Fuel Analysis and Burning Characteristics
Fuel Analysis and Burning Characteristics - Terms and Concepts

- Particle burning stages: drying - devolatilization – char
- Proximate & ultimate analysis
- Heating value
- Biofuels vs coals
- H and O in Fuels: H/C vs O/C diagram
Single Particle Burning of Polish Coal – 271.4 mg

800 °C

21% O₂ (air)

Burning in open furnace and the sample on a hook
Polish Coal Particle – 271 mg
Polish Coal Particle Residue after Burning
Single Particle Burning of Wood – 92.6 mg

800 °C
21 % O₂ (air)
Wood Sample Before Burning
Combustion of Solid Fuel Particles – Stages of Burning

Fuel particle → Drying → Pyrolysis/devolatilisation and gas combustion → Char combustion → Ash

Reactants: $H_2O$, $O_2$, $C_xH_y$, CO, CO$_2$, H$_2$O, $O_2$

Products: CO, CO$_2$, H$_2$O

Air
Single Particle Burning System

(Source: Åbo Akademi)
Single Particle Burning – On-line CO$_2$ Analysis

![Graph showing CO$_2$ formation over time with peaks indicating pyrolysis and char combustion.](image-url)
Single Particle Burning – Volatile vs. Char Carbon

The graph illustrates the release of CO₂ (ppm) over time during the burning process. It shows two distinct phases:

1. **Volatile carbon** release: This phase is characterized by a rapid increase in CO₂ concentration, peaking early and then rapidly decreasing. It is associated with the volatile components of the particle that are released initially.

2. **Char carbon** release: This phase follows the volatile carbon release and continues to release CO₂ over a longer period. It is associated with the char (residues) of the particle that slowly decomposes over time.

The graph effectively highlights the differences in the release profiles of volatile and char carbon during the burning process.
Magazine Paper Waste

- Standard fuel analysis
  - C 32,1 %
  - H 4,5 %
  - N 0,1 %
  - S 0,2 %
Burning Stages
Combustion of Solid Fuel Particles – Stages of Burning

- **Fuel particle**
- **Drying**
- **Pyrolysis/devolatilisation and gas combustion**
- **Char combustion**
- **Air**
- **CO, CO₂, H₂O**
- **CₓHᵧ**
- **O₂**
- **CO, CO₂**
- **H₂O**
- **Ash**
Drying

- Heat from surrounding atmosphere leads to vaporization of water in fuel
- Rate determined by heat transfer
Devolatilization/Pyrolysis

- Terms which can be used interchangeably
- Thermal break-down of fuel during heating
- Results in release of volatile organic gases
- Volatile gases: CH$_4$, CO, H$_2$, C$_x$H$_y$, tars, …
- Burns with visible flame (soot)
Volatile Yield

• At a given T & P
• Fuel dependent

• INCREASES WITH:
  • Increasing H/C ratio of fuel
    (example. wood vs. coal)
  • Increasing Temperature

• DECREASES WITH:
  • Increasing Particle/Droplet Size
  • Increasing Pressure
Char combustion

- Heterogeneous reaction (gas-solid)
- Rate dependent on pO2 and T
- Usually slower than pyrolysis
- No visible flame
Solid Fuels: Proximate Analysis

- Water
- Volatile Matter
- Char (Fixed Carbon)
- Ash
Proximate Analysis

1. **MOISTURE/WATER**: Dry a weighed sample of fuel at 105-115 °C & 1 atm.

2. **VOLATILES**: Heat up the dried fuel to a defined temperature and pressure (600-1000 °C, 1-10 bar) in an inert gas atmosphere (N₂, Ar). Weigh sample after thermal treatment.

3. **ASH**: Combust the remaining fixed carbon (CHAR) structure and weigh the residue (=ash).
Abbreviations/Terms

- **d = dry**: all water is removed
  \[ \text{dm = dry matter} \]

- **ad = air dry**: the amount of water in fuel is in balance with water content of surrounding gas (air) atmosphere

- **ar = as received**: principally equal to "as fired" condition of fuel

- **daf = dry and ash free**: the combustible fraction of fuel

- **Fuel ratio**: \( \frac{X_{\text{FC}}}{X_{\text{VOL}}} \)
  
  \[ X_i: \text{Wt. fraction of } i \]
  
  \[ \text{FC: Fixed Carbon} \]
  
  \[ \text{VOL: Volatiles} \]
Summary of terms and concepts for analysis of solid fuels

Fuel

- air dry (ad)
- as received (ar)

Dry matter (dm)
- dry (d)

Moisture

Drying

Pyrolysis/devolatilization

Char combustion

Combustion

Moisture + Volatiles + Fixed carbon + Ash = Proximate Analysis
Ultimate/elemental Analysis

• Ultimate analysis:
  Fuel elemental composition C, H, S, N (& O)

• Elemental analysis:
  Ash forming matter (AFM) elements
  as such: Si, Ca, Mg, K...
  or
  as their typical oxides: SiO₂, CaO, MgO, K₂O...
Summary of terms and concepts for analysis of solid fuels

Fuel
- Air dry (ad)
- As received (ar)

Dry matter (dm) - Dry (d) - Moisture

Drying

Pyrolysis/devolatilization

Combustion
Char combustion

Combustible matter (daf)
- Volatiles
- Fixed carbon
- Ash

Ultimate/elemental Analysis

Combustible matter = Proximate Analysis

Moisture + Volatiles + Fixed carbon + Ash = Proximate Analysis
### Exercises

1) Identify which information in given fuel analysis is from:
   a) Proximate analysis?
   b) Ultimate/elemental analysis?

2) What is the amount of fixed carbon for respective fuel as (% (d))

3) What is the difference in (% (d)) between ash and AFM?

<table>
<thead>
<tr>
<th>Fuel</th>
<th>1 (MJ/kg (d))</th>
<th>2 (MJ/kg (d))</th>
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<tbody>
<tr>
<td>Moisture</td>
<td>% (ar) 11.1</td>
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<td>Dry matter</td>
<td>% (ar) 88.9</td>
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<tr>
<td>Ash</td>
<td>% (d) 11.5</td>
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<td>Volatiles</td>
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<td>Carbon</td>
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<td>Nitrogen</td>
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<td>Magnesium</td>
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<td>CO3 g/kg (d) 10</td>
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<tr>
<td>sum</td>
<td>g/kg (d) 68.09</td>
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</tbody>
</table>
van Krevelen diagram

Increased Heating Value

Wood
Lignin
Cellulose
Anthracite
Lignites
Coals

Biomass
Peat
Lignite
Coal
Anthracite

Atomic H : C Ratio x 10

Atomic O : C Ratio
Coalification Process

Decaying vegetation

Peatification: Bacterial and fungal decay in a water saturated anaerobic environment

Peat

Lignification:
Air oxidation followed by decarboxylation (-COOH → CO₂ (g)) and dehydration (H₂O split off)

Lignite/Brown Coal

Bituminisation: Continued decarboxylation

Bituminous Coal

Anthracitisation:
Condensation of small aromatic ring systems to larger ones and Dehydrogenation (H₂ split off)

Anthracite Coal

(Graphite)
*It takes an ~100m deep pile of decaying plant material to make a 1m deep seam of coal

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Mean Age (x10^6 yrs)</th>
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<tr>
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<td>Bituminous</td>
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<td>Sub-bituminous</td>
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<td>Lignite</td>
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<tr>
<td>Peat</td>
<td>&lt;1</td>
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Heating Values
Storage for Solar Energy

$CO_2 + H_2O \xrightarrow{hv} CH_2O + O_2$
Energy release during combustion

• In combustion energy is first put into the fuel/oxidizer mixture to initiate the reaction by breaking the first bonds and forming the first radicals.

• During combustion, new/stronger bonds are formed, releasing energy.

• This released energy/unit of fuel combusted is called the Heating Value (HV).

*can also be called ”calorific value” or ”energy value”
Heating value can be approximated for fuels with well defined structure

Estimating the HV of gases with Average Bond Energies

\[ \Delta H_{\text{comb}} = \sum \text{Energy of Bonds Broken} - \sum \text{Energy of bonds formed} \]

(Remember: bond energies given are average values for gas molecules)

The structure of most solid fuels is not well known
→ In practical cases: Heating value determined experimentally

Calorimetric determination of HHV
1) Known heat capacity \( C \) (Joule/Kelvin) for system
2) Combust known amount of fuel (\( m_{\text{fuel}} \))
3) Register temperature rise (\( \Delta T \)) of system
4) \( \text{HHV} = (C \cdot \Delta T)/m_{\text{fuel}} \)
• **Lower Heating Value (LHV):**
  – C,H,S -> CO2, H2O, SO2
  – Water assumed to be as vapor in flue gas (like in many real cases)
  – Also called the ”net” heating value
  – Commonly used in Europe

• **Higher Heating Value (HHV):**
  – Includes the energy from condensed water vapor and fully oxidized components of fuel
  – Also called ”gross” heating value
  – Commonly used in North-America
Lower vs Higher Heating Value

LHV = HHV – Heat to vaporise H₂O

H₂O: fuel moisture + H₂O formed from H in fuel

• HHV is obtained from fuel analysis (calorimeter)
• HHV determined for dry fuel (MJ/kg dry fuel)
  • HHV converted to LHV
Lower vs Higher Heating Value

LHV = HHV − Heat to vaporise H$_2$O

H$_2$O: fuel moisture + H$_2$O formed from H in fuel

\[
\text{LHV/kg dry fuel} = \frac{\text{LHV}}{\frac{\text{MJ}}{\text{kg dry fuel}}} - \left( \frac{\text{HHV}}{\frac{\text{MJ}}{\text{kg dry fuel}}} - \left( \frac{18}{2} \frac{w_H}{\frac{\text{kg H}}{\text{kg dry fuel}}} \right) \frac{H_{\text{vaporisation}}^{H_2O}}{\frac{\text{MJ}}{\text{kg H}_2O}} \right)
\]

LHV/kg wet fuel

HHV/kg wet fuel

Moisture

H$_2$O formed from H

2.26 MJ/kg H$_2$O

\[
\text{LHV/kg dry fuel} = \frac{\text{HHV}}{\frac{\text{MJ}}{\text{kg dry fuel}}} - \left( \frac{18}{2} \frac{w_H}{\frac{\text{kg H}}{\text{kg dry fuel}}} \right) + \frac{w_{H_{\text{vaporisation}}}^{H_2O}}{\frac{\text{MJ}}{\text{kg H}_2O}}
\]

LHV/kg wet fuel

HHV/kg wet fuel

Moisture

H$_2$O formed from H

2.26 MJ/kg H$_2$O
Comparison of fuel properties

- Higher Heating Value, MJ/kg (d)
- Volatile matter, % (d)

Coal
Brown coal
peat
Wood

- H is hydrogen content wt-%(daf)
- C is carbon content wt-%(daf)

Ekman, E., Kiinteiden polttoaineiden koostumus ja muut ominaisuudet, VTT
## Exercises

1) Identify which information in given fuel analysis is from:
   a) Proximate analysis?
   b) Ultimate/elemental analysis?

2) What is the amount of fixed carbon for respective fuel as (% (d))

3) What is the difference in (% (d)) between ash and AFM?

4) Use the graph showing comparison of fuel properties to determine the type (wood, peat, brown coal, coal) of respective fuel (1 and 2).

### Fuel Analysis Table

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<tr>
<th>Fuel</th>
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<td>Moisture</td>
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### EXAMPLES OF FUEL COMPOSITION

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<th>Nitrogen</th>
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The fuel properties are decisive for the design of equipment

- Proximate and elemental analyses → amounts of air and combustion products

- Energy content (moisture) and volatiles → heat balance and combustion behaviour

- Precursors to gaseous emissions (N,S,Cl)

- Ash-forming elements (K,Na,Ca,Mg,Al,Si,P)

- Trace elements (Cd,Tl; Hg; Sb,As,Pb,Cr,Co,Cu, Mn,Ni,V;....)
Fuel Analysis and Burning Characteristics - Terms and Concepts

- Particle burning stages: drying - devolatilization – char
- Proximate & ultimate analysis
- Heating value
- Biofuels vs coals
- H and O in Fuels: H/C vs O/C diagram