

Coal: Composition, Properties and Classification

Coal Origin and Basic Characteristics

- **Definition and Formation:**

- Naturally occurring, combustible, black or brown sedimentary rock
- Formed from plant material (branches, roots) mixed with clay soil and rock
- Coalification occurs through heat, pressure, humidity, and microbial action
- Classification based on maturity:
 - Peat (least mature)
 - Lignite
 - Bituminous
 - Anthracite (most mature)

Coal Composition and Structure

Organic Components

- **Fixed Carbon (FC):**

- Carbon-rich residual matter remaining after heating
- Major contributor to energy content (GCV)
- Calculated as: $100\% - \text{moisture}\% - \text{VM}\% - \text{ash}\%$

- **Volatile Matter (VM):**

- Released when coal is heated to 925°C for 7 minutes without air
- Contains H, N, O-rich hydrocarbons with low molecular weight
- Contributes to calorific value
- Aids coal ignition and provides activation energy for combustion
- Some volatile matter may come from mineral matter decomposition

- **Hydrocarbon Structure:**

- Varies based on original plant characteristics
- Affected by extent of coalification over time
- Determines reaction kinetics and caking properties
- Can be analyzed through FTIR and NMR spectroscopy

Inorganic Components

- **Mineral Matter:**

- Inorganic salts containing Al, Si, Ca, Mg, Na, K, Fe, etc.
- Converts to individual oxides during combustion (ash)
- Quantified as: $\text{MM} = 1.1 \times \text{Ash content}$
- High silica content increases abrasiveness

- **Moisture:**
 - Present in inherent or external forms
 - Lower moisture content is generally preferred
 - Creates pores when evaporated, increasing surface area
 - Helps determine coal maturity level

Coal Analysis Methods

Proximate Analysis

- Uses 72 mesh (212 micron) coal sample
- **Moisture Determination:**
 - 1g sample in hot air oven (100°C, 1 hour)
 - Mass loss measured as moisture content
 - Reporting bases: as received, air dry, or equilibrated
- **Volatile Matter (VM):**
 - Coal heated to 925°C without air for 7 minutes
 - Mass loss represents volatile matter content
- **Ash Content:**
 - Coal heated with oxygen at 800°C
 - Residue mass represents ash content

Ultimate Analysis

- Elemental composition using 4-15 mg sample
- Measures:
 - **Carbon (C):** Present in both VM and FC
 - **Hydrogen (H):** Typically 4-5%
 - **Nitrogen (N):** Typically 2-3%
 - **Sulfur (S):** In hydrocarbons and mineral matter
 - **Oxygen (O):** Typically 5-8%, calculated by difference

Advanced Analysis Techniques

- **Petrographic Analysis:**
 - Microscopic examination of coal structure
 - Gray coloration indicates carbon-rich regions

Coal Quality Parameters

Energy Content

- **Gross Calorific Value (GCV):**

- Energy released during complete combustion
- Measured in kcal/kg or kJ/kg using bomb calorimeter
- Quality classification:
 - Premium coal (Grade 1): 7000 kcal/kg
 - Good quality: 6000 kcal/kg
 - Common quality: 3000 kcal/kg
- Low ash coal typically has higher GCV

Physical Properties

- **Hardgrove Grindability Index (HGI):**

- Measures coal's grinding difficulty
- Uses 50g sample ground to 72 micron
- Scale interpretation:
 - 40-60: Good grindability
 - 60: Soft coal, easier to grind

- **Abrasion Index:**

- Measures coal's abrasive nature
- Caused primarily by quartz, alumina, and silica content
- Units: mg/kg (wear caused by using 1 kg coal)
- Affects equipment: conveyor belts, crushers, mills, screens, bunkers

Coking Properties

- **Caking and Swelling Characteristics:**

- Measured through:
 - Caking index
 - Free swelling index (FSI)
 - Plasticity/fluidity index
 - LTGK (Low Temperature Gray-King) analysis

- **Coking Process:**

- During heating without air, coal undergoes thermal cracking
- Transitions through plastic/fluid phase
- Resolidifies as hard solid (coke)
- Volatile matter released during process

- **Quality Requirements:**

- Low ash content (<18%)
- High plasticity for proper coke making
- Good swelling properties
- Used primarily in steel industry

Impurities in Coal

Ash Content

- **Performance Impacts:**
 - Reduces calorific value (GCV)
 - Increases hardness and grinding difficulty
 - Causes equipment abrasion
 - Ash fusion temperature depends on composition
 - Liquid ash damages furnaces and boilers
- **Environmental Concerns:**
 - May contain toxic elements (lead, mercury)
 - Reflects composition of nearby clay compounds
 - Creates unnecessary transport burden
- **Remediation:**
 - Coal cleaning/washing reduces ash content

Sulfur Content

- **Forms of Sulfur:**
 - **Pyritic Sulfur:** As iron pyrites (FeS_2) and chalcopyrite (CuFeS_2)
 - Appears as veins up to 100mm length, 150mm thickness
 - Forms nodules of framboids (10-20 microns)
 - Individual crystals: 1-40 microns
 - **Sulfate Sulfur:** As FeSO_4 , CaSO_4 , MgSO_4
 - **Organic Sulfur:** In hydrocarbons as mercaptan, thiols, sulfides
 - Includes thiophenols, thioethers, bithioethers
 - Contains aliphatic, aromatic, and heterocyclic compounds
- **Environmental Impact:**
 - Releases SO_2 and SO_3 when burned
 - Forms H_2S during coke making
 - Generally limited to 1% in specifications
 - Creates acid mine drainage:
 - Generates H_2SO_4 through weathering and microbial activity
 - Chemical process: $\text{FeS}_2 + \text{O}_2 + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + \text{SO}_4^{2-} + \text{H}^+$
 - Full reaction: $4\text{FeS}_2 + 15\text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{Fe}^{2+} + 8\text{SO}_4^{2-} + 4\text{H}^+$

Other Impurities

- **Chlorine and Phosphorus:**
 - Measured case-by-case
 - Affects steel quality when present

Coal Classification and Market Value

Grading Systems

- **Coking Coal:**
 - Steel Grade 1-2: 0-15% to 18% ash
 - Washery Grade 1-6: 18-21-24-28-35-42-49% ash
- **Semi-Coking Coal:**
 - Grade 1-2: 0-19% to 24% ash

Regional Characteristics

- **Indian Coal:**
 - Distribution: 88% non-coking, 12% coking
 - Ash content standards:
 - 30%: Very good quality
 - 40%: Acceptable quality
 - 50%: Poor quality
 - Northeast India coal:
 - High sulfur (4-10%)
 - Good GCV and coking properties
 - Limited use due to sulfur content
 - Suitable for cement industry
- **Global Comparison:**
 - 10% ash: Normal global standard
 - 30% ash: Considered high internationally

Market Value

- Coking coal: ₹10,000-15,000 per ton
- Non-coking coal: ₹4,000-6,000 per ton

Industrial Applications

Thermal Power Plants

- Requirements:
 - High VM and FC content
 - High GCV, low ash and sulfur
 - Non-coking properties

Steel Industry

- Requirements:
 - High GCV coking coal
 - Low VM and moisture
 - Quality measured by caking index, FSI, LTGK

Cement Industry

- Requirements:
 - Good GCV coal
 - Can utilize high ash coal
 - Non-coking properties preferred

Direct Reduced Iron (DRI) Technology

- Converts non-coking coal to synthetic gas
- Generally more cost-effective than traditional methods

Coal Sampling, Size Reduction and Cleaning

Coal Heterogeneity and Sampling Considerations

- **Distribution Characteristics:**
 - Coal contains extremely heterogeneous distribution of mineral matter and hydrocarbons
 - Proper sampling is critical for accurate analysis
 - Representative samples must account for this variation

Size Reduction and Liberation

- **Liberation Size Concept:**
 - Size must be reduced until particles can be separated into:
 - High mineral matter particles
 - High hydrocarbon particles
 - This critical size is termed "liberation size"
 - Practical limitations typically prevent reduction below 75 microns
 - Smaller sizes require higher energy consumption
 - Excessive grinding generates more fines, creating handling issues
- **Size Reduction Effects:**
 - Even after crushing to similar sizes, particles may have different distributions of:
 - Mineral matter
 - Hydrocarbons
 - Size reduction to lowest possible size improves separation efficiency

Coal Cleaning Methods

Physical Cleaning Processes

- **Density-Based Separation:**
 - Exploits density differences between components:
 - Hydrocarbons: 1.2-1.3 g/cc
 - Mineral matter: 2.6-2.7 g/cc
 - Separation solutions include:
 - Kerosene
 - Tetrachloroethylene
 - Bromoform
 - Zinc chloride solutions
 - Generally, coal with:
 - Lower specific gravity has lower ash content
 - Higher specific gravity has higher ash content
- **Surface Property-Based Separation:**

- **Hydrophobicity Differences:**
 - Hydrocarbons are hydrophobic (water-repelling)
 - Mineral matter is hydrophilic (water-attracting)
 - Used in froth flotation processes
- **Surface Charge Characteristics:**
 - Differential charges used in oil agglomeration processes
- **Chemical Reagent Affinity:**
 - Selective separation based on differential chemical affinities

Chemical Cleaning Processes

- Utilizes chemical reactions or dissolution processes
- Either hydrocarbons or mineral matter selectively react with specific reagents
- Can target specific impurities not easily removed by physical methods

Biochemical Cleaning Processes

- Employs microorganisms to selectively remove impurities
- Can be particularly effective for certain sulfur compounds
- Generally slower but potentially more environmentally friendly

Washability Analysis

- **Purpose and Procedure:**
 - Identifies optimal separation parameters
 - Determines cutoff values for GCV/ash/sulfur
 - Detailed plots prepared to identify cutoff specific gravity
- **Analytical Steps:**
 1. Individual specific gravity fractions are separated
 2. Fractions are washed, dried and analyzed for:
 - Mass percentage
 - Complete coal characterization (proximate analysis, GCV)
 - Additional parameters relevant to end-use
- **Data Presentation:**
 - Tables and plots prepared on:
 - Differential density basis
 - Cumulative basis
 - Analysis focus varies by coal type:
 - Coking coal: Proximate analysis vs. specific gravity most important
 - Non-coking coal: Proximate analysis and GCV vs. specific gravity essential
 - Additional properties (FSI, Caking index) measured for final consideration

Cleaning Objectives and Implementation

- **Key Goals:**

- Reduce sulfur content (environmental benefit)
- Reduce ash content (improves thermal performance)
- Increase overall resource utilization efficiency

- **Typical Implementation Timing:**

- After mining operations
- Before utilization in power plants or other applications

- **Particle Composition Variations:**

- Same size coal particles can have different:
 - Mineral compositions (SiO_2 , Al_2O_3 , FeO , K_2O , etc.)
 - Hydrocarbon structures (long chain, branched chain, cyclic, aliphatic, aromatic)
- These variations affect both cleaning efficiency and end-use performance

Coal Combustion Fundamentals

Basic Combustion Chemistry

- **Combustion Process:**
 - Involves chemical reactions between coal hydrocarbons and oxygen
 - Typically uses air (21% O₂ by volume, 23% by weight) as oxygen source
 - Approximately 80% of air is nitrogen (non-reactive)
 - Combustion is exothermic (releases heat energy)
- **Energy Release Mechanism:**
 - Energy stored in chemical bonds (C-C, C-H, C-O, C-S) is released
 - Products (CO₂, H₂O) have lower internal bond energy than reactants
 - Energy release measured as Gross Calorific Value (GCV) in kcal/kg
 - Activation energy required to initiate reactions
- **Key Reaction Types:**
 - Complete combustion: $C_xH_y + O_2 \rightarrow CO_2 + H_2O$
 - Partial combustion: $C_xH_y + O_2 \rightarrow CO + H_2O$
 - Simplified representation: $C + O_2 \rightarrow CO_2$
 - Additional reactions occur with S, N, P, Cl, producing various oxides

Combustion Kinetics and Controlling Factors

- **Reaction Rate Variations:**
 - Different coal hydrocarbon structures burn at different rates
 - Reaction rates vary with coal origin, age, and plant source material
 - Same mass (1 kg) of different coals require different time to complete combustion
 - Heat release rate (kcal/min) varies between coals of similar calorific value
- **Influencing Factors:**
 - Mineral matter and inorganic salts modify reaction kinetics
 - Some compounds have catalytic (accelerating) effects
 - Others have inhibitory (slowing) effects
 - Coal maturity affects hydrocarbon composition and reactivity
- **Diffusion-Controlled Combustion:**
 - Initial reaction occurs at coal particle surface
 - Ash layer quickly forms around burning coal
 - O₂ must diffuse inward through ash layer to reach unreacted coal
 - Combustion products (CO₂, H₂O, SO₂) must diffuse outward
 - Reaction rate limited by diffusion through ash layer

- Rate progressively slows as ash layer thickens
- **Ash Layer Effects:**
 - Critical ash properties affecting combustion:
 - Thickness
 - Porosity
 - Mineral matter composition
 - High-ash coal burns slower and with more difficulty
 - Smaller particles (<75 μm) reduce diffusion limitations

Thermogravimetric Analysis (TGA) of Coal

- **TGA Methodology:**
 - Coal heated in oxidative environment (O_2)
 - Temperature increases from ambient to high temperature
 - Typical heating rate: $10^\circ\text{C}/\text{min}$
 - Mass loss measured and recorded continuously
 - Mass loss profile analyzed against temperature
- **Critical Temperature Points:**
 - T_i (Ignition Temperature): Where mass loss rate exceeds $1\%/\text{min}$
 - T_p (Peak Temperature): Maximum mass loss rate (DTG_{max})
 - T_f (Burnout Temperature): Where mass loss rate falls below $1\%/\text{min}$
- **Combustion Sequence:**
 - Moisture loss ($\sim 100^\circ\text{C}$)
 - Volatile matter release ($300\text{--}400^\circ\text{C}$)
 - Volatile matter ignition
 - Fixed carbon combustion
 - Burnout phase
- **Temperature Profile Interpretation:**
 - T_i (Ignition Temperature):
 - Lower values indicate higher VM content
 - Easier ignition with lower T_i
 - Indirectly indicates hydrocarbon types
 - T_p (Peak Temperature):
 - Indicates maximum combustion rate
 - Primarily represents fixed carbon combustion
 - Low T_p with high energy release may indicate hazardous fuel
 - High T_p indicates difficulty extracting energy quickly
 - T_f (Burnout Temperature):

- Indicates combustion completion
- Higher values suggest longer combustion time requirements
- Related to slowly reacting hydrocarbons
- **Industrial Significance:**
 - TGA profiles predict industrial combustion behavior
 - Industrial coal must burn within specific timeframes
 - Heat release must occur in targeted boiler zones
 - Combustion profiles must match boiler design parameters

Boiler Design and Coal Selection

- **Burning Profile Considerations:**
 - Each coal has unique burning characteristics
 - Boiler design based on specific coal burning profiles:
 - Dimensions
 - Temperature profile
 - Fireball characteristics
 - Tube placement
- **Coal Variability Challenges:**
 - Properties vary between mines and within same mine
 - Day-to-day and source-to-source differences
 - TGA/DTG profiles should remain consistent
 - Acceptable variations limited to $\pm 5-10^{\circ}\text{C}$ in key temperatures
 - Variations can cause:
 - Unburned carbon
 - Excessive temperatures
 - Ash melting
- **Blended Fuel Effects:**
 - Coal/coal or coal/biomass blends alter burning profiles
 - Changes affect:
 - Fireball behavior
 - Emission characteristics
 - Non-additive properties require testing of actual blends

Particle Characteristics and Combustion Efficiency

- **Optimal Particle Properties:**
 - Size must match combustion system design
 - Fluidized bed: 2-10 mm
 - Pulverized coal: $< 75\ \mu\text{m}$
 - Density must allow proper suspension time

- Settling velocity affects residence time
- Insufficient residence time causes incomplete combustion
- **Temperature Profile Effects:**
 - Particle size and density control heat release rates
 - Early ignition creates wider, cooler fireballs
 - Delayed combustion causes concentrated, hotter fireballs
 - Concentrated fireballs can cause:
 - Tube overheating
 - Increased NO_x formation
 - Equipment damage
- **Design Coal Requirements:**
 - Use coal with properties matching combustor design
 - Reference values available in boiler manufacturer manuals
 - When design coal unavailable, analyze combustion profile of alternatives
 - Combustion characteristics should be measured directly
 - Flue gas composition provides key monitoring data
- **Troubleshooting Indicators:**
 - CO present with no O₂: Secondary air insufficient
 - Both CO and O₂ present: Combustor problems (mixing issues)

Analytical Limitations and Practical Considerations

- **Coal Characterization Challenges:**
 - Standard tests (proximate, ultimate, GCV) don't identify specific compounds
 - Measures thermal stability (VM, FC) rather than chemical structure
 - Detailed chemical analysis is difficult and costly
 - Heat release rate (kcal/min) more important than total heat content (kcal/kg)
- **Historical Energy Context:**
 - Energy released during combustion was originally captured during photosynthesis
 - Plants converted solar energy to chemical energy in hydrocarbons
 - Enthalpy balance: original reactants to final products plus released heat

Coal Properties and Their Effects on Combustion

Chemical Composition and Its Impact

Volatile Matter (VM)

- **Characteristics and Behavior:**
 - Low molecular weight hydrocarbons (present naturally or formed by heating)
 - Exists in gas/vapor phase, enabling better mixing with air through Brownian motion
 - VM combustion releases heat that ignites Fixed Carbon (FC)
 - High VM coal has lower ignition temperature (CH_4 ignites at atmospheric conditions)
 - Low VM coal (Jhama coal, coke, pet coke) has higher ignition temperature
- **Optimal Content:**
 - 20% VM minimum for trouble-free combustion
 - 25-30% VM is ideal; 35% VM is excessive
 - <20% VM may require blending with alternate fuels for proper ignition
 - FC/VM ratio should be ~ 1 (0.8-1.25) for optimal performance
- **Excessive VM Problems:**
 - Unstable combustion with rapid heat release
 - Excess temperature, tube overheating, refractory damage
 - Difficult fireball maintenance
 - High VM means lower FC content (petroleum products have 100% VM)
 - TGA/DTG curve becomes sharper with lower T_i and T_f

Fixed Carbon (FC)

- **Characteristics and Behavior:**
 - Very high molecular weight, carbon-rich compounds
 - Residual carbon after heating coal at 925°C for 7 minutes
 - Most H and O released as VM; negligible/zero H content
 - Not pure carbon (FC differs from C in ultimate analysis)
 - Difficult to ignite but burns steadily once ignited
 - Provides stable heat release and smooth combustion
 - Generally contains more energy (GCV) than VM
- **Combustion Profile:**
 - TGA/DTG curve is flatter with higher T_i and T_f
 - Higher FC gives stable combustion/heat release in boilers

Moisture Content

- **Classification and Properties:**

- Always present in coal; indicates coal maturity
- Peat/lignite: high moisture (>15%)
- Bituminous/anthracite: low moisture (<5%)

- **Effects on Combustion:**

- During heating, creates vacant pores as it escapes
- Improves surface area for chemical reactions
- Oxygen adsorption in pores (minor mass gain in TGA)
- High moisture coal reacts more easily at higher rates
- Low moisture coal has higher ignition temperature
- Combustion behavior results from combined effect of maturity and surface area

Mineral Matter and Ash

- **Composition:**

- Inorganic salts of metals, P, S, Cl, etc.
- Coal: Higher SiO_2 , Al_2O_3 (85-95%) with minor Fe_2O_3 , CaO , MgO , TiO_2 , K_2O , Na_2O , P_2O_5
- Biomass: Higher alkali oxides (CaO , MgO , Na_2O , K_2O)
- MM converts to individual oxides during heating/oxidation
- Alkali oxides cause greater boiler tube corrosion

- **Ash Fusion Issues:**

- Ash Fusion Temperature (AFT) is a key parameter
- Melted ash creates operational problems:
 - Sticks to refractory walls, boiler tubes, air valves, flue gas paths
 - Absorbs latent heat during phase change, reducing efficiency
 - Reduces heat transfer to tubes
- Regular monitoring of ash composition needed
- Coal sources have different ash compositions

- **Combustion Effects:**

- Ash layer controls diffusion of O_2 and CO_2
- Thicker ash layer slows gas diffusion and reaction rates
- High ash coal has lower combustion and heat release rates
- Less suitable for high-temperature applications

- **Operational Challenges:**

- Higher ash reduces combustibles percentage and GCV
- Increases solid waste generation (fly ash, bottom ash)
- Creates crushing/grinding difficulties (abrasive, harder coal)
- High ash coal requires finer grinding (around $50\text{ }\mu\text{m}$) for efficiency
- Ash deposits on boiler tubes reduce heat transfer

Physical Properties and Their Impact

Particle Size

- **Size Requirements by Process:**
 - Fluidized bed combustion: 2-10 mm particles
 - Pulverized combustion: <75 µm particles
 - Similar sizes for coal gasification
- **Size Trade-offs:**
 - Smaller particles: Higher handling costs, operational difficulty, pollution
 - Larger particles: Uncertain mineral matter/combustible distribution
 - High-temperature applications require smaller particles
- **Combustion Performance Effects:**
 - Larger particles increase ash layer thickness
 - Slower combustion rate and lower heat release
 - Increased unburned carbon
 - Longer residence time needed for complete combustion
 - Higher settling velocity and lower air retention time
 - Require higher air velocity for fluidization/primary air
 - Need effective ash layer removal mechanisms

Particle Density

- **Composition Relationship:**
 - Higher density correlates with higher ash percentage
 - Generally results in reduced GCV and heat release rate
- **Mill Separation Effects:**
 - Lighter particles are transported to the combustor
 - Heavier particles report to mill reject
 - Primary air velocity designed for specific particle transport
 - Mills separate based solely on weight, not composition
 - Typical cutoff in Indian mills: specific gravity of 1.85
 - Valuable coal with SG >1.85 can be lost to rejects
- **Operational Impacts:**
 - Increases transportation and conveying costs
 - Requires higher primary air/fluidization velocity
 - Forms thicker ash layer during combustion
 - Increases unburned carbon
 - Requires longer residence time
 - Results in higher settling velocity and less air retention

- Needs special ash removal mechanisms

Grindability

- **Hardgrove Grindability Index (HGI):**

- Critical for pulverization efficiency
- Grinding must complete within mill residence time
- Hard coal (low HGI): Requires more grinding time
- Soft coal (high HGI): Can result in overgrinding

- **Processing Consequences:**

- Improper grinding increases unburned carbon and hydrocarbon emissions
- Can increase fly ash generation and ESP load
- May cause faster heat release if particles are too fine
- Valuable coal lost if density exceeds design parameters

Combustion Process Requirements

Air Supply

- **Fundamental Principles:**

- Combustion follows Le Chatelier's Principle
- Coal combustion occurs in steps:
 1. $C + O_2 \rightarrow CO$ (initial)
 2. $CO + O_2 \rightarrow CO_2$ (secondary)
- Product gas removal drives reaction forward
- Solid coal + $O_2 \rightarrow$ various hydrocarbons (H_2 , CH_4 , etc.) and CO
- O_2 becomes limiting reactant as reaction proceeds

- **Air Staging:**

- Primary air: Initial oxygen supply for fuel ignition
- Secondary/tertiary air: Added at later stages for complete combustion
- Multiple injection locations ensure complete combustion
- Secondary air crucial for solid fuels to prevent high CO in flue gas

- **Fuel-Specific Requirements:**

- Solid fuels: Secondary air essential
- Liquid fuels: ~10% excess air
- Gaseous fuels: ~5% excess air
- Coal: ~20% excess air

- **Thermal Efficiency Factors:**

- N_2 in air (80%) doesn't participate but absorbs heat
- Heat loss = $m \cdot C_p \cdot (T_{out} - T_{in})$

- Excess air increases heat losses through:
 - Unused O₂ in flue gas
 - Additional N₂ requiring heating

Combustion Calculations

- **Input Requirements:**

- CHNSO analysis essential for calculations
- MM% (1.1 × ash%) + moisture% + CHNSO% = 100%
- Ultimate analysis on moisture-free coal avoids H source conflicts

- **Calculation Principles:**

- Based on stoichiometric mole calculations
- Elements converted from weight to mole basis
- Key reactions:
 - $C + O_2 \rightarrow CO_2$
 - $S + O_2 \rightarrow SO_2$
 - $4H + O_2 \rightarrow 2H_2O$
- Key molecular weights:
 - C = 12, O₂ = 32, S = 32, N₂ = 28
 - CO₂ = 44, SO₂ = 64, H₂O = 18

- **Flue Gas Determination:**

- Gas composition converted using ideal gas law ($PV = nRT$)
- Final flue gas includes:
 - CO₂, H₂O, SO₂ from combustion
 - Excess O₂ from air
 - N₂ from air and fuel

Key Considerations for Optimal Combustion

- Coal properties significantly impact combustion behavior
- Standard characterization may not reflect actual combustion performance
- TGA/DTG burning profile analysis provides better combustion indicators
- Coal should be:
 - Properly sized for the combustion system
 - Matched to boiler design specifications
 - Supplied with appropriate primary and secondary air
- Inappropriate coal selection results in:
 - Combustion issues
 - Higher environmental pollution
 - Reduced energy efficiency

Coal Combustion Methods

Overview of Coal Combustion Technologies

- **Classification of Coal Combustion Methods:**

- Several methods exist for burning coal in domestic and industrial applications
- Each method has its own merits, demerits, and optimal applications
- Three primary combustion approaches:
 - Fuel bed combustion: Burns lump coal (larger size) on grates
 - Pulverized coal combustion: Burns finely powdered coal
 - Fluidized bed combustion: Burns crushed coal in a fluidized state

Fuel Bed Combustion

- **System Configuration:**

- Coal is burned on a grate system
- Typically charged from the top of the bed or from bottom in some designs
- Forms distinct combustion layers during operation
- Five different layers are observed:
 - Freshly charged coal (known as green coal)
 - Drying zone: Layer where coal loses moisture
 - Distillation zone: Coking layer where coal releases volatile matter
 - Combustion zone: Coke layer where fixed carbon is burned
 - Ash zone: Region where ash is cooling

- **Operating Principles:**

- Primary air enters and gets heated in the ash layer
- Air passes through the coke layer (approximately 1200°C), initiating combustion: $C + O_2 \rightarrow CO_2$
- In upper zones, reactions continue: $CO_2 + C \rightarrow 2CO$
- Carbon monoxide mixes with volatile matter and moisture
- Final gas mixture contains CO_2 , CO , H_2O , and N_2
- Secondary air must be added to ensure complete combustion

- **Underfeed Systems:**

- Coal is fed from the bottom through mechanical arrangements like screw conveyors
- Primary air passes through holes to mix with fresh coal
- Primary air first removes moisture and volatile matter from coal
- Gas mixture then passes through the coke zone for volatile matter combustion
- Secondary air is required for complete combustion

- **Performance Characteristics:**

- Primarily used for lower temperature applications
- Slower combustion rate with some unburned carbon in ash
- Simpler operation with less stringent coal preparation requirements
- Requires longer time for complete combustion
- Easy to operate, minimal coal crushing required

Pulverized Coal Combustion

- **System Design:**

- Used in large installations like thermal power plants and cement kilns
- Coal is fired in pulverized form with consistency similar to talcum powder
- Coal is pulverized in ball mills or impact mills
- Typical fineness is 85% below 200 mesh size (75 μm)
- Preheated air at approximately 110-300°C passes over coal during grinding
- Waste heat from flue gas often used to preheat the coal

- **Combustion Process:**

- Coal is premixed with primary air to transport coal mixture to burners
- Remaining combustion air (secondary and tertiary) is supplied later
- Coal particles are heated by flame radiation as they travel through burner
- Volatile matter is emitted and burned in this process
- Typical residence time for complete combustion is less than 5 seconds
- Furnaces classified as horizontal, vertical, or tangential firing based on configuration

- **Advantages:**

- **Operational Benefits:**

- Low excess air requirement
- Reduced fan power consumption
- Higher boiler efficiency
- Fast response to load changes
- High combustion efficiency
- Reduces time for raising steam temperature
- Readily adaptable to automatic control systems

- **Fuel and Performance Flexibility:**

- Ability to burn wide variety of coals
- Easy integration with alternate fuels
- Can work successfully alone or with gas and oil
- Ability to release large amounts of heat in small combustors
- Achieves higher steam temperatures
- Produces fly ash suitable for various applications
- Can replace liquid and gaseous fuel applications

- **Disadvantages:**

- **Economic Considerations:**

- Added cost for coal preparation and grinding
- Complicated equipment requirements
- Higher auxiliary power consumption
- Additional power required for fly ash and flue gas handling
- Increased costs for pollution control equipment

- **Environmental and Safety Concerns:**

- Higher particulate emissions without controls
- Special efforts required for ash collection
- Increased explosion risk
- Storage of powdered coal requires special fire protection

Fluidized Bed Combustion

- **Fundamental Principles:**

- Process involves combustion of solid fuels in a fluidized state
- Fluidization converts granular material from static solid state to dynamic fluid-like state
- Coal is fluidized using pressurized air through a bed with gaps
- Fuel particles are suspended in a hot, bubbling fluidity bed
- Bed typically contains sand, limestone, and recycled ash
- Jets of air provide oxygen required for combustion
- Fast mixing of gas and solids promotes rapid heat transfer and chemical reactions

- **System Components:**

- Coal: Primary fuel that burns in the combustion chamber
- Limestone: Removes sulfur gases (SO_x) during combustion
- Bed material/Sand: Optimizes the fluidization process
- Ash: Initially absent but later supplied from ash recycling

- **FBC Technology Types:**

- **Atmospheric Fluidized Bed Combustion (AFBC):**

- Coal crushed to 1-10 mm depending on coal rank
- Fluidizing air velocity ranges from 1.2 to 3.7 m/sec
- Uses in-bed evaporator tubes for heat extraction
- Typical bed depth ranges from 0.9 m to 1.5 m

- **Circulating Fluidized Bed Combustion (CFBC):**

- Higher intra-furnace gas velocity at 4 to 8 m/s
- Feed coal particle size approximately 6-12 mm
- Includes cyclone for recycling material back to boiler
- Recycling maintains bed height and increases de-nitration

- **Internal Circulating Systems (ICFBC):**
 - Cyclone separator placed nearby or inside combustor
 - Provides better temperature control and reduces heat loss
 - Internal circulation improves heat transfer efficiency
 - Increases residence time for more complete combustion
- **Pressurized Systems (PICFBC):**
 - ICFBC system mounted in a pressurized vessel
 - Higher pressure improves combustion driving force
 - Increases partial pressure of oxygen
 - Enables reduced reactor size for same thermal output
- **Advantages:**
 - **Performance Efficiency:**
 - High combustion efficiency (over 95%) regardless of ash content
 - Overall thermal efficiency around 84%
 - Smaller boiler size due to high heat transfer rates
 - Less excess air required, resulting in higher CO₂ concentration
 - **Fuel Flexibility:**
 - Operates efficiently with various fuel types
 - Handles low-grade fuels effectively (washery rejects, agro waste)
 - Different fuels can be fed independently or in combination
 - Excellent for burning fines and low-grade coal
 - **Environmental Benefits:**
 - Superior control of SO_x and NO_x emissions
 - Easier ash removal with no clinker formation
 - No grinding required for coal (2-10 mm size sufficient)
 - Operating temperature around 900°C reduces NO_x formation
- **Disadvantages:**
 - Limited to lower temperature and capacity applications
 - Longer time required for complete combustion
 - Higher erosion rate for boiler tubes
 - Lower capacity compared to pulverized coal units
 - Increased polycyclic aromatic hydrocarbon emissions due to lower temperatures

Coal Combustion System Selection Guidelines

- **Critical Selection Factors:**
 - Secondary air supply is essential for complete combustion
 - System selection should be based on:

- Coal properties (ash content, volatile matter, moisture)
- Required output capacity and temperature
- Available space and infrastructure
- Environmental regulations and emission limits
- Economic considerations and efficiency requirements

- **Application-Specific Recommendations:**

- Pulverized coal systems:

- Best for large-scale, high-temperature applications
 - Suitable when high-quality coal is available
 - Preferred for maximum power generation efficiency

- Fluidized bed systems:

- Optimal for lower-grade fuels and waste materials
 - Excellent when emissions control is a priority
 - Good for medium-scale applications with variable fuels

- Fuel bed systems:

- Appropriate for smaller-scale, lower-temperature applications
 - Suitable when operational simplicity is required
 - Best when coal preparation capabilities are limited

Coal Combustion Pollutants and Environmental Impact

Types of Pollutants

Solid Waste

- **Coal Ash:** Solid residue after combustion (solid waste materials from power plant)
 - **Bottom Ash:** Heavier ash particles that settle down
 - **Fly Ash:** Lighter ash particles that flow with flue gas
 - Chemical composition differs between bottom ash and fly ash
 - Contains various metal/non-metal oxides, some toxic and harmful to environment
 - Contributes to air, soil, and ground water pollution
 - Distribution varies based on combustion methods

Emissions to Atmosphere

- **Particulate Matter**
 - PM10 and PM2.5 (power sector contributes 7% of PM2.5)
 - Biomass combustion releases nano-sized ash particles
- **Gaseous Pollutants**
 - **Sulfur Oxides (SO_x):** Power sector accounts for 51% of SO₂ emissions
 - **Nitrogen Oxides (NO_x):** Power sector accounts for 20% of emissions
 - **Carbon Dioxide (CO₂):** Power sector accounts for 43% of emissions
 - **Unburned Hydrocarbons:**
 - Present in flue gas as tar, CO, hydrocarbons
 - Present in bottom ash and fly ash
 - **Heavy Metals:** Present in coal ash and emissions

Environmental and Health Impacts

- **Air Quality Impacts:**
 - SO_x, NO_x, and mercury undergo chemical reactions to form compounds
 - These compounds can travel long distances (transport characteristics of air)
 - Severe negative impacts on human health from ambient air pollution
- **Health Effects:**
 - Fine particles and compounds contribute to death and serious respiratory illness
 - Causes asthma, chronic bronchitis, and other respiratory conditions

Energy Generation Context

- As of May 2023, 50.7% of India's total installed capacity was coal-based
- Including other fossil fuels (diesel and gas), total fossil fuel capacity reaches about 56.8%

Incomplete Combustion Issues

Causes of Unburned Carbon in Ash

- Unburned carbon originates from incomplete combustion of coal due to various reasons:
 - Inadequate O_2 supply during combustion (limiting reactant)
 - Improper mixing of coal and air
 - Insufficient residence time in combustion zone (particles escape before complete combustion)
 - Particle density issues:
 - Very low density particles escape directly to flue gas exit
 - Very high density particles easily settle down in bottom ash
 - Coal characteristics factors:
 - Lower volatile matter causing delayed ignition (high difference between T_i and T_f)
 - Higher fixed carbon requiring longer combustion time
 - Higher burnout temperature of coal (flat DTG curve)
 - Larger coal particles (insufficient residence time)
 - Ash layer inhibiting gas diffusion

Causes of Unburned Hydrocarbons in Flue Gas

- Unburned hydrocarbon gases/vapors like CH_4 , H_2 , aromatic and aliphatic compounds, along with CO may be present in flue gas due to:
 - Inadequate oxygen supply (primary cause)
 - Low combustion temperature
 - Excess primary air without secondary/tertiary air supply
 - Delayed combustion (higher ignition temperature of coal)
 - Insufficient time/oxygen for volatile matter combustion
 - High primary air velocity
 - Mismatch between coal characteristics and combustor design
 - Improper mixing of coal and air

Combustion System Diagnostics

Flue Gas Analysis

- Functions like a "blood test" for combustion systems
- Key components analyzed: CO_2 , O_2 , N_2 , CO, HC, H_2 , NO_x , SO_x

Interpreting Flue Gas Results

- **Complete Combustion:** Presence of only CO_2 , SO_x
- **Incomplete Combustion:**
 - Presence of CO indicates incomplete combustion
 - Presence of H_2 , HC confirms incomplete combustion

- **Other Indicators:**

- N_2 is normal (originates from air)
- NO_x indicates excessive temperature in combustor
- O_2 indicates excess air used or incomplete mixing of coal and air
- Combined presence of CO and O_2 signifies major problems in combustion system

Fly Ash Characteristics and Management

Fly Ash Properties

- Particle size distribution of feed coal and fly ash particles is most important
- Pulverized coal is burned at $<75\text{ }\mu\text{m}$ (maximum size, with 80% particles less than $75\text{ }\mu\text{m}$)
- For coal with 30% ash content, residue coal particle size should theoretically be $22.5\text{ }\mu\text{m}$ (75×0.3)
- In actual practice, as mineral matter distribution in coal is not uniform, most ash particles are less than $10\text{ }\mu\text{m}$
- Composition of mineral matter or fly ash is important as it may corrode or damage equipment

Air Pollution Control Technologies

1. Cyclone Separator

Operating Principle

- Primarily works on centrifugal force ($f = m \cdot v^2/r$)
- Mass of particle (m) depends on density and size/diameter of particle

Efficiency Factors

- Larger particle diameter \rightarrow higher centrifugal force \rightarrow better collection efficiency
- Smaller particle diameter \rightarrow lower centrifugal force \rightarrow particles exit with flue gas
- Higher particle density \rightarrow better separation
- Lower particle density \rightarrow poorer separation
- Larger cyclone diameter \rightarrow lower centrifugal force \rightarrow lower separation efficiency

Performance Metrics

- **Collection efficiency:** Mass percentage of ash particles collected at bottom
- **Cut diameter:** Particle size in flue gas collected with 50% collection efficiency

Cut Diameter Formula

- $d_{50} = (9\mu B_c / 2\pi N v_i (\rho_p - \rho))^{1/2}$
- Where:
 - μ = viscosity (Pa-s)
 - B_c = inlet width (m)
 - N = effective number of turns (5-10 for common cyclone)
 - v_i = inlet gas velocity (m/s)
 - ρ_p = particle density (kg/m^3)

- ρ = gas density (kg/m³)
- Key parameters: Inlet gas velocity, cyclone diameter, particle density, viscosity of air

Advantages

- Overall cost of separation is low
- No operating cost, only installation cost
- Effective for larger ash particles (>10 micron)
- Can operate at higher temperatures, making them suitable for flue gas purification
- Can be constructed from ceramic, metals, and other durable materials
- Reduces load on downstream equipment like bag filters or ESPs by removing larger particles
- Very cost-effective solution

2. Bag Filter / Fabric Filter

Operating Principle

- Used in air purification by filtering the air through porous fabric
- One cloth/similar material with pores separates dust particles
- Flue gas is forced through the filter, with dust particles collected on the fabric surface

Performance Characteristics

- Very high collection efficiencies (about 99.9%) for both coarse and fine particles (0.01-100 μ m)
- Fabric requires replacement every 2-4 years
- Hot gases must be cooled; operates in temperature range of 120°C-180°C
- Efficient for micron or nano-sized particles, depending on filter media
- Can be modified with ceramic or metallic filter in modern designs

Limitations

- Can only be used with low-temperature flue gas
- Not common in thermal power plants, more common in other coal-based industries
- Cannot operate at higher temperatures due to fire hazard
- Temperature increases may cause fire
- Should be used after cyclone separator and waste heat recovery
- Requires regular cleaning via shaking mechanism, vibration, or pulse jet

Design Parameters

- Pressure drop
- Air-to-cloth ratio
- Collection efficiency
- Fabric type
- Cleaning mechanism
- Temperature control
- Bag spacing

- Compartment design
- Space requirements and cost

3. Electrostatic Precipitator (ESP)

Operating Principle

- Utilizes electricity (high voltage DC) to capture ash particles
- Electrodes at high voltage create corona effect (ionized atmosphere)
- Corona effect charges passing particles
- Charged particles experience transverse electrostatic force pulling them toward collecting plates
- Plates periodically "rapped" (vibrated) to make collected particles fall into receiver basket

Process Flow

- Fly ash particles pass through electrodes
- Particles get charged due to corona effect and move to collector plates
- Collector plates carry opposite charge to particles
- Particles attracted to collector plates, removing them from gas stream
- Deposited particles occasionally removed by rapping or washing collector plates

Efficiency Formula

- $\eta = 1 - e^{(-wA/Q)}$
- Where:
 - η = fractional collection efficiency
 - w = drift velocity (m/min)
 - A = available collection area (m²)
 - Q = volumetric flow rate (m³/min)

Advantages

- Very high separation efficiency (99.9-100%)
- Low pressure drop
- Can handle high ash particle loads
- Can operate at higher temperatures
- Most efficient for thermal power plants, cement plants, etc.
- Often used with cyclone separator for cost-effective separation

Limitations

- Higher operating and installation costs
- Lower efficiency for smaller ash particles without increased voltage/electricity
- Efficiency depends on ash composition (electron affinity varies with molecules)
- ESP efficiency may vary if coal source changes

4. Settling Chamber / Tank

Operating Principle

- Used for larger ash particles at lower temperatures
- Water improves particle mass, causing faster settling (dry chambers have lower efficiency)
- Can add chemicals to water to remove gaseous pollutants if needed
- Ash particles captured in water slurry through slurry tank

Limitations

- Lower efficiency for smaller ash particles
- Requires efficient sprinklers with surface modifier addition for smaller particles
- Only larger ash particles can be effectively removed
- Dry settling tanks have lower efficiency but don't consume water
- Higher water consumption in wet/spray methods
- Low installation cost but higher operating and maintenance costs

5. Wet Scrubbers

Operating Principle

- Used for particles 0.2 mm or larger
- Works by spraying fine liquid droplets into incoming gas stream
- Droplets capture particles, liquid is then removed for treatment
- Rectangular or circular chamber with mounted nozzles
- Optimized droplet size (smaller droplets provide better cleaning)
- Polluted spray collected, particles settled out, liquid recycled

Advantages

- Can handle high-temperature gas (higher water consumption)
- Can handle high particle loading
- Loading fluctuations don't affect removal efficiency
- Can handle explosive gases with minimal risk
- Gas adsorption and dust collection handled in single unit
- Corrosive gases and dusts neutralized

Limitations

- High corrosion potential
- Effluent scrubbing liquid creates water pollution issues

6. Venturi Scrubber

Operating Principle

- Dirty gas enters chamber at high inlet velocities
- Liquid at low pressure added to gas stream at inlet throat
- Achieves efficiency around 95% for particles larger than 0.2 mm

Comparative Analysis and Best Practices

- Cyclone separators most efficient for larger ash particles
- ESP and bag filters achieve nearly 100% efficiency but have higher costs
- ESP efficiency varies with ash composition
- Settling tanks/spray methods best for larger particles, especially in FBC plants
- Combination of 2-3 equipment types used to optimize cost efficiency
- Feed size coal and ash particle size must be continuously monitored for efficient ash removal

Emission Control Technologies for Coal Combustion

SOx Emission Control

Sources and Prevention

- SOx in flue gas originates from sulfur present in fuel
- Control approaches include:
 - **Pre-utilization:** Coal desulfurization using various cleaning methods
 - **During combustion:** Use of limestone during fluidized bed combustion/gasification
 - **Post-combustion:** Flue gas desulfurization (FGD) systems
 - Blending with low-sulfur fuel to reduce consumption of high-sulfur coal
 - Some industries use high excess air to dilute SOx (total SOx remains the same)

Flue Gas Desulfurization (FGD) Systems

Classification

- **By process type:**
 - Wet scrubbers
 - Dry scrubbers
 - Spray dryers
 - Dry sorbent injection processes
 - Regenerable processes
 - Circulating fluid-bed and moving-bed scrubbers
 - Combined SO₂/NOx/dust particle removal systems
- **By regeneration:**
 - **Regenerative:** Chemical used to remove SO₂ can be regenerated and used again
 - **Non-regenerative:** Chemical passes to disposal after use

Sorbents and Products

- **Common sorbents:**
 - Calcium-based (CaCO₃, CaO)
 - Magnesium-based
 - Potassium or sodium-based
 - Ammonia
 - Seawater
- **Reaction products:**
 - Calcium-based: Forms hydrous calcium sulfate (CaSO₄·2H₂O, gypsum)
 - Ammonia-based: Forms ammonium sulfate [(NH₄)₂SO₄]

- Provides both sulfur and nitrogen for crops
- Growing market in fertilizer formulations

Wet FGD Technology

- Involves contact of flue gas with solution or slurry for SO₂ removal
- **Regenerative processes:** Recover elemental sulfur or sulfuric acid
- **Non-regenerative processes:** Produce calcium sulfite or calcium sulfate sludge for disposal

Dry FGD Technology

- Includes lime/limestone spray drying, dry sorbent injection, and circulating fluidized bed scrubbers
- **Advantages:**
 - Produces dry waste products that are easier to dispose than wet scrubber waste
 - Spray dry scrubbers are second most widely used method for utility coal-fired plants
 - Lower cost compared to wet scrubbing systems

Spray Drying Process

- **Sorbents:** Typically lime (CaO) or hydrated lime (Ca(OH)₂)
- **Process flow:**
 - Hot flue gas exits boiler air heater and enters reactor vessel
 - Slurry of lime and recycled solids is atomized/sprayed into absorber
 - Slurry formation: $\text{CaO(s)} + \text{H}_2\text{O(l)} \rightarrow \text{Ca(OH)}_2\text{(s)} + \text{heat}$
 - SO₂ absorption reactions:
 - $\text{Ca(OH)}_2\text{(s)} + \text{SO}_2\text{(g)} \rightarrow \text{CaSO}_3 \cdot \frac{1}{2}\text{H}_2\text{O(s)} + \frac{1}{2}\text{H}_2\text{O(v)}$
 - $\text{Ca(OH)}_2\text{(s)} + \text{SO}_3\text{(g)} + \text{H}_2\text{O(l)} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O(s)}$
 - Small alkaline stream prevents corrosion of system walls and pipes

Comparison of Wet vs. Dry FGD

- **Dry FGD advantages:**
 - Lower capital and operational costs
 - Lower power consumption and pumping requirements
 - No liquid waste production
 - Waste suitable for landfilling and can be disposed with fly ash
- **Dry FGD disadvantages:**
 - Lower reagent utilization efficiency
 - More expensive than wet FGD for same SO₂ removal performance

NO_x Emission Control

Formation Mechanism

- NO_x generated during combustion by reaction of N₂ and O₂
- Formation increases significantly at temperatures:

- Above 1000°C: Very low yield
- Above 1400°C: High yield
- Nitrogen sources: Fuel hydrocarbon (CHNSO) or air (~80% N₂)
- N₂ cannot be removed from combustor; only formation rate can be controlled

Control Technologies

Combustion Modifications

- **Temperature control:** Maintain below 1200-1300°C to reduce formation rate
- **Excess air control:** Precise use of primary and secondary air
- **Flue-gas recirculation:** Return portion of flue gas to combustion chamber to:
 - Help cool the process
 - Maintain peak flame temperatures below critical levels
 - Recycle excess air, allowing for lower fresh air input
- **Oxyfuel combustion:** Use pure O₂ during combustion (costly method)

Post-Combustion Treatment

- **Selective Catalytic Reduction (SCR):**
 - Ammonia or urea injected and mixed with gases before catalyst chamber
 - Chemical reactions:
 - $2\text{NO} + 2\text{NH}_3 + \frac{1}{2}\text{O}_2 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O}$
 - $\text{NO}_2 + 2\text{NH}_3 + \frac{1}{2}\text{O}_2 \rightarrow 1.5\text{N}_2 + 3\text{H}_2\text{O}$
 - $\text{NO} + \text{NO}_2 + 2\text{NH}_3 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O}$
 - Optimal temperature range: 357-447°C
 - Can operate as low as 227°C with longer residence time

Advanced Combustion Technologies

Chemical Looping Combustion (CLC)

- Metal oxide oxygen carriers transport oxygen from air to fuel
- Avoids direct contact between coal and air
- **Process flow:**
 - In fuel reactor: Fuel oxidized by oxygen carrier to CO₂ and H₂O
 - Pure CO₂ recovered after H₂O condensation
 - Reduced oxygen carrier transported to air reactor
 - In air reactor: Carrier reacts with air and is re-oxidized
 - Exit gas from air reactor contains only N₂ and unreacted O₂
- Still under development

Oxyfuel Combustion

- Coal/fuel burned in O₂-rich environment with minimal N₂
- **Advantages:**
 - Minimizes NO_x formation

- Flue gas consists mainly of CO₂ and H₂O
- CO₂ easily captured for industrial use or storage
- Reduced flue gas volume (75-80% less than air-fired combustion)
- Easier removal of pollutants (SO_x, mercury, fly ash)
- Greatly reduced NO_x production

Process Components

- **Oxygen production:** Air separation unit (ASU)
- **Oxy-combustion boiler:** Fuel conversion unit
- **CO₂ purification and compression**

Implementation

- Cryogenic temperature (-200°C) used to separate O₂ and N₂
- Yields stream approximately 85% O₂
- Flue gas recycled to regulate flame temperature
- CO₂ easily separated from steam by cooling

Challenges and Benefits

- **Challenges:**
 - Capital cost and energy consumption of oxygen separation
 - Operational challenges of oxygen separation
- **Benefits:**
 - Reduced reactor/combustor volume (80% volume from N₂ eliminated)
 - Better thermal efficiency, heat loss control
 - Space saving, lower investment and maintenance costs
 - Enhanced combustion rate (higher O₂ concentration)
 - Complete combustion achieved more easily
 - Reduced unburned carbon and CO
 - Pure CO₂ obtained for industrial applications

CO₂ Capture and Storage

Capture Technologies

Solvent-based Systems

- Rely on chemical or physical absorption of CO₂ from flue gas into liquid carrier
- **Process:**
 - CO₂ absorbed in absorption column
 - Liquid carrier transported to second column
 - Heat or pressure drop releases CO₂ and regenerates carrier
- **Common solvents:**

- Monoethanolamine (MEA)
- Methyl-diethanol-amine (MDEA)
- 2-Amino-2-methyl-propanol (AMP)
- Piperazine (PIPA)
- Diglycolamine (DGA)
- Diethanolamine (DEA)
- Di-isopropanolamine (DIPA)
- **Challenges:** Cost, environmental toxicity, availability, energy requirements

Adsorbent/Sorbent-based Capture

- Solid sorbents (carbon, zeolites, metal organic frameworks) take up CO₂
- Heat/pressure reduction releases CO₂ and regenerates sorbent
- Inert gas can displace CO₂ in some systems
- **Advantages:** Potential energy savings, waste reduction, process simplification
- **Challenges:** Sorbent durability, capacity, specificity, cost

Membrane Separation

- Permeable/semi-permeable materials (metal, polymer, ceramic) selectively separate CO₂
- **R&D targets:** Improved selectivity, permeability, durability, stability, pressure drop

Cryogenic Separation

- Gases cooled until different constituents liquefy or freeze
- High energy and cost requirements
- Feasible for very high CO₂ concentration streams

Microalgae-based Capture

- CO₂-enriched waste streams used to enhance plant growth
- Microalgae cultures (closed reactors or open ponds) convert CO₂ to biomass
- Produces food, animal feed, nutritional supplements, fuels, chemicals
- **Limitation:** Slower kinetics compared to physical-chemical approaches

CO₂ Utilization Applications

- **Enhanced Oil and Natural Gas Recovery:**
 - High-pressure supercritical CO₂ injected into oilfields (below 2000 ft)
 - CO₂ reduces oil viscosity and surface tension
 - Improves oil production compared to steam-only injection
 - Some CO₂ returns with oil and is recycled; remainder stays underground
- **Chemicals and Plastics:**
 - Feedstock for methanol, urea, and other chemicals
 - Used in fertilizers, deicers, explosives, animal feed, food processing

- Applications in pollution control, personal care, pharmaceuticals, resins
- **Bioconversion and Bioproducts:**
 - CO₂-enriched air enhances microalgae growth
 - Used in biodiesel production, chemical and pharmaceutical precursors
- **Food and Beverage Processing:**
 - Carbonation for soft drinks and beer
- **Other Applications:**
 - Extraction and cleaning solvent
 - Refrigerant (dry ice, liquid CO₂)
 - Inerting agent and fire suppression
 - Abrasive cleaning (dry ice pellets)
 - Medical oxygen additive
 - Aerosol propellant

CO₂ Storage

- Geological storage options:
 - Deep saline reservoirs
 - Depleted oil and gas reservoirs
 - Other rock formations
 - Offshore basalt rocks

Summary

- For SO_x reduction, controlling sulfur at source is required
- SO_x can be captured using limestone by various methods
- NO_x generation can be avoided by controlling combustion temperature or using oxyfuel combustion
- Oxyfuel combustion eliminates many issues but is costly
- CO₂ can be used for various value-added applications
- CO₂ may be stored underground with various advantages and disadvantages

Coal Gasification

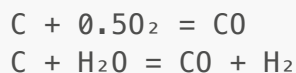
Basic Principles

- Gasification is the process of converting solid fuel (coal or similar) to gaseous form (mixture of CO, H₂, CH₄, CO₂, N₂ etc.)
- Produced gases have good fuel value, may be used as gaseous fuel
- Once coal is converted to gaseous fuel, it has all the advantages of being gaseous fuel compared to heterogeneous solid fuel (coal)
- It is partial combustion of coal, providing 25-40% of O₂ required for combustion
- Steam also can be added during this reaction
- Product gas is known as synthesis gas or syngas (Mixture of N₂+CO) along with other gases such as H₂, CO₂, CH₄ and water vapor etc.

Gasification Components

- **Fuel:** Coal, coke, biomass, lignite etc. as available and suitable
- **Reactants:** Air, O₂, CO and Steam (H₂O)
- **Products:** CO, H₂, CH₄, CO₂ and water vapor

Basic Reactions



Gasification Process

- Gasification is a partial oxidation process
- The term partial oxidation means that lesser amount of oxygen is used in gasification than would be required for combustion (i.e., burning or complete oxidation) of the same amount of fuel
- During gasification, the coal is blown through with oxygen and steam, while also being heated (and in some cases pressurized)
- During the reactions, oxygen and water molecules oxidize the coal and produce a gaseous mixture of CO₂, CO, water vapor and H₂ or similar gases
- Some by-products like tar, phenols, etc. are also possible end products, depending on the specific gasification technology utilized and temperature of exit gas
- This process has also been conducted in-situ within natural coal seams, referred to as underground coal gasification

Chemical Process

- The chemistry of gasification is quite complex and is accomplished through a series of physical transformations and chemical reactions within the gasifier
- In a gasifier, the carbonaceous feedstock undergoes several different processes and/or reactions

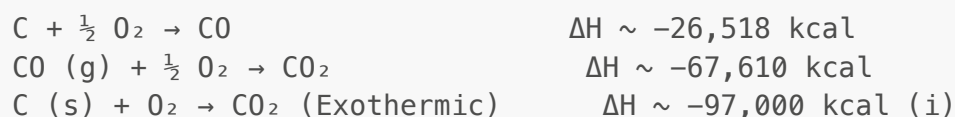
- Some of the major chemical reactions are known as:
 - Dehydration
 - Pyrolysis/devolatilization
 - Oxidation/combustion
 - Reduction/gasification
 - Water gas/shift reaction
 - Methanation

Advantages of Gasification

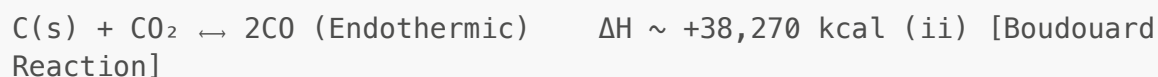
- Coal converted to gaseous fuel: easy to transport through pipelines
- Ash is disposed at the source; ease to landfilling, saving in transportation cost
- Better combustion efficiency for syngas
- Production of fuel for use in electric power generation units
- Generation of fuel gas (low to medium heating value) for industrial purposes

Gasification Reactions

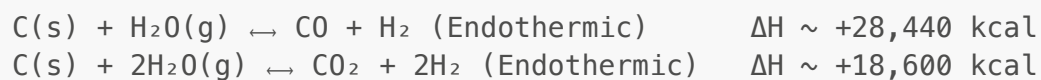
Combustion Reactions



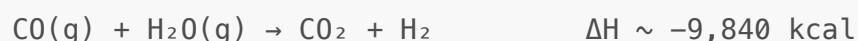
Reduction Reactions



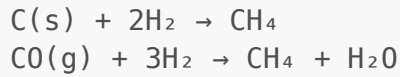
Water-Gas Reactions



Water Gas Shift Reaction



Methanation Reactions



$\Delta H \sim -20,840 \text{ kcal}$
[High pressure favors this reaction]

Reaction Sequence

- As long as oxygen is in excess, carbon dioxide is formed by reaction (i):
 - $\text{C(s)} + \text{O}_2 \rightarrow \text{CO}_2$ (Exothermic) $\Delta H \sim -97,000 \text{ kcal}$
 - Initially CO and further CO_2
- Then undergoes reduction into CO by Boudouard reaction (ii), which is most important reaction controlling the gasification process:
 - $\text{C(s)} + \text{CO}_2 \rightleftharpoons 2\text{CO}$ (Endothermic) $\Delta H \sim +38,270 \text{ kcal}$
 - This is an endothermic reaction. Its equilibrium constant increases with rise in temperature
 - The content of CO in the equilibrium mixture of CO and CO_2 at 1 atm increases sharply above 500°C
 - At around 1000°C the CO % is nearly around 99.6%

Secondary Reactions

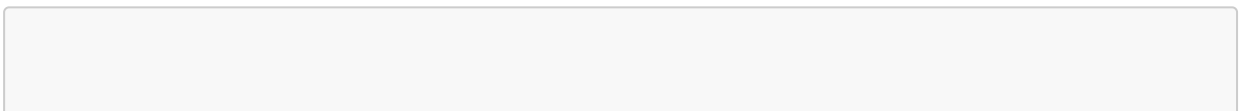
- After the gases leave the fuel bed, the CO partly dissociates into CO_2 and C:
 - $2\text{CO} \rightarrow \text{CO}_2 + \text{C}$ $\Delta H \sim -38,270 \text{ kcal}$
 - This is reversal of Boudouard reaction and is known as Neumann reversal reaction
- Produced gas contains CO, CO_2 , H_2 , CH_4 , N_2 and O_2
- Exact gas composition depends on the reaction conditions such as pressure, temperature, availability of O_2 , coal composition etc.
- Purpose of gasification is to generate syngas not heat release
- Reactions are conducted/controlled to increase the yield of gas like CO or H_2

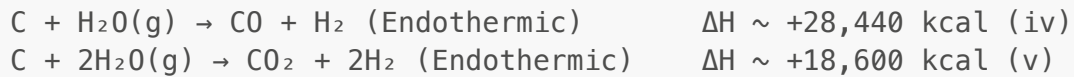
Reaction Parameters

- As it is chemical reaction between coal and gas ($\text{air/O}_2/\text{H}_2\text{O}$) all the reaction parameters related to coal combustion will be same
- Concepts of ash layer, effects of VM, FC, porosity, ash composition, AFT, ignition temperature etc. will be there
- As reactants (source of coal) and products are different, reaction kinetics may not be exactly same every time but similar
- Overall coal conversion may not be same every time

Role of Steam and Air

- If only air is used, H_2 gas concentration in product is less
- The demerits of air blown gas producer are removed by using steam along with air, which enriches the hydrogen percentage in producer gas
- Additional Water-Gas Reactions take place:





- The reaction (iv) is water gas reaction and is active at and above 1000°C, while reaction (v) predominates between 500-600°C
- Both the reactions are endothermic, utilize heat liberated by carbon in the bed to potential heat in the combustible gases formed viz., CO and H₂
- As the CO₂ is undesired component of the product gas, reaction (v) should be suppressed by maintaining high temperature and choosing proper amount of steam

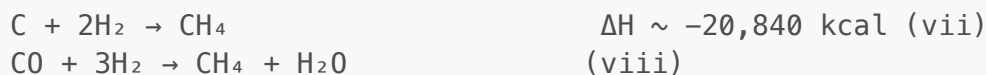
Benefits of Steam Addition

- Total combustible gas components like CO, H₂ and CH₄ increased in product gas
- Inert gas content such as N₂ and CO₂ decreased
- Calorific value of product gas improves
- A part of sensible heat liberated by combustion of carbon is used for conversion of H₂ producing reaction
- In case of only air, bed temperature is extremely high, ash melting/fusion probability is reduced if H₂O is used

Water Gas Shift Reaction



Additional Methanation Reactions



- Reaction (viii) is made to take place when the aim is to maximize the concentration of methane by maintaining the ratio of CO to H₂ as 3:1

Other Gaseous Products

- In the low-oxygen, reducing environment of the gasifier, most of the feedstock's sulfur converts to hydrogen sulfide (H₂S), with a small amount forming carbonyl sulfide (COS)
- Nitrogen chemically bound in the feed generally converts to gaseous nitrogen (N₂), with some ammonia (NH₃), and a small amount forming hydrogen cyanide (HCN)
- Chlorine is primarily converted to hydrogen chloride (HCl)
- In general, the quantities of sulfur, nitrogen, and chloride in the fuel are sufficiently small that they have a negligible effect on the main syngas components of H₂ and CO
- Trace elements associated with both organic and inorganic components in the feed, such as mercury, arsenic and other heavy metals, appear in the various ash and slag fractions, as well as

in gaseous emissions, and need to be removed from the syngas prior to further use

Role of Coal Properties

- Coal reactivity is the main parameter to decide the gasification kinetics
- Mineral matter, VM, FC etc. all play important roles during gasification
- As it is chemical reactions among hydrocarbons present in coal and reactant gases (O_2 , CO, H_2 , H_2O etc.), reactions at individual components occur
- Mineral Matter composition also has negative/positive role during such chemical reaction
- All the reactions are like coal combustion reaction: Simply reactions between hydrocarbons and reactant gases in presence of impurities (MM)
- Hence reaction kinetics and product gas composition will vary depending on coal composition, reaction conditions etc.

Role of Moisture

- Fuel Used: Coal, lignite, coke, biomass, municipal waste etc.
- Fixed-bed gasifiers can accommodate moisture contents of up to 35 percent, provided the ash content is not in excess of about 10 percent
- Pre-drying may be performed if the moisture and ash contents are above these amounts
- Entrained-flow or fluidized-bed gasifiers require the moisture content to be reduced to less than about 5 percent by drying to improve coal handleability
- In the entrained-flow system, the residual moisture contributes to the gasification steam but requires heat to evaporate it

Role of Ash

- Chemical composition may affect reaction kinetics, Ash Fusion, Heat transfer, temperature control inside reactor
- Ash should be kept at a minimum, since provisions must be made for introducing it to, and withdrawing it from the system, provisions that add to the complexity and cost of the overall system
- Ash can be used as a heat transfer medium, either by its flow countercurrent to the products of gasification and gasifying agents in fixed-bed systems or by provisions in entrained-flow systems
- In fixed-bed systems, ash accumulates at the base of the fuel bed and is withdrawn by a mechanical grate if un-fused or through a tap hole if it is a liquid slag
- In the entrained-flow system, it is removed as a liquid slag

Ash Fusion Temperature

- The ash fusion temperature is a measure of when the ash will melt and transform from a solid to liquid state
- This temperature is an important parameter for the design and operation of gasification systems:
 - For systems that operate below the ash fusion temperature to avoid fusion, sintering, or clinkering of the ash
 - For systems that operate above the ash fusion temperature to promote slag production

- Another important ash characteristic is the relationship between temperature and ash viscosity, since it is the flow characteristics of the slag that are critical

Ash in Different Systems

- In fluidized-bed systems, the ash is mixed with the char, and the ash is separated either by sintering and agglomeration of the ash or circulation from the bed through a fully entrained combustor to melt and separate the ash as a liquid slag
- Fluidized-bed and entrained flow gasifiers tend to have higher losses of carbon in the ash than the fixed-bed systems
- Ash constituents are important in the selection of materials of construction, particularly in slagging combustors
- In addition, proper ash composition, or its chemical manipulation through the addition of fluxing agents, is necessary for desirable slagging operations

Role of Volatile Matter (VM)

- The volatile matter from the coal can add to the products of gasification without incurring steam decomposition or oxygen consumption
- The volatile matter, which can vary from less than 5 percent (on a moist, ash-free basis) for anthracite to over 50 percent for subbituminous coal or lignites, can consist of carbon oxides, hydrogen, and traces of nitrogen compounds
- The volatile matter composition, the type of coal, and the conditions under which the volatile matter is driven off all affect the nature of the residual fixed carbon or char that remains
- Composition of VM may add impurity (gases) in the product gas if not gasified properly

Role of Fixed Carbon (FC)

- The nature of the fixed carbon, which is the major component of the char after the moisture and volatile matter is driven off, is important to the performance of the gasifier and can vary physically and chemically
- Properties such as density, structure, friability/strength, and reactivity depend primarily on the original coal, but they are influenced by the pressure, the rate at which the coal is heated, and its final temperature
- Caking Tendencies: The coal's caking tendencies—strongly caking and swelling, weakly caking, and noncaking—must be considered during the design of the gasifier process
- Some gasifiers can be designed to handle caking and swelling coals, but others will require the coal to be pretreated

Scope of Gasification

Advantages

- Wide variety of coal can be used to generate syngas—a gaseous fuel
- Multiple fuels can be co-gasified in one reactor
- Unused coal/inferior quality coal can be used
- Product gases can be used for power generation

- Advantage of gaseous fuel from solid fuel-coal
- Syngas can be used in different industries
- Can be used in iron ore reduction: replacement of coke; known as direct reduced iron (DRI) method
- If individual gases are separated; CO, H₂, CH₄ etc., can have higher market value
- H₂ as clean fuel for fuel cell and other applications

Applications

- Syngas can be transported through pipeline/tankers etc. without transporting mineral matter/ash
- Ash can be disposed at source
- Production of Hydrogen gas is possible—only hydrogen generation methods from hydrocarbons
- Coal to chemicals—Fischer-Tropsch chemical reaction
- CO, H₂, CH₄ etc. can be used for synthesis of different organic chemicals (coal to chemicals)
- Coal to methanol and other chemicals

Challenges

- Coal properties vary from day to day or year to year, difficult to get design coal
- Gas yield may vary if source coal/feedstock changes—difficult to maintain product quality
- Some amount of heat is wasted during gasification

Summary

- Coal gasification helps to convert solid fuel to gaseous form
- In gaseous form usability is far better and can replace/compete with other gaseous fuels
- Air is mostly used in gasification
- Water/steam addition improves the H₂/hydrocarbon rich gas concentration in product gas
- Reaction kinetics is the major parameter to be controlled in commercial plants
- Coal properties can modify the product gas composition and hence profitability of plant

Gasifier Types and Syngas Cleaning

Downdraft Gasifier

- The downdraft gasifier is a co-current reactor
- The gasification agent enters the gasifier at a certain height below the top, and it mixes with the pyrolysis gas products while flowing downward in parallel with the solids (char and ash) through the oxidation and gasification zones
- The drying and pyrolysis zones lie above the oxidation zone and they are maintained at the required temperature by conduction of the heat generated from the combustion of pyrolysis vapors (including tar precursors)
- The gases leaving the oxidation zone, mainly CO_2 and H_2O , are reduced into CO and H_2 on the glowing char in the gasification area
- The gas temperature decreases due to the occurrence of the endothermic gasification up to a level at which no further reaction takes place
- The unreacted char and the ash are discharged from the bottom
- The synthesis gas is removed from the reactor close to the ash grate

Updraft Gasifier

- An updraft gasifier is one of the oldest and simplest of all designs
- Updraft gasifier can be classified as updraft fixed-bed gasifiers, fluidized-bed gasifiers, and circulating fluidized-bed gasifiers
- Here, the gasification medium (air, oxygen, or steam) travels upward while the bed of fuel moves downward, and thus the gas and solids are in countercurrent mode
- The product gas leaves from near the top of the gasifier
- Gasifying medium enters the bed through a grate or a distributor, where it meets with the hot bed of ash
- The ash drops through the grate, which is often made moving (rotating or reciprocating), especially in large units to facilitate ash discharge
- Feedstock material is first introduced into the drying zone at the top, followed by the pyrolysis and reduction zone, and finally the unconverted solid passes through the combustion zone
- In the combustion zone, solid charcoal is combusted producing heat, which effectively transfers to the solid particles during counter-current flow of the rising gas and descending solids
- In this gasification system, the contamination of substantial amount of tars is the major problem of updraft gasifiers

Crossdraft Gasifier

- Cross-draught gasifiers are mostly used for high carbon containing feedstock; charcoal
- Charcoal gasification results in very high temperatures (1500°C and higher) in the oxidation zone, which can lead to material problems
- In cross-draught gasifiers, thermal insulation against these high temperatures is provided by the fuel (charcoal) itself
- Advantages of the system lie in the very small scale at which it can be operated

- A disadvantage of cross-draught gasifiers is their minimal tar-converting capabilities and the consequent need for high-quality (low-volatile content) charcoal

Comparison of Gasifier Designs

- Overall Gasification can be done through Downdraft, updraft or cross draft gasifier
- Sequence of reactions are different in different designs and hence design may be modified as per requirement
- Chemical composition and yield of any gas can be different based on design of reactor
- Product gas may contain some impurities or undesirable gas in different designs
- Temperature profile of reactor will be different based on the reactor design
- Exit gas temperature and exit ash temperature will depend on the design

Commercial Gasifier Types

Lurgi Gasifier

- Lurgi gasification process is one of the several processes for which commercial technology has been fully developed
- Developed in Germany before World War II, this process has been used in a large number of commercial plants throughout the world
- This process produces low- to medium-calorific value gas as product gas
- The older version of Lurgi process is dry ash gasification process that differs significantly from the more recently developed slagging gasification process
- The Lurgi gasifier is a pressurized, dry-ash, moving bed gasifier that produces syngas from lump coal, steam, and oxygen as an oxidant
- The dry ash Lurgi gasifier accepts crushed noncaking coals only
- In this gasifier, coal sized between 1.5 to 4 mesh reacts with steam and oxygen in a slowly moving bed
- The process is operated semi-continuously

Key Components of Lurgi Gasifier

- The gasifier is equipped with the following hardware parts:
 - Coal lock hopper - An automated coal lock chamber for feeding coal from a coal bin to the pressurized reactor
 - Coal distributor - Through which coal is uniformly distributed into the moving bed
 - Revolving grate - Through which the steam and oxygen are introduced into the reacting zone (coal bed) and the ash is removed
 - Ash lock chamber - For discharging the ash from the pressurized reactor into an ash bin, where the ash is cooled by water quenching
 - Gas scrubber - In which the hot gas is quenched and washed before it passes through a waste heat boiler

Lurgi Gasifier Process

- Coal enters the top of the gasifier through a lock hopper and is handled by a rotary distributor as it begins its descent through the gasifier
- The coal feed is supported at the base of the reactor by a revolving grate through which the steam and oxygen mixture is introduced and the ash removed
- Steam and oxygen enter from the bottom, while ash is removed at the bottom by a rotating grate and lock hopper
- This process takes place at around 24 to 31 atm and in the temperature range of 620 to 760°C
- The residence time in the reactor is about 1 hour
- Steam introduced from the bottom of the reactor provides the necessary hydrogen species, and the heat is supplied by the combustion of a portion of the char
- The product gas from a high-pressure reactor has a relatively high methane content compared to a non-pressurized gasifier
- The high methane content of the product gas is a result of the relatively low gasification temperature
- If oxygen is used as an injecting (and gasifying) medium, the exiting gas has a heating value of approximately 450 Btu/scf
- A high ratio of steam to oxygen helps moderate the temperature such that the ash does not melt, but rather is removed as dry ash
- The crude gas leaving the gasifier contains a substantial amount of condensable products including tar, oil, phenol, etc., which are separated in a devolatilizer, where gas is cleaned to remove unsaturated hydrocarbons and naphtha
- Exiting raw syngas at up to 550°C is cooled and quenched using recycle water to condense tars and oils
- A water jacket cools the gasifier vessel and generates part of the steam needed by the gasifier
- The gas is then subjected to methanation ($\text{CO} + 3\text{H}_2 = \text{CH}_4 + \text{H}_2\text{O}$) to produce a high-Btu gas (pipeline quality)

Advantages of Lurgi Gasifier

- High "cold-gas" thermal efficiency, when the heating value of the produced hydrocarbon liquids is accounted for
- Cold-gas thermal efficiency is a measure of how much chemical energy from a solid fuel is retained in the product gas
- Simplicity of gasifier configuration and operation, high equipment efficiency
- Relatively low oxidant (oxygen or air) requirement
- Less complex feedstock preparation with the use of coarse coal particles
- Product gas at relatively low temperatures, thus no need for expensive high-temperature heat recovery equipment
- Feedstock flexibility: suitable to handle coals with high reactivity and moisture
- More reactive feedstocks are preferred due to the relatively low-temperature operation
- High methane content in product gas

Disadvantages of Lurgi Gasifier

- Limited ability to handle coal fines
- Caking coals require design modifications to the gasifier

- Long feedstock residence time in gasifier and slag flow characteristics require carefully controlled feed size distribution for proper operation
- Hydrocarbon liquids such as tars and oils are produced; increased effort to clean produced gas if it is used for applications other than direct heating
- Explosion hazard without careful process monitoring

Fluidized Bed Gasifier

- Fluidized Bed Gasifier works in a similar way to Fluidized Bed Combustion units
- Air/steam is used to fluidize the solid fuel such as coal, biomass, coke and other feedstock
- Bed material, limestone etc. are also added in the gasifier
- High ash coal can be gasified
- Gasification happens in a bed of inert materials that is hot (usually sand or alumina) and is suspended through an upward motion of the gasifying medium
- As the flow rate of the gas increases, the bed materials start rising and become "fluidized"
- This fluidization process increases the reactivity between the bed material (inert material) and biomass
- The rate of reaction is higher in the fluidized bed gasification process in comparison to the fixed bed gasification process
- Due to the enhanced performance over fixed-bed systems, fluidized bed systems can be operated with a higher range of biomass feedstock materials, and also at larger scales, and potentially yield a production gas with higher calorific value
- However, fluidized bed systems are quite costly and are more complex in operation

Winkler Gasifier

- This is the oldest fluidized bed gasifier, and has been in commercial use for many years
- Depending upon its operating conditions, we can group Winkle gasifiers under low temperature and high-temperature types
- Winkler gasifier, which operates at atmospheric pressure, is a refractory-lined shaft reactor, which can process coal of about -10.0 mm size
- Coal is continuously fed by a screw from a pressurized hopper and fluidized by a primary blast immediately above the bottom grate
- A secondary blast just above the fluidized bed serves to gasify any unreacted char in the product gas stream
- Ash not leaving with this stream (and removed in an external cyclone) is withdrawn through the base of the reactor by means of a rotating scraper
- Depending on whether a producer gas or syngas is to be made, either an air-steam or an oxygen-steam blast is used, and outputs can be varied over a relatively wide range without appreciable loss of efficiency
- A typical syngas will contain 36-37% hydrogen, 45% carbon monoxide, and 16% carbon dioxide
- However, owing to the construction of the reactor, maximum temperatures must not exceed ~980°C, and this restricts fuels for Winkler gasification to lignites and sub-bituminous coals
- Higher rank coals are, as a rule, insufficiently reactive at such comparatively low temperatures at atmospheric pressure, but now with the use of pressurized systems all coal can be used

KRW Gasifier

- The KRW gasifier is a pressurized, dry-feed, fluidized-bed slagging gasifier developed by M.W. Kellogg Company
- The KRW gasifier can gasify all types of coals, including high-sulfur, high-ash, low-rank, and high-swelling coals
- Crushed Coal and limestone to less than 1/4 inch are fed into the bottom of the gasifier, with the air or oxygen entering through concentric high velocity jets
- This ensures thorough mixing of the fuel and air/oxygen
- The coal immediately releases its volatile matter upon entering the gasifier, which oxidizes rapidly, producing the heat for the gasification reactions

Koppers-Totzek Gasifier

- The Koppers-Totzek process, which has been commercially used since 1938, is an entrained-solids process which operates at atmospheric pressure
- The reactor is a relatively small, cylindrical, refractory-lined coal "burner" into which coal, oxygen, and steam are injected through two or four tangentially disposed "burner heads"
- Steam is introduced around these heads to cover the reaction zone and protect the vessel walls from excessive heat
- Product gas is taken off through a collector pipe at the top
- Ash leaves as a molten slag through the bottom
- The feed coal for the process is crushed (70% passing 75 μm), mixed with O_2 and low-pressure steam, and injected into the gasifier through a burner head
- The heads are spaced 180° or 90° apart (representing two-headed or four-headed opposed burner arrangements) and are designed such that steam envelopes the flame and protects the reactor walls from excessive heat
- The reactor typically operates at an exit temperature of about 1480°C and the pressure is maintained just slightly above atmospheric
- Only about 85%–90% of the total carbon may be gasified in a single pass through the gasifier because carbon conversion is a function of the reactivity of the coal and approaches 100% for lignite
- Gasification proceeds rapidly at temperature of 1500-1950°C in the chamber
- The product gas leaves the gasifier at 1400-1500°C and is passed through a radiation boiler and waste heat boiler for the recovery of sensible heat
- Appreciable amount of coal dust is carried with the gas. This is removed in dust catchers and the coal is used again
- Half of the ash is deposited on gasifier wall as a fluid slag. It flows down and finally removed from the bottom
- This process generates no tars, and yields a substantially methane-free synthesis gas that typically may contain 30-32% H_2 , 55% CO and 12% CO_2
- The heat in the reactor causes the formation of slag and is removed from the bottom of the gasifier through a water seal
- Gases and vaporized hydrocarbons produced by the coal immediately pass through a zone of very high temperature in which they decompose so rapidly that coal particles in the plastic stage do not agglomerate, and thus, any type of coal can be gasified irrespective of caking tendencies, ash content, or ash fusion temperature

- High operating temperature ensures that the gas product contains no ammonia, tars, phenols, or condensable hydrocarbons
- The raw gas can be upgraded to synthesis gas by reacting all or part of the carbon monoxide content with steam to produce additional hydrogen plus carbon dioxide

Advantages of Koppers-Totzek Gasifier

- Major advantage is its ability to accept all types of coal without any prior treatment other than pulverization and some flexibility in ash removal
- Instead of being tapped off as a slag, ash can also, where so desired, be removed as fly ash with the raw gas and then separated from it in an external cyclone
- The high operating temperature also allows very fast gasification
- In view of this exceptionally high capacity and the modest cost of the Koppers-Totzek generator, its relatively low carbon inventory and consequent above-average oxygen consumption are generally not serious disadvantages

Disadvantages of Koppers-Totzek Gasifier

- Disadvantage is the loss of sensible heat when the raw gas, which exits at 1260–1480°C, is cooled to ambient temperatures for cleaning
- The need to compress the clean gas for downstream chemical syntheses

Syngas Cleaning

- During Gasification, syngas is produced. Major useful components are H₂ and CO gas
- However, the syngas produced from reactor may contain other gases, vapors as well as fine particles
- Major contaminants present in syngas generally include:
 - SPM (Suspended Particulate Matter)
 - Condensable hydrocarbons (i.e. tars)
 - Sulfur compounds
 - Nitrogen compounds
 - Alkali metals and their salts (primarily potassium and sodium)
 - HCl
- Exact gas composition depends on feedstock characteristics and gasification reaction kinetics
- The level of cleaning that is required may also vary substantially depending on the end-use technology and/or emission standards
- CO₂ is also considered as an impurity if not desired by the user industries

SPM (Suspended Particulate Matter)

- Particle matter released from a gasifier range of about 1 mm–100 µm, and can vary widely depending on the feedstock and process
- Inorganic compounds and residual solid carbon from the gasification of coal/biomass constitutes the bulk of the SPM, although bed material or catalysts can also be elutriated
- The inorganic content includes:
 - Alkali metals (potassium and sodium)

- Alkaline earth metals (mostly calcium)
- Silica (SiO_2)
- Other metals such as iron and magnesium
- Minor constituents present in trace amounts are primarily derived from solid fossil carbon feedstocks and include arsenic, selenium, antimony, zinc, and lead
- Many syngas applications require greater than 99% particulate removal
- Fouling, corrosion and erosion can cause efficiency and safety concerns

Tar

- Tars are composed of condensable organic compounds
- They vary from primary oxygenated products to heavier deoxygenated hydrocarbons and polycyclic aromatic hydrocarbons (PAHs)
- Thermochemical conversion processes create hundreds or even thousands of different tar species in response to the operating parameters
- The complex chemical nature of tar creates difficulties in collecting, analyzing, and even defining what constitutes tar

Sulfur

- Sulfur contaminants occur mostly as H_2S with lesser amounts of carbonyl sulfide (COS)
- H_2S may range in concentration from 0.1 mL/L to 30 mL/L, depending on the feedstock
- Biomass has significantly less sulfur than coal
- Some forms of biomass, including a few grasses and black liquor (a byproduct of the pulp and paper industry), can still have sulfur contents exceeding 1 g/kg
- Sulfur compounds corrode metal surfaces
- If syngas is burned, sulfur contaminants are oxidized to sulfur dioxide (SO_2)
- Even small amounts of sulfur can poison catalysts used to clean or upgrade syngas
- Sulfur removal to ppb levels is often required to avoid their detrimental effects

Nitrogen Compounds

- Most nitrogen contaminants in syngas occur as NH_3 and HCN
- The pyrolysis stage of gasification and combustion releases nitrogen from protein structures or heterocyclic aromatic compounds in the feedstock
- The amount of NH_3 and HCN released is heavily dependent on intrinsic properties (N content, functionalities) and physical properties (particle size) as well as process conditions
- NH_3 is typically the dominant form of nitrogen contaminants compared to HCN or others
- It can be formed directly from biomass in primary reactions or from HCN in secondary gas phase reactions
- As the temperature increases, HCN as well as NH_3 concentration increases
- Availability of H_2 and residence time will convert the HCN to NH_3

Alkali and Alkaline Earth Metals

- Many gasification feedstocks naturally contain alkali and alkaline earth metals

- Concentrations of alkali in biomass can vary substantially but are typically much greater than in coal
- Woody biomass tends to contain more alkaline earth metals, while herbaceous biomass contains higher levels of alkali metals
- The alkali metals are primarily potassium and to a lesser extent sodium, and are more problematic in syngas applications than alkaline earth metals due to their higher reactivity

Chlorides

- Chlorides are the predominant halide in syngas, usually in the form of HCl
- Chlorine in biomass occurs as alkali metal salts, which readily vaporize in the high temperature environment of combustors, pyrolyzers, or gasifiers and react with water vapor to form HCl
- Raw syngas may contain up to several milliliters of chloride for every liter of syngas

Gas Cleaning Considerations

There are many variables in gas cleaning, and the precise area of application of a given process is difficult to define. Factors that need to be considered include:

- The types and concentrations of contaminants in the gas
- The degree of contaminant removal desired
- The selectivity of acid gas removal required
- The temperature, pressure, volume, and composition of the gas to be processed
- The desirability of sulfur recovery due to process economics or environmental issues
- The CO₂ to hydrogen sulfide ratio in the gas

Gas Cleaning Methods

Based on the impurities present, individual or combined pollutant removal mechanisms are adopted:

- For SPM: Cyclone separator, settling tank etc.
- For Sulfur, Nitrogen compounds: Chemical-based absorption or adsorption or catalytic reactions
- For Hydrocarbons/Tar: Suitable catalytic reaction or absorption or adsorption etc.

Cogeneration and Coproduction

- Cogeneration or coproduction in the context of gasification refers to the ability for a gasification plant to vary the downstream processing of the produced syngas depending on market conditions, to optimize profits as well as sustain in difficult situations
- For example, gasification plant may add additional units/plants in downstream such as:
 - Integrated gasification combined cycle (IGCC) based power plant
 - Supplying waste heat to nearby other plants
 - Supplying steam (generated from heat released during gasification) to other chemical plants
 - Installing plants for converting the syngas into chemicals or liquid fuels
 - Purifying syngas to produce individual CO, H₂, CH₄ etc. gases
- Such approach helps the gasification plants to survive or increase profit

Summary

- Coal gasification can be used as center point for different industries
- Hydrogen and other gases can be produced from coal through gasification route
- Gasification opens the pathways for coal to chemicals
- Gasification at low temperature results in impurities in syngas but no slagging of ash
- Gasification at high temperature results in better quality syngas but slagging of ash occurs
- Lurgi gasifier as well as fluidized bed gasifier both can be used in gasification depending on types of feedstock and syngas quality requirement
- Gasification can be used as additional step for coal utilization in power generation, particularly for inferior quality coal/feedstock

Coal-Based Power Generation

Overview of Coal Combustion Technologies

- Pulverized coal combustion (>90% of plants) and Fluidized Bed combustion (<10%) are most commonly used
- Gasification-based plants are very limited in number
- In Pulverized coal combustion units, Run of Mine (ROM) coal or washery middling is used
- Requirements include:
 - GCV > 3500 kcal/kg or ash < 45% in coal
 - High ash content creates difficulties in plant operation and increases cost
 - Grinding of coal to -75 µm is required
 - Coal handling section (CHP) ends at grinding of coal
- Presently biomass pellets are also mixed with crushed coal and ground in mill

Fluidized Bed Combustion (FBC)

- For high ash coal: reject coal, lignite, coal slurry fines, coal washery tailings, etc. are used in FBC
- Co-firing of other fuels is very easy for FBC: biomass, municipal solid waste, coke powder, etc.
- Crushing of coal to -10 mm is required in FBC
- Coal handling section (CHP) ends at crusher, no grinding required
- Typically, bigger plants of 100 MW or more in single unit are Pulverized fired
- Smaller plants of 5-20-30 MW in single unit are FBC based
- Older plants (installed before 2000) have much lower capacity
- Newer plants have much larger capacity due to improvements in technology

Coal Handling Plant (CHP)

- CHP receives coal from mines, feed size about 1000 mm
- Coal is unloaded by wagon tripler, trucks, or bottom discharge wagon
- All movement of coal is through conveyor belts (abrasive index is important)
- Coal is either stored in stockpile or directly fed to CHP for crushing and burning
- Initial crushing to below -50 mm, followed by -12.5/3 mm crushing
- Suitable size screens are also placed
- Crushed coal is fed to bunker/silo with storage capacity for 12-18 hour plant operation
- Silos convert the process from batch to continuous mode
- FBC plant CHP ends here, with coal burned directly in the combustor

Additional Processing for Pulverized Combustion

- From silos, coal is sent to pulverizer (mill) - Hardgrove Grindability Index (HGI) is important
- Primary air is also supplied to blow/transport powdered coal (-75 µm) to combustor (particle density is important)
- Coal is burned in combustor
- After combustion, bottom ash, fly ash, and flue gas are generated

- These are captured by cyclone separator, ESP, flue gas desulfurizer unit, etc. as required
- Fuel oil is used for initial ignition as well as to maintain the desirable flame temperature inside boiler

Power Generation Principles

- Electricity is induced in varying magnetic field (interaction between electrical coils & magnetic field)
- In a turbine, magnet rotates and electricity is generated in electrical cables
- Rotational movement is created by fluid releasing energy at turbine blades
- Fluid should have high kinetic energy to be released at turbine blades and converted to:
 - Rotational energy → Electromagnetic energy → Electricity
- High temperature steam drives steam turbine in thermal power plant
- Based on Fleming's left hand rule: interaction between electrical coils & magnetic field induces electricity

Power Plant Operation

- Power plant operates at constant output capacity (e.g., 500 MW)
- Based on design, plant needs constant steam quality (temperature and pressure) and mass flow rate (kg/min) to generate desired power
- Steam is used as operating fluid: medium to transport energy from combustor to turbine
- Steam quantity (mass flow rate) and quality (pressure & temperature) must be maintained by the boiler by burning coal at desirable heat release rate
- Coal must be burned properly with desirable heat release rate (kcal/min)
- Coal's Gross Calorific Value (GCV) is important, but combustion rate is most critical

Coal Feed Requirements

- Pulverizer must grind coal to $-75\ \mu\text{m}$ within desired time (hard coal takes longer for grinding)
- Primary air flow rate must match design to transport coal particles (with desired density) to the boiler
- Coal GCV, combustion rate are all correlated and must be as per design

Model Calculation of Coal Feed Rate:

- For 500 MW plant, output is 500 MW (1 MW = 860,420.8 kcal/h)
- Plant overall efficiency (Rankine cycle, generator, etc.): ~40%
- Heat output required = $500\ \text{MW} \div 0.40$ (in kcal/h)
- Coal GCV: e.g., 5000 kcal/kg
- Coal feed rate = Heat required \div GCV

Operating Temperatures

- For FBC based plants, temperature is about 850-900°C
- High sulfur coal may be used in FBC unit
- Ash Fusion Temperature (AFT) is important in design of pulverized boiler
- Maximum temperature is decided based on AFT and other parameters

- Super thermal, ultra super thermal plants are classified based on maximum steam temperature and pressure
- Design depends on metallurgical limits of boiler tube material, combustion technology, and grade of coal available

Power Grid Considerations

- Auxiliary power is required for plant operation and running equipment before plant generates its own electricity
- Grid connectivity is essential - isolated single plants cannot operate
- Electricity peak demand, lean demand, and sudden demand fluctuations are important factors
- Electricity must meet standard requirements (frequency: 50 Hz)

Boiler Design and Operation

Inside the boiler, water is converted to steam in three different sections:

Economizer

- Used to increase feed water temperature from $\sim 30^{\circ}\text{C}$ to about 100°C
- Uses low temperature heat available inside boiler
- Mostly waste heat released from flue gas is utilized here

Evaporator

- In this zone, water is vaporized from liquid phase to vapor phase
- Only latent heat of phase change is required
- This is a significant amount as latent heat is higher than sensible heat

Superheater

- In this zone, steam is superheated from about 100°C to desired conditions for the turbine
- Typical conditions around 560°C , 200 bar (varies from plant to plant)
- High temperature flue gas ($\sim 1300^{\circ}\text{C}$) is used for this purpose

Working Fluid Characteristics

- Any fluid (gas/vapor/liquid) can be used as working fluid with specific quality parameters
- It must have higher heat transport capacity to transfer energy from boiler to turbine
- High specific heat capacity (C_p), latent heat (λ) allow it to carry more heat with lower temperature differences
- Must be easily available (to meet plant demand), cheap, non-toxic, environmentally friendly, non-corrosive, etc.
- Boiling temperature must match heat transport requirements and turbine profile

Water as Working Fluid

- Pure water is primarily used in thermal plants for normal cycle
- Mercury (Hg) was used in earlier designs

- Some organic liquids are used in low temperature Rankine cycle (combined cycle plants)
- Water can transport more heat as steam at high temperature and pressure
- Steam temperature vs. enthalpy relationship is important - water must be at high pressure and temperature to transport desired energy
- Changes in steam pressure/temperature can lead to phase change of water from vapor to liquid, which is highly undesirable and can damage the turbine
- Pumps are used to pressurize liquid water and send it to the boiler

Electricity Generation Process

- Turbines convert kinetic energy available in steam to rotational energy
- Rotor containing armature (electrical cable) rotates near magnetic field
- Due to variations of magnetic field, electricity is induced in armature, converting mechanical energy to electrical energy
- Produced electricity is stepped up - voltage (volts) is increased and current (amps) is reduced as per grid/consumer requirements
- A separate electrical power transmission unit handles this process

Condenser Function

- Purpose of condenser is to recycle the working fluid from vapor phase to liquid phase
- It removes unused heat from steam and transfers it to cooling tower/nearby water body
- Unused steam must be condensed immediately to increase pressure difference across turbine so it rotates at high speed
- Some water vapor is lost at condenser, so makeup water is continuously added as working fluid

Water Quality Requirements

- Steam with minerals (dissolved salts, chemicals, organic compounds) can be corrosive at high temperature
- Water is purified to the highest standards (almost pure H₂O, zero Total Dissolved Solids)
- A separate water treatment plant handles this process
- Nearby large water body (river, large lake) is essential
- Similarly, ash handling section, Electrostatic Precipitator (ESP), cyclone, etc. are included for pollution control

Plant Efficiency

- Efficiency of Rankine cycle is determined by thermodynamics:
 - About 42% to 46% in steam turbine
 - Due to other losses in system, overall efficiency is typically below 35%
 - Well-proven technology, most widely used worldwide
- Overall efficiency = $\eta(\text{boiler}) \times \eta(\text{cycle}) \times \eta(\text{turbine}) \times \eta(\text{generator})$
- $\eta = 1 - q_2/q_1$ (where q_1 is heat input, q_2 is heat rejected)

Other Operational Factors

- Auxiliary Fuel: Liquid Fuel, Fuel Oil

- Auxiliary Power Consumption: Electricity consumed in plant operation
- Coal Handling Plant (CHP) also consumes electricity
- Fly ash utilization: Solid waste transferred to other consumers/plants
- Power transmission to grid
- Steam pressure vs. efficiency relationship is important
- Reheating cycle, medium and low pressure turbines: Based on plant complexity/simplicity desired and process control aspects

Cogeneration

- In many industrial applications, heat or steam is also required for material processing
- In such plants, waste heat or steam released from power generation unit is sent to material processing section
- Plants using fuel for both electricity generation and heat are called cogeneration plants
- This approach increases overall energy efficiency and reduces pollution levels

Gas Turbine Power Generation

- A gas turbine generates power by burning fuel to create hot gases that rotate the turbine
- Based on Brayton cycle for power production
- Process:
 - Air is compressed by rotor (compressor) and sent to combustor
 - Fuel is burned at high temperature and pressure, generating flue gas
 - Flue gas rotates the turbine, which is connected to generator to produce electricity
 - Some energy generated is used to operate the compressor
- Coal, liquid fuel, gaseous fuel can be used
- Efficiency is about 30-35%
- Advantages: Less installation time and cost, quick start and stop
- Disadvantage: Higher operating cost as it mostly uses liquid/gaseous fuel

Combined Cycle Power Generation

- Two or more power generation cycles operated in series to increase energy efficiency
- Exhaust energy from one power generation cycle is used in next cycle
- Example: GT+ST cycle
 - First cycle: Gas Turbine (GT) cycle generates electricity
 - Exhaust flue gas is used to generate steam and produce electricity using Rankine cycle (Steam Turbine, ST)
- Other configurations: GT+GT, ST+ST, or ST+GT
- Major advantage: Increased efficiency (e.g., GT (200 MW) + ST (100 MW) is more efficient than GT 200 MW alone)
- Disadvantage: Complex plant operation, higher investment cost
- Dual cycle is also used in many ST-based plants

Integrated Gasification Combined Cycle (IGCC)

- In IGCC, coal is used to fulfill multiple purposes in a single plant:

- Coal gasification with removal of pollutants and recovery of valuable resources
- GT-based power generation
- ST-based power generation
- Cogeneration of heat if required

IGCC Process Flow

- Coal is gasified to produce CO, H₂, CH₄ and other gas mixture (syngas)
- During gasification, recovery/removal of sulfur is carried out
- Syngas is purified to remove H₂S, NH₃, etc.
- Syngas is used as fuel gas in gas turbine
- Electricity is generated in gas turbine
- Exhaust heat is used to generate steam for ST-based power generation
- Heat produced during gasification is used as byproduct for cogeneration of steam or other applications
- In parallel, syngas can also be used for production of chemicals (coal to chemicals)

IGCC Advantages and Disadvantages

- Advantages:
 - Higher energy efficiency
 - Minimum pollution
 - Production of valuable chemicals
- Disadvantages:
 - Complex network of energy transfer
 - Higher investment cost
 - Multiple products to handle and marketing challenges

Summary

- Coal is the major fuel used in power generation
- Rankine cycle-based plants are most commonly used
- Gas turbine and combined cycle are less popular despite operational advantages
- Energy efficiency of Rankine cycle is about 42%
- Steam quality is a major concern for power generation, indirectly affecting coal quality and combustion requirements
- IGCC can be used for electricity generation as well as for other downstream plants
- Despite being a cleaner technology compared to direct combustion methods, IGCC is not widely adopted for power generation due to operational complexity

Underground Coal Gasification (UCG) and Coal Bed Methane (CBM)

Underground Coal Gasification (UCG)

- In UCG, coal is gasified at the coal mine itself, without mining the coal
- Entire coal mine/coal seam acts like the reactor for coal gasification
- Water/steam and air or oxygen are injected into a coal seam
- The injected gases react with coal to form a combustible gas
- Product syngas is collected at the surface, purified/cleaned for impurities and used
- Major cost-saving and simplifying advantage of not requiring the coal to be mined in order to be gasified

UCG Process

- Injection wells are drilled into an unmined coal seam, and either air or oxygen is injected into the seam along with water
- The coal face is ignited, and the high temperatures (about 1200°C) from the combustion and limited oxygen causes nearby coal to partially oxidize into H_2 , CO, CO_2 , and some amounts of CH_4 , H_2S and other gases
- These products flow to the surface through one or more production wells located ahead of the combustion zone
- As the face is burned and an area depleted, the operation is moved to follow the seam

Site Selection for UCG

Site selection is paramount to a successful UCG project:

- The characteristics of the coal seam, the permeability and fault structure of the local strata and the geology and hydrogeology of the area which surrounds the target coal seam must be fully understood
- This requires the drilling of pilot bore holes to coal seam depth for coring and seam characterization, and a good quality seismic survey (preferably 3D) of the whole area
- Modeling of the hydrogeology will also be required to meet most countries' groundwater requirements

Coal Seam Requirements for UCG

- **Seam thickness:** Gasification rate decreases and heat value increases with increase in seam thickness
 - Seams >1.3 m thick are considered satisfactory
 - Coal seams with a thickness >2 m are preferred for long tunnel, large section technology
- **Coal type:** All ranks from lignite to anthracite can be gasified
 - Low rank coals are the easiest to gasify
 - UG trials have been successfully carried out elsewhere in anthracites (highest rank coals)

- Produced syngas needs to be cleaned from H_2S , NH_3 and other gases

Advantages of UCG

- As gasification occurs inside the coal mines, different coal mining activities, coal handling etc. are not required to get syngas
- UCG may save many other environmental pollution originated from coal mines
- For starting coal mining activities, land requirement and other infrastructure related to coal can be avoided without impacting coal utilization
- UCG is a very good alternative for coal mines where mining activities are extremely difficult due to:
 - Soil characteristics
 - Rock properties
 - Adsorbed gases inside coal
 - Nearby forest/protected areas

Challenges in UCG

- Infrastructure development is too costly
- If rocks are faulty, syngas may escape from different locations, creating extremely hazardous conditions
- Supplied heat through steam may be absorbed by the rocks causing inefficiencies
- Drilling in horizontal direction is difficult in many cases
- Ground water may get contaminated
- Land subsidence due to coal extraction requires geological information about the land/soil/rock characteristics

Coal Bed Methane (CBM)

Coal Bed Methane (CBM) is an unconventional source of natural gas now considered as an alternative source for augmenting energy resources:

- The term refers to methane adsorbed into the solid matrix of the coal
- It is called 'sweet gas' because of its lack of H_2S
- The presence of this gas is well known from its occurrence in underground coal mining, where it presents a serious safety risk
- CBM is gas which is created during the formation of coal and is trapped within a coal seam by formation water

Characteristics of CBM

- CBM is chemically identical to other sources of gas, but is produced by non-conventional methods
- Generally more than 95% methane and is often marketed as being "green" as it contains no sulfur compounds such as H_2S
- CBM (CH_4) in gaseous form has its origin in the coalification process occurring over millions of years from accumulated plant material
- The methane is in a near-liquid state, lining the inside of pores within the coal (called the matrix)

- The open fractures in the coal (called the cleats) can also contain free gas or can be saturated with water
- Unlike natural gas from conventional reservoirs, CBM contains very little heavier hydrocarbons such as propane or butane, and no natural-gas condensate
- Coal bed gas contains a variety of constituents like CH₄, CO₂, N₂, H₂O, C₂H₆ and other hydrocarbons, but methane is found in high concentrations in most underground coal seams
- It often contains up to a few percent CO
- CBM grew out of venting methane from coal seams for mine safety

CBM Formation and Entrapment

- Some coal beds have long been known to be "gassy," and as a safety measure, boreholes were drilled into the seams from the surface to vent methane before mining
- Intrinsic properties of coal as found in nature determine the amount of gas that can be recovered
- It is trapped in coal bed and released during and after mining when pressure is released
- The amount of methane present in coal seams increases with rank of coal and depth of coal seams
- CBM is a versatile source of energy that can be readily stored and transformed into alternative forms of energy such as electricity

CBM Extraction Process

- To extract the gas, a steel-encased hole is drilled into the coal seam 100 to 1,500 meters (330 to 4,920 ft) below ground
- As the pressure within the coal seam declines due to natural production or the pumping of water from the coal bed, both gas and produced water come to the surface through tubing
- The gas is sent to a compressor station and into natural gas pipelines
- The produced water is either:
 - Rejected into isolated formations
 - Released into streams
 - Used for irrigation
 - Sent to evaporation ponds
- The water typically contains dissolved solids such as sodium bicarbonate and chloride, but varies depending on the formation geology

CBM Production Characteristics

- Coalbed methane wells often produce at lower gas rates than conventional reservoirs, typically peaking at near 300,000 cubic feet (8,500 m³) per day (about 0.100 m³/s)
- Can have large initial costs
- The production profiles of CBM wells are typically characterized by a "negative decline" in which the gas production rate initially increases as the water is pumped off and gas begins to desorb and flow
- A dry CBM well is similar to a standard gas well

Coal Characteristics Suitable for CBM Development

Typically, coal suitable for CBM development has the following characteristics:

- **High gas content:** 15 m³ – 30 m³ per ton is typical
- **Good permeability:** 30 mD – 50 mD is typical
- **Shallow depth:** Coal seams are less than 1,000 m in depth
 - The pressure at greater depths is often too high to allow gas flow even when the seam has been completely dewatered
 - This is because the high pressure causes the cleat structure to close, reducing permeability
- **Coal rank:** Most CBM projects produce gas from Bituminous coals, but it can be possible to access gas in Anthracite

CBM Resources in India

- The prognosticated CBM resources in India are about 92 TCF (2600 BCM) in 12 states
- Government of India formulated CBM policy in 1997 wherein CBM, being Natural Gas, is explored and exploited under the provisions of:
 - OIL Fields (Regulation & Development) Act 1948 (ORD Act 1948)
 - Petroleum & Natural Gas Rules 1959 (P&NG Rules 1959)
 - Administered by Ministry of Petroleum & Natural Gas (MOP&NG)
- The Gondwana sediments of eastern India host the bulk of India's coal reserves and all the current CBM producing blocks

CBM Projects in India

- The vast majority of the best prospective areas for CBM development are in eastern India, situated in Damodar Valley and Son Valley
- CBM projects exist in:
 - Raniganj South, Raniganj East and Raniganj North areas in the Raniganj coalfield
 - The Parbatpur block in Jharia coalfield
 - The East and West Bokaro coalfields
- Son Valley includes the Sonhat North and Sohagpur East and West blocks
- Commercial production has commenced from Raniganj South CBM block
- India is one of the prominent emerging players in the CBM market with 6-7 CBM fields either producing or on the verge of production
- The estimated domestic production from all CBM fields for 2017-2018 was 1 BCM and was expected to rise substantially
- CBM was expected to contribute 5% to 8% of India's gas production
- India houses the world's fourth-largest coal reserves
- The country has identified 26,000 square km of area for CBM operation with total estimated CBM Resources of 2,600 billion cubic meters (91.8 TCF)

Coal Mine Methane (CMM)

- Methane, the principal component of natural gas, is often present in deep coal seams and is a safety hazard to miners because it is explosive in concentrations ranging from 5 to 15 percent in air

- CMM refers to methane released from the coal and the surrounding rock strata due to mining activities
- Although CMM is similar to CBM, it refers specifically to the methane found within mining areas, while CBM refers to methane in coal seams that will never be mined or are very difficult to mine
- In underground mines, CMM can create an explosive hazard to mine workers and is removed through ventilation and degasification systems

CMM Safety and Recovery

- As CMM would be released during mining activities, recovery and use of CMM are considered essential for mine safety and emissions avoidance
- In abandoned mines (AMM) and surface mines, methane can also escape to the atmosphere through natural fissures or other diffuse sources
- Gassy underground coal mines employ large-scale ventilation systems to move fresh air into the mine
- These systems dilute methane released into the mine workings as coal is extracted and remove the gas from the mine, maintaining safe working conditions
- In-mine methane concentrations must be maintained well below the lower explosive limit, so ventilation air exhausts contain very dilute concentrations of methane (typically less than 1% and often less than 0.5%)

Ventilation Air Methane (VAM)

- Because mine exhaust flow rates are so high, ventilation air methane (VAM) constitutes the largest source of methane emissions at most mines
- Emissions of VAM waste a clean energy resource and contribute significant global greenhouse gas emissions
- Methane is a potent greenhouse gas with a global warming potential more than 25 times that of carbon dioxide
- Deploying technologies that destroy VAM emissions or convert VAM into useful forms of energy (such as electricity and heat) can yield substantial greenhouse gas emission reductions

Challenges with CMM/VAM

- Gas concentration depends upon the gassiness of coal mine
- Gas concentration may vary, impacting the quality of feed into power plants
- Challenges exist in commercialization of VAM/CMM
- CMM and AMM are major causes of different types of accidents in coal mines
- Gassy coal mines need removal or extraction of methane before any equipment/person can enter
- It is an extreme fire hazard if concentration is on the higher side
- It can replace air/O₂ in mine and cause oxygen deficiency
- Many coal mine accidents originate from CMM/AMM