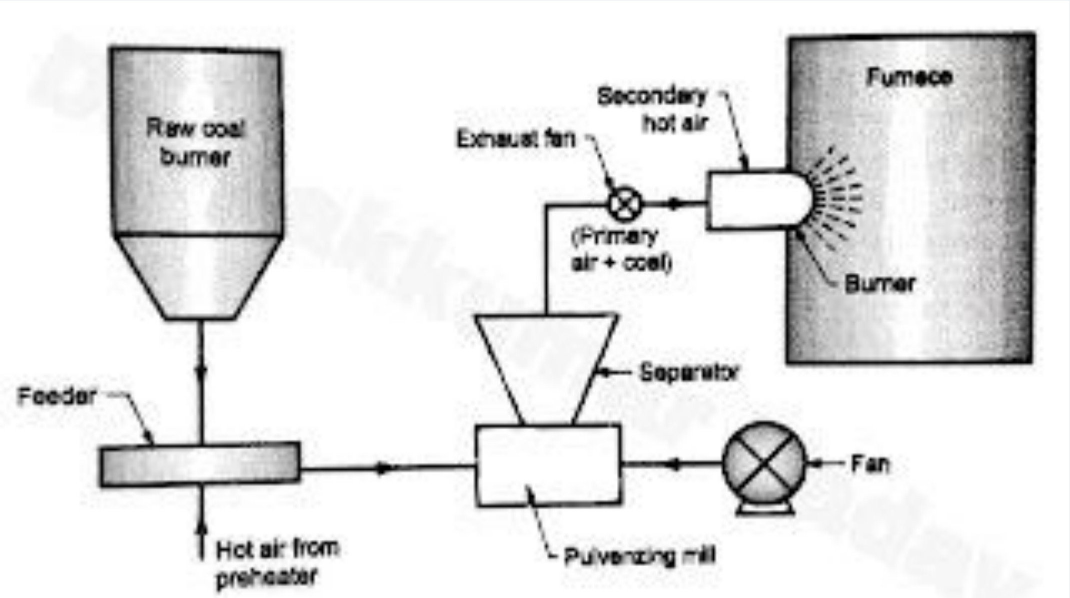

Figure 5: Pulverized Coal Firing, Unit System, Yadav, D. K. (2021). Pulverized Fuel Handling System. url:https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRILEZbSq_cMQBkCEQfqHuzYMvii3VC3Mum0OSfQKyuvSn1rsns

3. Pulverized Coal Firing

Cont…

A. Central System (Bin System)

- Pulverized coal is prepared in large mills, then stored in bins or bunkers, and finally supplied to burners as needed.
- One central pulverizer feeds multiple burners.
- Pulverizing mills can operate independently of boiler operation.
- Useful when many boilers share a common coal preparation plant.
- The processes are:

  Coal → Pulverizer → Storage Bin → Burner → Furnace

4. Fuel-Oil Firing Systems

- Unlike gaseous fuels, which readily mix with air, or solid fuels, which burn on a grate, liquid fuels present a unique challenge.
- A Fuel-Oil Firing System is an integrated assembly designed to store, prepare, deliver, and combust fuel oil in a controlled and efficient manner [4].
- Its primary function is to atomize the oil and mix it with combustion air.
- Fuel-oil firing involves burning liquid petroleum-based fuels (e.g., diesel, kerosene, heavy fuel oil) in boilers or furnaces to generate heat or steam.
- Fuel-oil firing systems are employed where coal handling is difficult or where clean and quick-start operation is essential (e.g., marine boilers, standby power plants, and industrial units).

4. Fuel-Oil Firing Systems

The Common Applications of fuel-oil firing systems include:

- Industrial boilers for process steam and heating.
- Marine propulsion and auxiliary power.
- Peak-load and standby power generation plants.
- Large residential and commercial heating systems.

Key Properties of Fuel Oils

- The design of an oil firing system is heavily influenced by the properties of the oil itself.
- Oils are classified by grade, from light (No. 1, Kerosene) to heavy (No. 6, Bunker C).

4. Fuel-Oil Firing Systems **Cont…**

To ensure efficient combustion, the following properties of fuel oil are important:

- Viscosity
  - ✓ The most critical property for handling and atomization.
  - ✓ It is a measure of the oil's resistance to flow.
  - ✓ Heavy oils must be preheated to reduce their viscosity for pumping.
- Calorific Value
  - ✓ higher than coal (approx. 10,000 kcal/kg).
- Pour Point
  - ✓ The temperature below which the oil will not flow.
  - ✓ Preheating may be necessary just to pump the oil from storage tanks.

4. Fuel-Oil Firing Systems

- Flash Point
  - ✓ The temperature at which the oil gives off enough vapor to ignite.
  - ✓ This is a key safety parameter for storage.
- Sulphur Content
  - ✓ leads to corrosion and pollution.
- Ash Content
  - ✓ usually very low compared to coal.

4. Fuel-Oil Firing Systems

Cont…

Fuel-Oil Handling System

- Before firing, oil must be properly stored, heated, and supplied to the burners.
- The components of fuel-oil firing systems are:

  1. Storage tanks – store oil in bulk; often provided with heating coils.
  2. Pumps – transfer oil from storage to day tanks and burners.
  3. Heaters – reduce viscosity for easy pumping and atomization.
  4. Filters & strainers – remove impurities and suspended solids.
  5. Pipelines & valves – control and direct oil flow.
  6. Burners – atomize oil and mix with air for combustion.

4. Fuel-Oil Firing Systems

Methods of Atomization

- Atomization is the process of breaking down the bulk liquid fuel into a fine mist of tiny droplets, creating a high surface-to-volume ratio for efficient combustion [5].
- The quality of atomization directly determines the efficiency, stability, and cleanliness of the flame.
- Poor atomization leads to large droplets that do not fully burn, resulting in soot, smoke, and carbon deposits.

The main atomization methods are:

1. Mechanical Atomization

✓ Oil is forced under pressure through a small nozzle.

✓ Common in small and medium-capacity boilers.

4. Fuel-Oil Firing Systems **Cont…**

2. Steam Atomization

- ✓ Steam is used to break the oil into fine particles at the nozzle tip.
- ✓ Suitable for large-capacity boilers; ensures fine atomization.

3. Air Atomization

- ✓ Compressed air atomizes the oil.
- ✓ Used in small burners or where steam supply is not available.

4. Fuel-Oil Firing Systems

Cont…

2. Types of Oil Burners

Based on the atomization method, oil burners are classified

- Pressure jet burner – uses high-pressure oil (mechanical atomization).
- Steam jet burner – uses steam jet to atomize oil.
- Air jet burner – uses compressed air for atomization.
- Rotary cup burner – oil is thrown from a rotating cup to form a fine spray.

4. Fuel-Oil Firing Systems **Cont…**

Once atomized, the combustion of a single droplet is a rapid, multi-stage process:

- Heating: The droplet is heated by radiation from the flame and convection from hot gases.
- Vaporization: The volatile components of the oil evaporate, forming a combustible vapor cloud around the droplet.
- Cracking (for heavy oils): Heavier molecules thermally decompose (crack) into lighter gases and a solid carbon residue (cenosphere).
- Ignition & Combustion: The vapor cloud ignites, creating a diffusion flame envelope around the droplet. The remaining carbon cenosphere burns afterwards.
- Burnout: Complete consumption of the carbon, leaving minimal ash.

4. Fuel-Oil Firing Systems

Cont…

Advantages of fuel-oil firing

- High calorific value
- Rapid startup and shutdown
- Compact system design
- Suitable for remote or backup applications

Limitations

- Higher fuel cost compared to coal or gas
- Requires careful handling and storage
- Emissions: CO_2, SOx, NOx
- Preheating needed for heavy oils

5. Gas Firing Techniques

- Gas firing refers to the combustion of gaseous fuels (e.g., natural gas, propane, biogas) in burners to generate heat for industrial or domestic applications [2].
- Gas firing techniques are primarily defined by the method and timing of mixing the gaseous fuel with combustion air.
- Compared to solid and liquid fuels, gaseous fuels offer:
  - ✓Clean and smokeless combustion.
  - ✓Higher thermal efficiency.
  - ✓Easier control and automation.

5. Gas Firing Techniques

- The common applications of gas firing are on:
  - ✓Steam boilers
  - ✓Furnaces and kilns
  - ✓Gas turbines
  - ✓Domestic heating systems

Types of Gas Firing Techniques

- Gas burners are classified based on the extent to which fuel and air are mixed prior to combustion.

5. Gas Firing Techniques

- According to the extent to which fuel and air are mixed prior to combustion, gas firing techniques are classified based on:

a. According to Air-Fuel Mixing

1. Premixed Firing

✓Fuel gas and primary air are mixed before entering the burner.

✓Produces short, hot, and clean flames.

✓Efficient mixing, smokeless flame

Example: Bunsen burner type.

5. Gas Firing Techniques

2. Diffusion (non-premixed) Firing

- ✓Fuel gas and air meet at the burner exit and mix during combustion.
- ✓Produces longer, luminous flames.
- ✓Safer operation, stable flame
- ✓Widely used in industrial boilers and furnaces.

b. According to Burner Type

1. Atmospheric Burners

- ✓Gas mixes with air before ignition.
- ✓Simple design, used in lab and domestic setups..

5. Gas Firing Techniques

2. Forced-Draft Burners

- ✓Air is supplied by a fan (forced draft).
- ✓Fuel and air thoroughly mixed before or at the burner nozzle.
- ✓Used in industrial boilers, furnaces.

3. High-Velocity Burners

- ✓Fuel gas is injected at very high velocity, entraining surrounding air for mixing.
- ✓Used for metallurgical furnaces, glass kilns.

4. Flameless (surface) Burners

- ✓Fuel burns over a porous refractory surface.
- ✓Produces low NOx emissions and uniform heating.

6. Combined Gas and Fuel-Oil Firing

- A combined gas and oil firing system (often called a dual-fuel system) is designed to burn either gaseous fuel, fuel oil, or both simultaneously in the same boiler or furnace to generate heat in boilers, furnaces, or turbines [6].
- A dual-fuel system is essentially an integration of a gas firing system and an oil firing system, sharing a common furnace, boiler, and often a common air register and control system.
- The purpose is to achieve flexibility, reliability, and efficiency in fuel usage.

6. Combined Gas and Fuel-Oil Firing

Cont…

Types of Combined Gas and Oil Burners

1. Separate Burners for Gas and Oil
    1. Two independent burners are fitted on the same furnace wall.
    2. Either fuel or both fuels can be used.
2. Dual-Fuel Burners (Combined Burners)
    1. Gas and oil firing systems are integrated in a single burner.
    2. The burner has gas nozzles and oil atomizers arranged together.
    3. Flame stability is ensured by using oil as a pilot when gas is unstable.

6. Combined Gas and Fuel-Oil Firing

Modes of Operation

1. Alternate Firing

- ✓ System runs on one fuel at a time.
- ✓ Switches based on availability or cost.

2. Simultaneous Firing

- ✓ Both fuels are burned together.
- ✓ Used to stabilize flame or meet high load demands.

3. Automatic Switchover

- ✓ System detects fuel interruption and switches automatically.
- ✓ Ensures uninterrupted operation.

Summary

- Fuel bed combustion involves burning solid fuel on a grate, commonly used in small and medium boilers for steady heat generation.
- Mechanical stokers automate fuel feeding and ash removal, improving combustion efficiency and reducing manual labor.
- Pulverized coal firing ensures better mixing of fuel and air, resulting in higher combustion efficiency and faster heat release.
- Fuel-oil and gas firing systems provide cleaner combustion, easier control, and faster response to load changes.
- Combined gas and fuel-oil firing systems enhance operational flexibility, allowing switching between fuels based on availability and cost.

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Thank you !