PARTICULATES #1

- Introduction
- Ash-forming elements in fuels
- Particulate emission standards
- Options for particulate control emissions
- Gravity settlers
- Gas cyclones
- Electrostatic precipitators

see: www.hut.fi/~rzevenbo/gasbook
Particulate (emissions) control: why?

• Regulations considering environmental / health hazard
  • Protection of gas turbines / expansion turbines
  • Protection / avoid problems with other gas clean-up equipment

• The particulate solid or the gas may be a valuable product
  • Dust explosion risks.
Ashes and solid residues during typical pulverised coal combustion
Typical size distribution for fly ash and bottom ash from pulverised coal combustion
Ash-forming elements and ash formation #1

Coalification

Mineral impurities during combustion or gasification
Ash-forming elements and ash formation #2

Pulverised coal combustion

Fluidised bed coal combustion
Ash-forming elements and ash formation #3

Biomass fuels
## Ash content of fuels (dry %wt)

<table>
<thead>
<tr>
<th>Fossil fuels</th>
<th>Biomasses &amp; waste derived fuels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal, lignite</td>
<td>Wood</td>
</tr>
<tr>
<td>5 - 40</td>
<td>0.1 - 0.5</td>
</tr>
<tr>
<td>Oil</td>
<td>Bark</td>
</tr>
<tr>
<td>&lt; 0.1</td>
<td>2 - 8</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Straw</td>
</tr>
<tr>
<td>-</td>
<td>4 - 8</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>Sewage sludge</td>
</tr>
<tr>
<td>&lt; 0.01</td>
<td>15 - 20</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>Car tyre scrap</td>
</tr>
<tr>
<td>~0.04</td>
<td>5 - 8</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>Munical solid waste (MSW)</td>
</tr>
<tr>
<td>&lt; 0.01</td>
<td>5 - 25</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>Refuse derived fuel (RDF)</td>
</tr>
<tr>
<td>~0.04</td>
<td>10 - 25</td>
</tr>
<tr>
<td>Peat</td>
<td>Packaging derived fuel (PDF)</td>
</tr>
<tr>
<td>4 - 10</td>
<td>5 - 15</td>
</tr>
<tr>
<td>Petroleum coke, “petcoke”</td>
<td>Auto shredder residue (ASR)</td>
</tr>
<tr>
<td>~1</td>
<td>~25</td>
</tr>
<tr>
<td>Estonian oil shale</td>
<td>Leather waste</td>
</tr>
<tr>
<td>~40</td>
<td>~5</td>
</tr>
<tr>
<td>Orimulsion™</td>
<td>Black liquor solids</td>
</tr>
<tr>
<td>~1.5</td>
<td>30 - 40</td>
</tr>
</tbody>
</table>

Problem: “Ash content of fuel” $\iff$ Ash forming elements $\Rightarrow$ Fly ash, bottom ash
# Ash production from western US coal combustion in a 500 MW\textsubscript{elec} pulverised coal power plant

<table>
<thead>
<tr>
<th></th>
<th>Bituminous</th>
<th>Wyoming Powder River Basin</th>
<th>Montana Powder River Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal ash content, %-wt</strong></td>
<td>9.5</td>
<td>4.8</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Bottom ash, ton/year</strong></td>
<td>24560</td>
<td>17280</td>
<td>8600</td>
</tr>
<tr>
<td><strong>Fly ash, ton/year</strong></td>
<td>98260</td>
<td>69100</td>
<td>34390</td>
</tr>
<tr>
<td><strong>Total ash, ton/year</strong></td>
<td>122820</td>
<td>86380</td>
<td>42990</td>
</tr>
<tr>
<td>Fuel</td>
<td>New / Existing*</td>
<td>Plant size (MW_{th})</td>
<td>Emission standard (mg/m³_{STP, dry})</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------</td>
<td>----------------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Solid</td>
<td>Existing</td>
<td>&lt; 500</td>
<td>100 @ 6% O₂</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&gt; 500</td>
<td>50 @ 6% O₂</td>
</tr>
<tr>
<td>Solid</td>
<td>New</td>
<td>50 - 100</td>
<td>50 @ 6% O₂</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&gt; 100</td>
<td>30 @ 6% O₂</td>
</tr>
<tr>
<td>Liquid</td>
<td>Existing</td>
<td>all</td>
<td>50 @ 3% O₂</td>
</tr>
<tr>
<td>Liquid</td>
<td>New</td>
<td>50 - 100</td>
<td>50 @ 3% O₂</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>&gt; 100</td>
<td>30 @ 3% O₂</td>
</tr>
<tr>
<td>Gas</td>
<td>Existing</td>
<td>all</td>
<td>5 @ 3% O₂</td>
</tr>
<tr>
<td>Gas</td>
<td>New</td>
<td>all</td>
<td>5 @ 3% O₂</td>
</tr>
</tbody>
</table>

* Existing = plant existing on Nov. 27, 2002; or license for new plant requested before that date and plant entering operation before Nov. 27, 2003
## Dust emission standards for waste (co-) firing and cement plants for EU (directive 2000/76/EC)

<table>
<thead>
<tr>
<th>Type of plant</th>
<th>Size (MW\text{th})</th>
<th>Emission standard</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste incineration</td>
<td>all</td>
<td>$10 \text{ mg/m}^3_{\text{STP}} @ 10 % \text{ O}_2$, dry *</td>
<td>Daily average</td>
</tr>
<tr>
<td>Cement, incl. co-firing</td>
<td>all</td>
<td>$30 \text{ mg/m}^3_{\text{STP}} @ 10 % \text{ O}_2$, dry</td>
<td></td>
</tr>
<tr>
<td>Waste co-firing, all fuels</td>
<td>&lt; 100</td>
<td>$C_{\text{process}} = 50 @ 6 % \text{ O}_2$, dry for solid fuels and biomass, $@ 3 % \text{ O}_2$, dry for liquid fuels</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 100</td>
<td>$C_{\text{process}} = 30 @ 6 % \text{ O}_2$, dry, for solid fuels and biomass, $@ 3 % \text{ O}_2$, dry, for liquid fuels</td>
<td></td>
</tr>
</tbody>
</table>

* Until 1.1.2008 special exemption to emit $20 \text{ mg/m}^3_{\text{STP}} @ 10 \% \text{ O}_2$, dry may be authorised

$$C_{\text{co-firing}} = \frac{V_{\text{waste}} \cdot C_{\text{waste}} + V_{\text{process}} \cdot C_{\text{process}}}{V_{\text{waste}} + V_{\text{process}}}, \quad V = \text{exhaust volume}$$
Removal of particulates from (flue) gases

1. Methods based on external forces
   - Gravity settlers
   - Cyclones & centrifuges
   - Electrostatic precipitators
   - Decreasing particle size

2. Methods based on barriers
   - Bag filters
   - Ceramic barrier filters
   - Granular bed filters
   - Wet scrubbers
Parameters determining particulate control

**Process**
- Temperature
- Pressure
- Gas flow
- Concentration

**Particle**
- Size distribution
- Shape
- Surface properties
- Chemical composition:
  - carbon content
  - alkali content
  - tar content
  - sulphur content
- Melting point, softening point
- Chemical stability
# Particulate removal efficiencies needed for various coal firing methods

<table>
<thead>
<tr>
<th>Boiler configuration</th>
<th>Uncontrolled emissions g/m³</th>
<th>Controlled emission limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 mg/m³</td>
<td>100 mg/m³</td>
</tr>
<tr>
<td>Pulverised coal</td>
<td>8–20</td>
<td>99.37–99.75</td>
</tr>
<tr>
<td>Spreader stoker</td>
<td>2–5</td>
<td>99.00–99.50</td>
</tr>
<tr>
<td>Chain grate stoker</td>
<td>1–3</td>
<td>95.00–98.30</td>
</tr>
<tr>
<td>Cyclone</td>
<td>0.5–1.5</td>
<td>90.00–96.67</td>
</tr>
</tbody>
</table>
Efficiencies of several particulate control devices

<table>
<thead>
<tr>
<th>Control device</th>
<th>Removal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;1 μm</td>
</tr>
<tr>
<td>High efficiency ESP</td>
<td>96.5</td>
</tr>
<tr>
<td>Fabric filter</td>
<td>100</td>
</tr>
<tr>
<td>Venturi scrubber</td>
<td>&gt;70</td>
</tr>
<tr>
<td>Multicyclones</td>
<td>11</td>
</tr>
</tbody>
</table>
An inertial separator: a settling chamber
A gas cyclone

more than a useful pre-separator?

Advantages
Simple, cheap and compact
Large capacity

Disadvantages
Large pressure drop
Low efficiency
“Catch” removal problems
No removal below ~5 μm
Problems above ~ 400 °C
Cyclones: processes determining separation
A “standard” cyclone (Lapple)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High efficiency</th>
<th>Conventional</th>
<th>High throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of inlet H/D</td>
<td>0.5 ~ 0.44</td>
<td>0.5</td>
<td>0.75 ~ 0.8</td>
</tr>
<tr>
<td>Width of inlet W/D</td>
<td>0.2 ~ 0.21</td>
<td>0.25</td>
<td>0.375 ~ 0.35</td>
</tr>
<tr>
<td>Diameter of gas exit De/D</td>
<td>0.4 ~ 0.5</td>
<td>0.5</td>
<td>0.75</td>
</tr>
<tr>
<td>Length of vortex finder S/D</td>
<td>0.5</td>
<td>0.625 ~ 0.6</td>
<td>0.875 ~ 0.85</td>
</tr>
<tr>
<td>Length of body Lb/D</td>
<td>1.5 ~ 1.4</td>
<td>2.0 ~ 1.75</td>
<td>1.5 ~ 1.7</td>
</tr>
<tr>
<td>Length of cone Lc/D</td>
<td>2.5</td>
<td>2</td>
<td>2.5 ~ 2.0</td>
</tr>
<tr>
<td>Diameter of dust outlet Dd/D</td>
<td>0.375 ~ 0.4</td>
<td>0.25 ~ 0.4</td>
<td>0.375 ~ 0.4</td>
</tr>
</tbody>
</table>
Removal efficiency for Lapple cyclone

Number of gas turns (i.e. revolutions) before entering the vortex finder:

\[
N = \frac{L_b + \frac{L_c}{2}}{H}
\]

Grade efficiency:

\[
Eff(d_p) = \frac{1}{1 + \left(\frac{d_{50}}{d_p}\right)^2}
\]

“Cut size”:

\[
d_{50} = \sqrt{\frac{9 \eta_{\text{gas}} W}{2\pi N V_{\text{in}} \left(\rho_{\text{solid}} - \rho_{\text{gas}}\right)}}
\]

Typical material properties:

- Dynamic gas viscosity:
  \[
  \eta_{\text{gas}} \approx 1.8 \times 10^{-5} (T/293)^{2/3} \text{ Pa.s}
  \]
- Densities:
  \[
  \rho_{\text{solid}} = \text{typically 500 ... 3000 kg/m}^3
  \]
  \[
  \rho_{\text{gas}} = 1.2 \text{ kg/m}^3 \text{ at 20°C, 1 bar (air)}
  \]
Forces on particles in cyclones

**Centrifugal force**

\[ m_p' \omega^2 r = m_p' v_t^2 / r \]

**Drag force (Stokes)**

\[ 3 \pi v_r d_p \eta_F \]

into cyclone with velocity \( v_i \), inlet area \( A \)

**Force balance gives equilibrium radial position:**

1. \[ m_p' v_t^2 / r = 3 \pi v_r d_p \eta_F \]
2. \[ v_r \approx v_i A / (2\pi r h) \]
   \( (h= \text{length of cylindrical section}) \)
3. \[ v_t r^n = v_i R^n, \quad n \sim 0.5 \ldots 0.55 \]
   gives

\[ (r/R)^n = \pi h \rho_s v_i d_p^2 / (9 A \eta_F) \]

for capture: large \( r/R \) needed
Advanced (?) gas cyclone designs

Cyclone with vortex collector pockets

Aerodyne rotary flow cyclone
Typical lay-out of a wire-and-plate ESP
**Electrostatic precipitators (ESPs)**

*Where (conventional pulverised coal combustion):

Before (wet) scrubber for SO₂ control

Before (hot side) or after (cold side) air preheat

Usually before SCR for DeNOx ("hot side, low dust")

Before (hot side) or after (cold side) air preheat

*Alternative:*

baghouse filter, because 1) higher efficiency and

2) less effect of particle electric properties

*4 process steps:*

1. Particle charging

2. Particle movement relative to gas flow

3. Particle collection at deposition surface

4. Particle removal from deposition surface (often discontinuous)
ESP: basic principle, efficiency
Tubular ESP:

**basic design features**

1 — discharge electrode; 2 — tensioning weight; 3 — suspension frame; 4 — suspension rod; 5 — insulator; 6 — suspension-rod sheath; 7 — guide (spacer) frame; 8 — collecting electrode; 9 — casing; 10 — inlet stub; 11 — outlet stub; 12 — hopper; 13 — inlet plenum chamber; 14 — outlet plenum chamber; 15 — dust discharge port.
Electric field in ESP, configuration factor

Electric field, $E$ (V/m), and electric potential, $\phi$ (V):

$$E = -\nabla \phi$$

Electric field as function of distance $x$ from wire:

$$E(x) = \frac{\Delta U}{x F}$$

$\Delta U$ = voltage difference
$F$ = “configuration factor of the electrode system”

wire-in-tube: $F = \ln \left(\frac{R}{r}\right)$
ESP configuration factor

a. Wire-in tube
b. Wire-plate
c. Multiple wire - plate

δ = d/r, i.e.
relative electrode spacing
An ESP
at Kotka Finland
ESP: particle charging #1, using corona discharge (uni-polar, one direction)

Diffusion charging
Small particles (< 1 µm)
charge \( q_{\text{max}} \sim 10^8 e d_p \)  Note: charge \( e = 1.6 \times 10^{-19} \) C

Field charging (Pauthenier (1932))
Larger particles (> 1 µm)
relative dielectric constant, \( \varepsilon_r \)
dielectric constant of vacuum, \( \varepsilon_0 = 8.854 \times 10^{-12} \) C/(V m)
charge \( q_{\text{max}} \sim 12 \pi E_1 d_p^2 \varepsilon_0 \varepsilon_r / (\varepsilon_r + 2) \)
E-field \( E_1 \) in charging zone \( \sim 3 \times 10^6 \) V/m
Classical particle charging theory calculations

PARAMETERS

Temperature
$T = 300 \text{ K}$

Ion concentration $\times$ time
$N_0 t = 10^{13} \text{ ions s/m}^2$

Ion mobility
$Z_i = 10^{-4} \text{ m}^2/\text{V/s}$

Ion velocity
$v_i = 100 \text{ m/s}$

Electric field
$E = 10^5 \text{ V/m or } 10^6 \text{ V/m}$

Rel. dielectric constant
$\varepsilon_r = 2 \text{ or } \varepsilon_r = 100$
ESP : particle charging #2, particle drift velocity

*Alternative methods for charging*:

1) Uni-polar (+ or -) : bi-polar corona
2) Uni-directional ↔ bi-directional field charging
3) Pulsed corona techniques
4) Impact (contact, tribo,...) charging

*Electrical mobility, \( v_e \), of charged particle, in \( E \)-field \( E_2 \sim 10^4 \) V/m:

\[
\text{Coulomb force} = \text{Stokes' drag force}
\]

\[
q_p E_2 \approx 3\pi v_e \eta_{\text{gas}} d_p, \quad \text{with } \eta_{\text{gas}} = \text{dynamic gas viscosity (Pa.s)}
\]

Result 1: diffusion charging : \( v_e \approx 10^8 e E_2 / (3\pi \eta_{\text{gas}}) \sim 0.01 \text{ m/s} \)

Result 2: field charging : \( v_e \approx E_1 E_2 \varepsilon_0 d_p / ( \eta_{\text{gas}}(\varepsilon_r + 2)) \sim 0.1 - 1 \text{ m/s} \)
ESP efficiency: Deutsch equation

Set-up: vertical gas flow, velocity $u_{\text{gas}}$, plate height $H$, spacing $D$

Mass balance for particle concentration, $c$:

$$u_{\text{gas}} D L \left( c_x - c_{x+\Delta x} \right) = v_e \frac{1}{2} \left( c_x + c_{x+\Delta x} \right) \Delta x L$$

= mass removed

$v_e =$ charged particle electrical mobility

$$\Rightarrow u_{\text{gas}} D \frac{dc}{dx} = - v_e c$$

Integrate, $c = c_\text{in}$ at $x = 0$, to position $x$:

$c(x) = c_\text{in} \exp \left( - v_e x / (u_{\text{gas}} D) \right)$

$c_\text{out} = c_\text{in} \exp \left( - v_e A / Q_{\text{gas}} \right) @ x = H$

for gas flow $Q$ (m³/s) and plate area $A = 2 LH$

(2 sides !!!!!)

Efficiency $\eta_{\text{ESP}} = 1 - \exp \left( - v_e A / Q_{\text{gas}} \right)$ Deutsch Equation

Corrected (Matts-Öhnfeldt): $\eta_{\text{ESP}} = 1 - \exp - (v_e A / Q_{\text{gas}})^k \quad k = 0.4...0.6$
ESP and fly ash resistivity

Fly ash sulphur, temperature

(300 °F ~ 150 °C, 200 °F ~ 95 °C, 450 °F ~ 220 °C)

Moisture
Particle resistivity and electric drift velocity
“Rebouncing” of particles with (too) high conductivity
Difficult conditions for ESP (→) and options for improvement (↓)

- Flue gas conditioning (to lower fly ash resistivity)
- Pulse energisation (allows more useful power to be applied to the ESP)
- Humidification (spraying water into the flue gas to lower its temperature and reduce fly ash resistivity and cohesivity)
- Optimising existing surface
- Mechanical upgrades (such as increasing the specific collection area by adding additional fields or increasing the plate height, if space limitations allow)

- Operation near maximum resistivity (temperature approximately 150–190°C)
- Critical bulk resistivity for incipient back corona
  - Cold-side ESP: 1-3 x 10^{10} ohm cm
  - Hot-side ESP: 2-5 x 10^{9} ohm cm

- Bituminous coal ash
  - Sulphur: Low ≤1%
  - SiO_2 + Al_2O_3: High >80%
  - Fe_2O_3: Low <5%
  - Na_2O: Low <0.5%

- Lignite ash
  - Sulphur: Low ≤1%
  - CaO + MgO > Fe_2O_3: By 3-6 times
  - Na_2O: Low <0.5%
  - Free lime: Available

- Low gas moisture 5-7% volume

- Boiler fouling – loss of Na_2O with lignitic ash and hot-side ESP
ESP performance in relation to fuel-sulphur: the effect of fuel switching

(PRB is coal from Powder River Basin, Western USA)
Catalyst: $V_2O_5 / K_2O$ on $SiO_2$ honeycomb
**Typical cold-side ESP for coal fly ash: design data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Power / collector area</th>
<th>Ash resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>120 - 200°C</td>
<td>~ 43 W/m²</td>
<td>10^4-10^7 ohm.cm</td>
</tr>
<tr>
<td>Gas flow velocity</td>
<td>1 - 3 m/s</td>
<td>~ 32 W/m²</td>
<td>10^7 - 10^8 ohm.cm</td>
</tr>
<tr>
<td>Gas flow / collector area</td>
<td>15 - 125 s/m</td>
<td>~ 27 W/m²</td>
<td>10^9-10^10 ohm.cm</td>
</tr>
<tr>
<td>Plate-to-plate distance</td>
<td>0.15 - 0.4 m</td>
<td>~ 22 W/m²</td>
<td>~10^11 ohm.cm</td>
</tr>
<tr>
<td>Electric drift velocity</td>
<td>0.02 - 2 m/s</td>
<td>~ 16 W/m²</td>
<td>~10^12 ohm.cm</td>
</tr>
<tr>
<td>Corona current / collector area</td>
<td>50 - 750μA/m²</td>
<td>~ 11 W/m²</td>
<td>~10^13 ohm.cm</td>
</tr>
<tr>
<td>Corona current / gas flow</td>
<td>0.05 - 0.3 J/m³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>