1.1 Basic Concepts in Combustion

1.1.1 Fuels

- gaseous:
  - natural gas: light hydrocarbons, CO$_2$, N$_2$
  - other gases: CO, H$_2$

- liquid:
  - petroleum - hydrocarbons, small amounts of O, N, ash
  - others - alcohols, biodiesel (alkyl esters), bio-oil (acids, aldehydes, phenols, etc)
1.1.1 Fuels

- solid:
  - coal - essentially complex hydrocarbon, plus some O, N, ash and sulphur
  - wood, biomass - carbohydrates

Fuels contain C and H as the main combustible components, plus some O (small, except for biomass), N (small), S and ash (= minerals)
1.1.2 Reactions and Stoichiometry

Complete combustion
- all C converted to CO₂
- all H converted to H₂O

Incomplete combustion
- chain reactions cease before completion
- emission of intermediate products: CO
  (first to appear and most common),
  unburned hydrocarbons, aldehydes, soot
1.1.2 Reactions and Stoichiometry

Stoichiometric Combustion
- exact match between fuel and oxygen
- complete combustion with no oxygen left over
- only products CO$_2$, H$_2$O, and N$_2$ (from air)

Excess Air
- in practice, complete combustion can only be achieved with some excess of oxygen
- typically 10 -30% more than stoichiometric
- also called lean combustion (fuel-lean)
1.1.2 Reactions and Stoichiometry

Fuel-rich combustion
- excess of fuel (i.e. deficit of air)
- always results in incomplete combustion

In theory, the optimal efficiency of a combustion system would be achieved with stoichiometric air. In practice, deficiencies in mixing result in some incomplete combustion with stoich. air. The practical optimum therefore occurs with a small excess air.
1.1.2 Reactions - Pollutants

CO and other products of incomplete comb’n
- remedy: increase excess air, improve mixing, avoid quenching of flame on cold surfaces

\[ \text{NO}_x (= \text{NO} + \text{NO}_2) \]
- formed by high temperatures with high oxygen concentrations
- thermal \text{NO}_x - from \text{N}_2 + \text{O}_2 \text{ in air}
- “prompt” \text{NO}_x - from chain reactions of HC’s
- fuel \text{NO}_x - from N compounds in fuel
1.1.2 Reactions - Pollutants

**NO\textsubscript{x}**
- remedy (for all three): reduce temperatures and oxygen concentrations
- problem: this increases incomplete comb’n!
- solutions: two stage comb’n
  - exhaust gas recirculation

**SO\textsubscript{2}** (further oxidizes to SO\textsubscript{3} \rightarrow sulphuric acid)
- remedy: clean up gas after combustion (scrubber)
1.1.2 Reactions - Pollutants

soot (small carbon particles)
- formed by pyrolysis (thermal decomposition) of hydrocarbon vapour
- formed when fuel vapour is heated in absence of oxygen
- favoured by fuel-rich comb’n
- very important for radiation heat transfer
- soot gives flames yellow colour
1.1.3 Classification of Combustion

Premixed Combustion
- air and fuel completely mixed before reaction initiated
- flame propagates through mixture

**Diagram:**
- Burnt gases (products)
- Unburnt mixture
- Reaction zone (flame front)
- Flame motion
- Temperature
- Heat conduction, active species diffusion
1.1.3 Classification of Combustion

Simple premixed burner
- based on jet ejector
- examples: Bunsen burner, gas stove, domestic furnace
1.1.3 Classification of Combustion

Premixed combustion

Other examples
- gasoline engines
- some accidental explosions
1.1.3 Classification of Combustion

**Diffusion Combustion**

- fuel and air enter process separately and are mixed at the flame front itself
- mixing and reaction happen at the same place and time
- “diffusion” refers to the mixing process
  - laminar diffusion
    - through random molecular motion
  - turbulent diffusion
    - through turbulent eddies (much faster)
1.1.3 Classification of Combustion

Diffusion Combustion

Example: simple gas jet flame
- visualize with smoke jet
- replace smoke with fuel

smoke moves out

air moves in
1.1.3 Classification of Combustion

Structure of simple jet diffusion flame

Diagram showing the flow of air and fuel with arrows indicating the direction of flow and the formation of products and heat.
1.1.3 Classification of Combustion

Structure of simple jet diffusion flame
1.1.3 Classification of Combustion

Example: liquid droplet diffusion flame

- liquids evaporate, vapour burns as gas
- flame provides heat for vaporization
1.1.3 Classification of Combustion

Example: wood or coal combustion
- gives off gases ("volatiles") when heated, which then burn
- carbon residue ("char") burns afterwards
1.1.3 Classification of Combustion

Example: solid char particle combustion

Applications of diffusion combustion:
- most industrial burners for gas, oil or coal
- Diesel and gas turbine engines
- accidental fires
- candles, matches
1.1.3 Classification of Combustion

Diffusion vs. kinetic control of rate

Diffusion controlled combustion:

Chemical reaction rate $>>$ rate of diffusion

- diffusion limits supply of reactants, therefore diffusion, not kinetics, controls overall rate of reaction
- can approximate with infinitely fast reaction
- examples: most practical diffusion combustion processes (gas jet flames, droplets, sprays)
1.1.3 Classification of Combustion

**Diffusion vs. kinetic control of rate**

**Kinetically controlled combustion:**

Chemical reaction rate $\ll$ rate of diffusion

- diffusion supplies reactants much faster than reaction can consume them - therefore kinetics controls overall rate of reaction
- examples: ignition, low-temp. char combustion
- can sometimes approximate by ignoring diffusion, but often diffusion remains important