Power Plant Engineering

Lecture 3

Fuels and Combustion

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Lecture learning outcomes:

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

i. Understand the classification of fuels and their relevance in energy systems.

ii. Analyze coal using proximate and ultimate methods to assess its combustion properties.

iii. Apply combustion stoichiometry to calculate air-fuel ratios and predict reaction outcomes.

iv. Identify and interpret experimental techniques used to determine combustion products.

v. Evaluate the environmental impacts of fuel combustion and strategies for emission control.

vi. Relate fuel characteristics and combustion analysis to practical applications in power generation and industry.

Content

1. Classification of Fuels

- Fuels are substances that release energy through combustion or other chemical processes.
- This energy is harnessed for heating, transportation, electricity generation, and industrial operations.
- Most familiar fuels consist primarily of hydrogen and carbon.
- They are called hydrocarbon fuels – C_nH_m
- Liquid hydrocarbon fuels are mixtures of many different hydrocarbons, they are usually considered to be a single hydrocarbon.
- Most liquid hydrocarbon fuels are obtained from crude oil

  by distillation. Example: Gasoline, Kerosene, Diesel…

1. Classification of Fuels

Cont…

Key components of a good fuel:

- High calorific value: Should release a lot of energy per unit mass/volume.
- Moderate ignition temperature: Should ignite easily but not too easily to be dangerous.
- Low moisture content: Moisture reduces the heating value.
- Easy to transport & store: Should be stable and non-hazardous.
- Low cost & abundantly available.
- Clean combustion: Should produce minimal smoke or harmful gases (e.g., SO_2, NO_x).

1. Classification of Fuels

- Understanding fuel classification is essential for selecting appropriate energy sources based on efficiency, cost, and environmental impact.
- Fuels can be classified on several bases. The two most common methods are:
- Classification Based on Occurrence
  - ✓Primary Fuels (natural)
  - ✓Secondary Fuels (derived)
- Classification Based on Physical State
  - ✓Solid Fuels
  - ✓Liquid Fuels
  - ✓Gaseous Fuels

1. Classification of Fuels

Cont…

Classification Based on Occurrence

1. Primary Fuels
   - Found in nature in their natural form.
   - They are unprocessed.

   Example: Solid: Wood, Coal, Peat
   Liquid: Crude Oil
   Gaseous: Natural Gas

2. Secondary Fuels
   - Produced by processing or refining primary fuels.
   - They are artificial or manufactured.

   Example: Solid: Coke, Charcoal
   Liquid: Petrol, Diesel, Kerosene
   Gaseous: LPG, CNG, Biogas, Coal Gas

1. Classification of Fuels

Cont…

Classification Based on Physical State

1. Solid Fuels

- Easy to transport, require large storage space, high ash content, combustion is often incomplete and smoky.

Example: Wood, Peat, Lignite, Bituminous Coal, Anthracite, Coke, Charcoal, Briquettes

2. Liquid Fuels

- Higher calorific value than solids, easier to transport through pipelines, less storage space needed, burns without ash, cleaner combustion.

Example: Crude Oil, Petrol, Diesel, Kerosene, Heavy Fuel Oil.

1. Classification of Fuels

Cont…

3. Gaseous Fuels

- Highest calorific value by mass, easiest to transport via pipelines, mixes with air for complete combustion (smokeless), immediate control of heat, requires specialized storage.

Example:

- ✓Natural Gas
- ✓Liquefied Petroleum Gas (LPG)
- ✓Compressed Natural Gas (CNG)
- ✓Coal Gas, Biogas, Hydrogen Gas

1. Classification of Fuels

Cont…

- While not a formal classification, it's an important modern distinction to classify fuels as:

a. Conventional Fuels: Mostly fossil-based and finite.

Example:

- ✓ Coal
- ✓ Petroleum products
- ✓ Natural Gas

b. Alternative Fuels: Fuels aimed at replacing conventional fuels to enhance energy security and reduce environmental impact.

Example:

- ✓ Biofuels (Biodiesel, Bioethanol)
- ✓ Hydrogen
- ✓ Biogas
- ✓ Syngas

2. Proximate and Ultimate Analysis of Coal

- Coal is a complex organic rock composed primarily of carbon, hydrogen, oxygen, nitrogen, and sulfur.

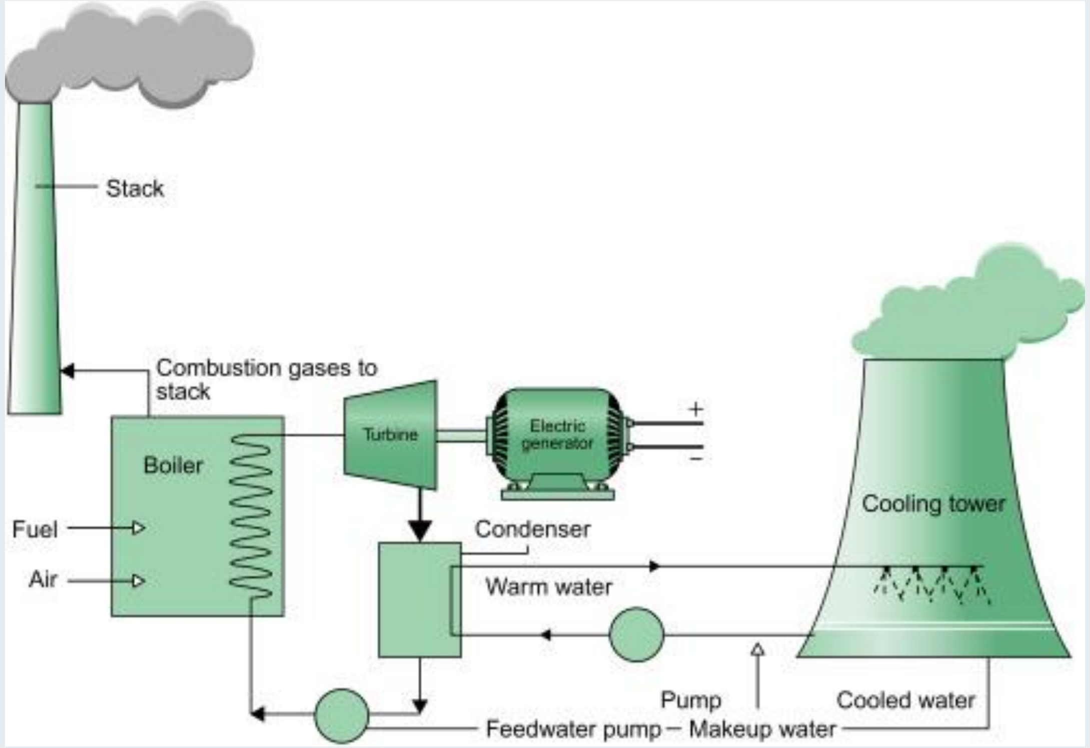

Figure 1: Coal-Fired Power Station, Paul Breeze, Power Generation Technologies (3rd Edition), (2019).
url: https://ars.els-cdn.com/content/image/3-s2.0-B9780128040058000033-f03-01-9780128040058.jpg

2. Proximate and Ultimate Analysis of Coal

- To use coal efficiently and economically in industries like power generation and steel production, understanding its properties is essential.
- To evaluate its quality and suitability for various applications, two key analytical methods are used:
  - ✓Proximate Analysis
  - ✓Ultimate Analysis

1. Proximate Analysis

- Proximate analysis is a practical, industry-standard test that provides a breakdown of a coal sample into four key components based on specific heating conditions [2].

2. Proximate and Ultimate Analysis of Coal Cont…

- Proximate analysis is relatively quick and inexpensive.
- It is used to determine the relative amounts of the following four components:
  - ✓Moisture: The water content present in the coal
  - ✓Volatile Matter (VM): The gases and vapors (e.g., H_2, CH_4, CO, tar) released when coal is heated in the absence of air.
  - ✓Fixed Carbon (FC): The solid combustible residue left after the volatile matter is driven off. It is mostly carbon.
  - ✓Ash: The inorganic, non-combustible residue left after all the combustible matter has been burned off.

2. Proximate and Ultimate Analysis of Coal Cont…

2. Ultimate Analysis

- Ultimate analysis provides a more fundamental and precise composition of coal.
- It gives the elemental composition of the organic mass of coal, expressed as percentages of the primary elements.

The elements measured are:

- ✓Carbon (C)
- ✓Hydrogen (H)
- ✓Nitrogen (N)
- ✓Sulfur (S)
- ✓Oxygen (O)
- ✓Ash and Moisture are also reported.

3. Combustion Stoichiometry and Air-Fuel Ratio

- Combustion is a chemical reaction between a fuel and an oxidizer (typically oxygen in air) that releases heat and often light.
- It's fundamental to energy conversion in engines, furnaces, and power plants.
  - ✓ Fuel: Typically hydrocarbons (e.g., methane, gasoline, diesel).
  - ✓ Oxidizer: Usually atmospheric oxygen.
  - ✓ Products: Mainly CO_2 and H_2O in complete combustion; CO, soot, and unburned hydrocarbons in incomplete combustion.
- Dry air can be approximated as 21% O_2 and 79% N_2.
- In the analysis of combustion, Argon in the air is treated as N_2 and gases existing in trace amount are disregarded.

3. Combustion Stoichiometry and Air-Fuel Ratio

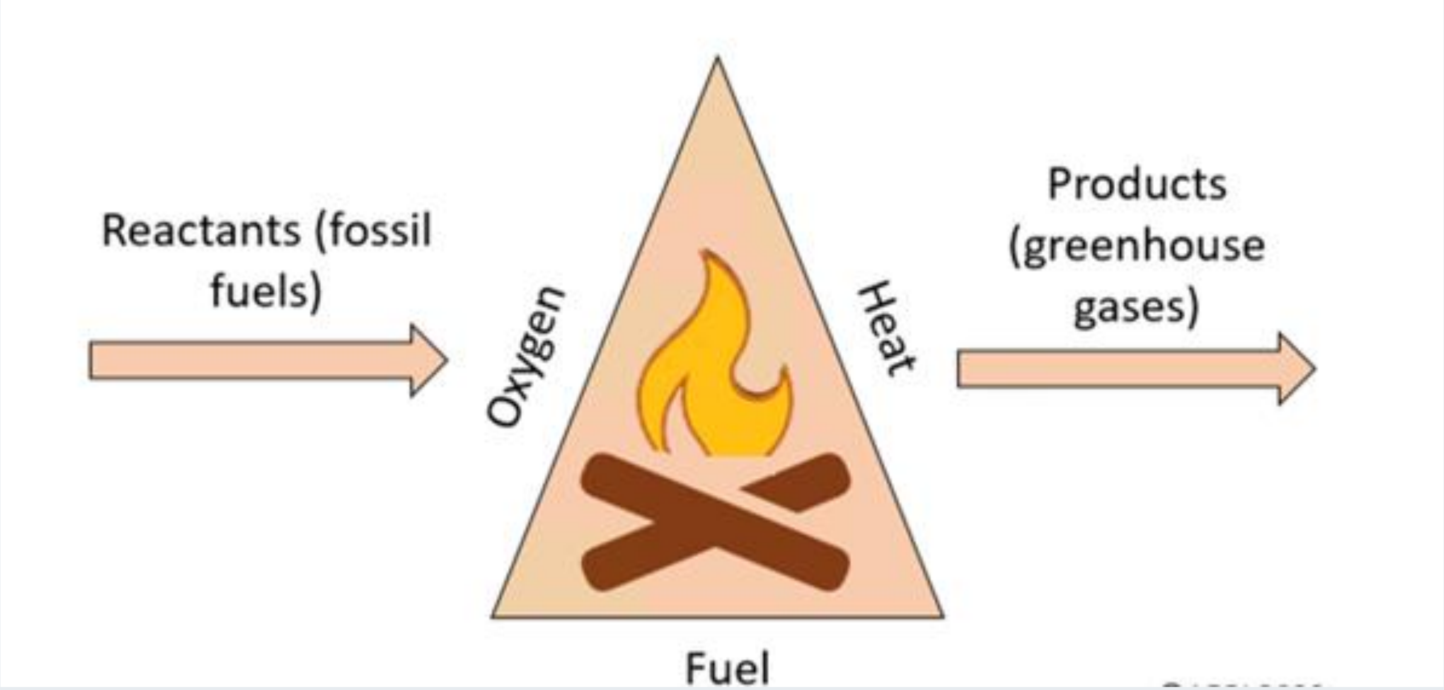

Figure 2: Combustion & Its Effects, GrittyTech Academy Blogs, (2025).
url: https://www.abpischools.org.uk/media/qu3fjbzt/combustion-triangle.png

3. Combustion Stoichiometry and Air-Fuel Ratio Cont…

Stoichiometric (Theoretical) Combustion

- Stoichiometric combustion is the ideal combustion process where a fuel is burned completely with exactly the right amount of air (oxidizer), leaving no unburned fuel and no free oxygen (O_2) in the products [3].
- It is a theoretical benchmark for perfect, efficient combustion.
- In practice, we need excess air to ensure complete combustion and prevent the formation of toxic Carbon Monoxide (CO).
- For stoichiometric calculations, air is approximated as: $Air = O_2 + 3.76N_2$
- General Reaction for a Hydrocarbon (C_xH_y):

$$C_xH_y + a(O_2 + 3.76N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76aN_2$$

- Where a is the stoichiometric coefficient for O_2, found by balancing the oxygen atoms.

3. Combustion Stoichiometry and Air-Fuel Ratio Cont…

Balancing the equation $$C_xH_y + a(O_2 + 3.76N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76aN_2$$

1. Carbon (C) Balance:

$$x\ moles\ of\ CO_2\ on\ product\ side \rightarrow x\ moles\ of\ C\ on\ reactant\ side.$$

2. Hydrogen (H) Balance:

$$\frac{y}{2} moles\ of\ H_2O\ on\ product\ side \rightarrow y\ moles\ of\ H\ on\ reactant\ side$$

3. Oxygen (O) Balance:

$$Oxygen\ in\ products = 2x + ({}^{y}/_{2})$$

$$Oxygen\ in\ reactants = 2a$$

Therefore: $2a = 2x + {}^{y}/_{2} \rightarrow \mathrm{a} = \mathrm{x} + {}^{y}/_{4}$

3. Combustion Stoichiometry and Air-Fuel Ratio Cont…

Example: Determine the stoichiometric combustion of methane (CH_4)

1. Unbalanced: $CH_4 + (O_2+3.76N_2) \rightarrow CO_2 + H_2O + N_2$

2. Balanced

   - Carbon (C): 1→ 1
   - Hydrogen (H): 4 $\rightarrow 2H_2O$ $(So\ 4\ H\ atoms)$
   - Oxygen (O): On product side, $CO_2(2\ O) + 2H_2O(2\ O) = 4\ O\ atoms$

Therefore, we need 2 O_2 $molecules\ on\ the\ reactant\ side\ (2 * 2 = 4\ O\ atoms)$

Final Balanced Equation:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

3. Combustion Stoichiometry and Air-Fuel Ratio Cont…

Non-Stoichiometric (Actual) Combustion

- In actual combustion processes, it is common practice to use more air than the stoichiometric amount:-
  - ✓ to increase the chances of complete combustion, or
  - ✓ to control the temperature of the combustion chamber.
- The amount of air in excess of the stoichiometric amount is called excess air.
- The amount of excess air is usually expressed in terms of the stoichiometric air as percent excess air or percent theoretical air [4].
- Amounts of air less than the stoichiometric amount are called deficiency of air and are often expressed as percent deficiency of air.

3. Combustion Stoichiometry and Air-Fuel Ratio Cont…

Air-Fuel Ratio (AFR)

- A frequently used quantity in the analysis of combustion processes to quantify the amounts of fuel and air is the air-fuel ratio, AFR.
- The air-fuel ratio (AFR) is the ratio of the mass of air to the mass of fuel used in a combustion process.

$$AFR = \frac{m_{air}}{m_{fuel}}$$

- The stoichiometric (theoretical) Air-Fuel Ratio (AFR) is the AFR for a stoichiometric mixture.

3. Combustion Stoichiometry and Air-Fuel Ratio Cont…

Example: AFR_s for Methane (CH_4)

From our balanced equation:

- Unbalanced: $CH_4 + (O_2 + 3.76N_2) \rightarrow CO_2 + H_2O + N_2$
- Final balanced equation:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

- Fuel mass: 1 mol CH_4 = (12 + 4*1) = 16 g
- Air mass: 2 mol O_2 + 2*3.76 mol N_2 = 2*32 + 7.52*28 = 64 g + 210.56 g = 274.56 g

$$AFR = \frac{274.56}{16} \approx 17.2$$

- This means 17.2 kg of air is required to completely burn 1 kg of methane.

3. Combustion Stoichiometry and Air-Fuel Ratio Cont…

Equivalence Ratio (ϕ)

- The Equivalence Ratio, denoted by ϕ (phi), is a fundamental parameter in combustion science that directly compares the actual air-fuel ratio to the stoichiometric air-fuel ratio.
- Equivalence ratio helps assess mixture richness or leanness.

$$\phi = \frac{Stoichiometric\ AFR}{Actual\ AFR}$$

$\phi = 1$: Stoichiometric Mixture

$\phi < 1$: Lean Mixture

$\phi > 1$: Rich Mixture

4. Experimental Techniques for Determining Combustion Products

- Experimental techniques for determining combustion products involve analyzing the gases and byproducts produced during the combustion of a fuel.
- Analyzing the composition of combustion exhaust is critical for:
  - ✓Efficiency optimization
  - ✓Controlling emissions
  - ✓Designing combustion systems
  - ✓Ensuring environmental compliance
- The experimental techniques includes:
  - ✓Sampling methods
  - ✓Analysis techniques

4. Experimental Techniques for Determining Combustion Products Cont...

Sampling Methods: The first critical step

- Sampling techniques refer to the methods used to extract, collect, and prepare gas or particle samples from a combustion system (like a flame, furnace, engine exhaust, or reactor) for further analysis [5].
- Before analysis, combustion products must be properly sampled.
- The common sampling techniques are:

1. Direct (In-situ) Sampling

- Measurements are taken directly in the combustion zone without extracting the sample.
- Often used with non-intrusive optical methods like laser diagnostics.

Example: Laser-Induced Fluorescence (LIF) and , FTIR spectroscopy.

4. Experimental Techniques for Determining Combustion Products Cont...

2. Extractive Sampling

- Gases are withdrawn from the duct or stack through a probe and conditioned (filtered, cooled, dried) before being transported to the analyzer.
- Most common in practical applications.
- Requires proper design to avoid chemical changes (oxidation, condensation) and minimize losses or contamination.

3. Cryogenic Sampling

- Rapidly freezes the combustion sample to preserve reactive or unstable species.
- Often used in research-grade experiments.

4. Experimental Techniques for Determining Combustion Products Cont...

4. Filter Sampling (for solids/particulates)

- Combustion exhaust is passed through filters to trap particulate matter like soot.
- Collected samples are then analyzed using Microscopy, Elemental analysis (XRF) and Carbon content analysis.

Key considerations in sampling

- Temperature control to avoid condensation of water or tars.
- Pressure compatibility with detectors.
- Chemical inertness of probes and lines (e.g., use stainless steel).
- Residence time minimization to avoid chemical reactions.
- Calibration of sampling systems to ensure quantitative accuracy.

4. Experimental Techniques for Determining Combustion Products Cont…

Analysis Techniques

1. Gas Chromatography (GC)

- Separates and quantifies individual species in a complex mixture.
- Used for: hydrocarbons, CO, CO_2, CH_4

2. Mass Spectrometry (MS)

- Identifies chemical species by mass-to-charge ratio
- It helps identify the amount and type of chemicals present in a sample by generating a mass spectrum.

4. Experimental Techniques for Determining Combustion Products Cont...

3. Non-Dispersive Infrared (NDIR) Sensors

- Common for measurement of CO_2, CO, CH_4, and SO_2.
- Based on IR absorption at specific wavelengths

4. Fourier Transform Infrared Spectroscopy (FTIR)

- Measures absorption of infrared light by gases
- Detects functional groups (e.g., CO_2, H_2O, CH_4, NO_x)

5. Laser-based Diagnostics (In-Situ)

- Tunable Diode Laser Absorption Spectroscopy (TDLAS)
- Laser-Induced Fluorescence (LIF)
- Used for species like hydroxyl radicals (OH), NO, H_2O, CO

5. Environmental Impacts of Fuel Combustion

- Fuel combustion is a primary source of energy worldwide, powering vehicles, industries, and homes.
- However, it also contributes significantly to environmental degradation through the release of pollutants and greenhouse gases.
- The major pollutants can be categorized by their impact:
  - ✓ Climate forcers: CO_2, CH_4, N_2O, Soot
  - ✓ Health & ecosystem damagers: NOx, SOx, CO, PM, Ozone, UHCs
  - ✓ Toxics: Heavy metals, polycyclic aromatic hydrocarbons (PAHs)

5. Environmental Impacts of Fuel Combustion Cont…

Primary pollutants and their formation

1. Carbon Dioxide (CO_2)

- Main product of complete combustion of any carbon-containing fuel (coal, oil, natural gas, biomass).
- Major contributor to global warming

2. Carbon Monoxide (CO)

- Produced from incomplete combustion
- Occurs when there is insufficient oxygen, poor mixing, or low temperature, preventing CO from oxidizing to CO_2.
- Toxic even at low concentrations
- Weakens oxygen delivery in the body

5. Environmental Impacts of Fuel Combustion Cont…

3. Nitrogen Oxides (NO_x)

- Formed at high combustion temperatures
- Contribute to smog and acid rain
- Precursor to ground-level ozone

4. Sulfur Dioxide (SO_2)

- Emitted from sulfur-containing fuels (e.g., coal, diesel)
- Causes acid rain
- Damages vegetation and aquatic ecosystems

5. Particulate Matter (PM)

- Includes soot, ash, and aerosols
- Penetrates deep into lungs
- Linked to respiratory and cardiovascular diseases

5. Environmental Impacts of Fuel Combustion Cont…

6. Volatile Organic Compounds (VOCs)

- Released from unburned hydrocarbons
- React with NO_x to form ozone
- Include carcinogenic compounds like benzene

7. Unburned Hydrocarbons (UHCs)

- Produced from incomplete combustion due to low temperature, poor mixing, or flame quenching

6. Fuel Properties and Selection Criteria

- A deep understanding of fuel properties ensures optimal system design, safe operation, and sustainable energy use [6].

The key fuel properties are:

1. Calorific Value (Heating Value): Amount of energy released during complete combustion of a unit mass or volume of fuel.
   - Higher Heating Value (HHV): Includes latent heat of vaporization of water.
   - Lower Heating Value (LHV): Excludes latent heat; more relevant for gas turbines.
2. Flash Point and Fire Point: Safety in storage and handling.
   - Flash Point: Lowest temperature at which fuel vapors ignite momentarily.
   - Fire Point: Temperature at which fuel sustains combustion.

6. Fuel Properties and Selection Criteria Cont…

3. Viscosity: Resistance to flow/ thickness.
4. Density and Specific Gravity
   - Density: Mass per unit volume.
   - Specific Gravity: Ratio of fuel density to water density.
5. Volatility: Tendency of fuel to vaporize.
6. Sulfur Content: Amount of sulfur in fuel.
7. Ash Content: Non-combustible residue after burning.
8. Moisture Content: Water present in fuel.
9. Ignition Temperature: Minimum temperature required to initiate combustion.

6. Fuel Properties and Selection Criteria **Cont…**

Fuel Selection Criteria

1. Application Suitability

   - Power generation, transportation, heating, or industrial processing.

   Example: Natural gas for turbines; coal for boilers.

2. Availability and Accessibility

3. Cost and Economic Viability

   - Fuel price, transportation, and processing costs.
   - Consider lifecycle cost, not just purchase price.

4. Environmental Impact

   - Emissions (CO_2, NOx, SOx, particulates).
   - Preference for low-carbon and renewable fuels.

6. Fuel Properties and Selection Criteria Cont…

5. Storage and Handling
   - Safety, space requirements, and regulatory compliance.

   Example: LPG requires pressurized tanks; coal needs large yards.

6. Combustion Efficiency
   - Completeness of combustion and heat recovery potential.
   - Influences system design and operational cost.

7. Compatibility with Equipment
   - Burner type, engine design, and material constraints.

   Example: High-viscosity fuels may clog injectors.

7. Applications in Power Generation, Industrial Processes and Transportation

- Combustion is the primary mechanism for:
  - ✓ Power Generation: Producing electricity for grids, industries, and homes.
  - ✓ Industrial Processes: Providing high-temperature heat for direct use in manufacturing and processing.
  - ✓ Transportation: Propelling vehicles

1. Power Generation

- The goal is to convert the chemical energy in fuel into mechanical energy (shaft work) and then into electrical energy.

4. Applications

Cont…

Application in Major Power Generation Power Plant Types

- Steam Power Plants (Rankine Cycle)
  - ✓ Fuel is combusted in a large boiler. The heat generated converts water into high-pressure steam.
- Gas Turbine Power Plants (Brayton Cycle)
  - ✓ Air is compressed, mixed with fuel, and combusted internally in a combustion chamber.
- Combined Cycle Gas Turbine (CCGT) Plants
  - ✓ Exhaust heat from a gas turbine (Brayton Cycle) is used to generate steam in a Heat Recovery Steam Generator (HRSG). This steam then drives a steam turbine (Rankine Cycle).

4. Applications

Cont…

Application in Major Power Generation Power Plant Types

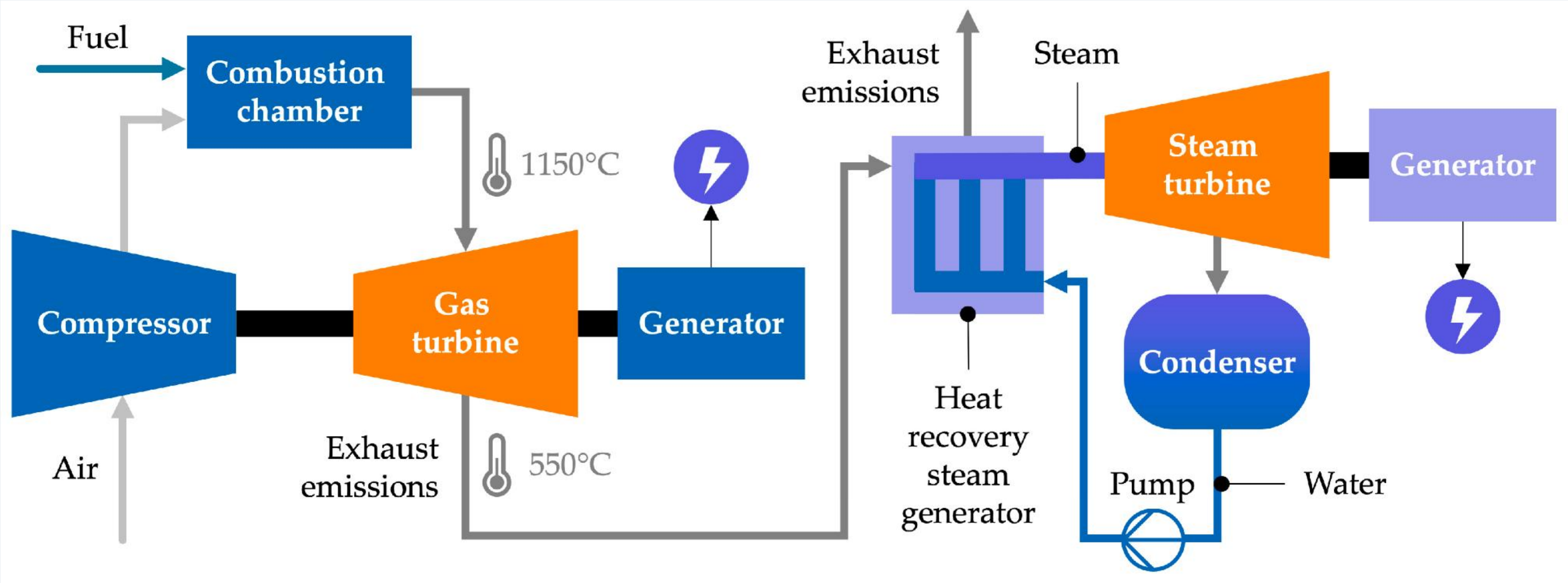

Figure 3: Combined Cycle Gas Turbine (CCGT) Plants, Matos, D., Lassio, J. G., Garcia, K. C., Raupp, I., Medeiros, A. M., & Abreu, J. L. S. (2024)
url: https://www.mdpi.com/gases/gases-04-00018/article_deploy/html/images/gases-04-00018-g002.png

4. Applications

2. Industrial Processes

The heat from combustion is used directly for process heating, often at very high temperatures.

Application in Major Industrial Process Power Plant Types

- Cement Manufacturing
  - ✓ Raw materials (limestone, clay) are fed into a long, rotating kiln heated to ~1450°C.
  - ✓ This causes a chemical reaction (calcination) to form clinker.
- Metal Production (e.g., Steel in a blast furnace)
  - ✓ Iron ore, coke, and limestone are loaded into the top of a blast furnace.

4. Applications

Cont…

- Glass Manufacturing
  - ✓ Raw materials (silica sand, soda ash, limestone) are melted in a regenerative furnace at temperatures around 1700°C.
- General Process Heating
  - ✓ Boilers for steam, furnaces for heat treatment of metals, drying ovens for food and materials, refinery heaters.

3. Transportation

Transportation systems rely heavily on fuels and combustion processes to power vehicles, aircraft, ships, and trains.

4. Applications

Cont…

Application in Major Transportation Systems

- Road Transport
  - ✓ Petrol and diesel are primary fuels.
  - ✓ Combustion in internal combustion engines (ICEs).
- Aviation
  - ✓ Refined kerosene-based fuels.
  - ✓ Combustion in gas turbine jet engines.
- Marine Transport
  - ✓ Uses heavy fuel oil or marine diesel.
  - ✓ Combustion in large marine diesel engines.

4. Applications

Cont…

The Future: Transition and Innovation of the Transportation Systems

- **Transition to Low-Carbon Fuels:** Switching from coal to natural gas, and incorporating biofuels (e.g., biodiesel, ethanol).
- **Hydrogen Combustion:** Hydrogen can be burned in turbines and engines, producing only water vapor (no CO_2) if produced using renewable energy ("green hydrogen").
- **Efficiency Improvements:** Advanced materials allow for higher operating temperatures, leading to more efficient engines and turbines, which use less fuel for the same output.

Summary

- Fuels are systematically classified by their physical state, origin, and characteristics like calorific value and volatility.
- Coal analysis is split into Proximate (practical, immediate qualities) and Ultimate (elemental chemical composition) to determine its quality and behaviour.
- Stoichiometry calculates the exact air-fuel ratio for complete combustion, which is critical for maximizing efficiency and minimizing pollutants.
- Experimental techniques like gas chromatography and infrared spectroscopy help identify combustion products
- Fuel selection for power, industry, and transport is a complex trade-off between properties like energy density, cost, handling, and environmental impact.

References

[1]. Power Plant Engineering, R.K. Rajput, 3rd Edition, 2011.

[2]. Combustion, Glassman, I., Yetter, R. A., & Glumac, N. G. (2014). (5th ed.). Academic Press.

[3]. An Introduction to Combustion: Concepts and Applications, Turns, S. R. (2012). (3rd ed.).

[4]. Gas Turbine Combustion: Alternative Fuels and Emissions, Arthur H. Lefebvre, Dilip R. Ballal (3rd Edition), CRC Press, 2010.

[5]. Non-intrusive optical diagnostics of co- and counter-swelling flames in a dual swirl pulverized coal combustion burner. Sung, Y., & Choi, G. (2016). Fuel, 174, 76-88. https://doi.org/10.1016/j.fuel.2016.01.014

[6]. Fuel Property Estimation and Combustion Process Characterization. Kiang, Y.-H. (2018), Academic Press.

Thank you !