AIR CLEANING TECHNOLOGIES

PlasTEP training course and Summer school 2011
Warsaw / Szczecin
Saulius Vasarevicius, VGTU
Every place on Earth is an ecosystem, including our club site.
What is in the Air Around Us?

Particulates:
- Dust
- Salt spray
- Material from volcanoes
- Soot from forest fires
Two Types of Air Pollutants

Particulate (Visible)

Gaseous
Stationary Source Control

Philosophy of pollution prevention (3P’s)
• Modify the process: use different raw materials
• Modify the process: increase efficiency
• Recover and reuse: less waste = less pollution

Philosophy of end-of-pipe treatment
• Collection of waste streams
• Add-on equipment at emission points

Control of stationary sources
• Particulates
• Gases
Three Types Of Control

- Mechanical
- Chemical
- Biological
Particulates

Regulated Particles

• 10 microns or less diameter
  – Human hair averages 25 microns
  – 25 microns is 1/1000 inch
Example Sources Of Particulate Pollution

- Wood Processing
- Rock Quarries
- Coal Power Plants
Particulate Control (Mechanical)

- Electrostatic precipitator
- Bag house fabric filter
- Wet scrubber
- High efficiency cyclones
Particulate Control Technologies

Remember this order:

- Settling chambers
- Cyclones
- ESPs (electrostatic precipitators)
- Spray towers
- Venturi scrubbers
- Baghouses (fabric filtration)

All physical processes
FIGURE 21-8. Comparison of removal efficiencies: (A) baffled settling chamber, (B) cyclone “off the shelf,” (C) carefully designed cyclone, (D) electrostatic precipitator, (E) spray tower, (F) venturi scrubber, (G) bag filter
Settling Chambers

- “Knock-out pots”
- Simplest, cheapest, no moving parts
- Least efficient
- Large particles only
- Creates solid-waste stream
- Can be reused
- Picture on next slide
Fig. 6.1. Simple gravity settling chamber.
Disadvantages

Large space requirement

Relatively low overall collection efficiencies (typical 20 - 60 %)
# Flue Gas Cleaning – The state of the art

## Selection criteria

<table>
<thead>
<tr>
<th></th>
<th>ESP</th>
<th>Bag house</th>
<th>Scrubber</th>
<th>Cyclones (normal)</th>
<th>Spraycone Cyclones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission mg/Nm³</td>
<td>100</td>
<td>30</td>
<td>200</td>
<td>250</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Reliability</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>++++</td>
<td>++++</td>
</tr>
<tr>
<td>Cost</td>
<td>++++</td>
<td>++++</td>
<td>+++</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
Evaluation of ESP for industrial boilers:
- High cost (investment, maintenance & operation)
- Complex large size plant with sub-systems
- Requires constant gas conditions (sulphur, temp, moisture)

Evaluation of bag filters for industrial boilers:
- High cost (investment, maintenance & filter bags)
- Difficult to handle sulphur and sparks
- Not robust (one faulty bag destroys efficiency)

Evaluation of wet scrubbers for industrial boilers:
- High cost (large water treatment plant)
- Difficult to separate fine particulate
- Sulphur control costly & difficult
Flue Gas Cleaning – The state of the art

Evaluation of cyclone “grid arrestor”:

- Low collection efficiency due to:
  - Wrong design (see velocity analysis)
  - Air ingress
  - Bad manufacturing quality
  - Lack of maintenance (blockage of cyclone cells)

But cyclone system advantages are low cost and robust installation

**Can a cyclone reach efficiencies of ESP / Bag filter / Wet scrubber?**

This question triggered our cyclone development Program in 1994 to improve cyclone efficiency and to invent the “dry spray agglomeration principle”
Cyclone

- Most Common
- Cheapest
- Most Adaptable
CYCLONES

Principle

- The particles are removed by the application of a centrifugal force. The polluted gas stream is forced into a vortex. the motion of the gas exerts a centrifugal force on the particles, and they get deposited on the inner surface of the cyclones.

Overall collection $\eta$

$$\eta(\%) = \frac{C_i - C_o}{C_i}$$

$C_i \rightarrow$ inlet concentration

$C_o \rightarrow$ outlet concentration
Construction and Operation

The gas enters through the inlet, and is forced into a spiral.

- At the bottom, the gas reverses direction and flows upwards.
- To prevent particles in the incoming stream from contaminating the clean gas, a vortex finder is provided to separate them. The cleaned gas flows out through the vortex finder.
Advantages of Cyclones

• Cyclones have a lost capital cost
• Reasonable high efficiency for specially designed cyclones.
• They can be used under almost any operating condition.
• Cyclones can be constructed of a wide variety of materials.
• There are no moving parts, so there are no maintenance requirements.
Mechanical Collectors – Cyclones

Advantages: Good for larger PM

Disadvantages: Poor efficiency for finer PM

Difficult removing sticky or wet PM
Figure 4.3  General relationship of collection efficiency versus particle size for cyclones.

NOTE: Efficiency versus size curves represent broad generalizations, not exact relationships.
Cyclone Operating Principle

“Dirty” Air Enters The Side.
The Air Swirls Around The Cylinder And Velocity Is Reduced.
Particulate Falls Out Of The Air To The Bottom Cone And Out.
\[ d_{0.5} = \left[ \frac{9 \mu B^2 H}{\rho_p Q_g \theta} \right]^{\frac{1}{2}} \]

\[ \theta = \frac{\pi}{H} \left( 2L_1 + L_2 \right) \]

d_{0.5} = \text{cut diameter at 50% removal}
m = \text{dynamic viscosity of gas, Pa-s}
B = \text{width, m}
H = \text{height, m}
r_p = \text{particle density, kg/m}^3
Q_g = \text{gas flow rate, m}^3/\text{s}
q = \text{effective number of turns}
Cyclone Grade Efficiency

High Efficiency Cyclones
2 x HE 750
Barel Ø 750 mm
11,800 am ³/h
200 °C
Ex. 6-9

Given:
\( D_2 = 0.5 \) m
\( Q_g = 4 \) m\(^3\)/s
\( T = 25 \) °C
\( r_p = 800 \) kg/m\(^3\)

\( Q \) = What is the removal efficiency for particles with ave diameter of 10 mm?

\[ d_{0.5} = \left[ \frac{9(18.5 \times 10^{-6})(0.13)^2 (0.25)}{(800)(4)(37.7)} \right]^{0.5} = 2.41 \times 10^{-6} \]

\[ d = 10 \text{ mm} \]

\[ \frac{d}{d_{0.5}} = \frac{10}{2.41} = 4.15 \]

For standard Cyclone:
\( B = 0.25 \) \( D_2 = 0.13 \) m
\( H = 0.5 \) \( D_2 = 0.25 \) m
\( L_1 = L_2 = 2 \) \( D_2 = 1 \) m

\[ \theta = \frac{\pi}{0.25} \left( 2(1) + 1 \right) = 37.7 \]

\[ h = 0.95 \]
Flue Gas Cleaning – The state of the art

History:

1975 - 1980 work with Prof. Stairmond (UK)
Cyclones for coal fired gas turbine 80 MW PFBC

1993 – 1998
basic research in
cyclone technology

**CyDesign** - Cape Town
development center
Flue Gas Cleaning – The state of the art

On site technology studies & testing:

JTA boiler training center

Glass melting furnace
Commercial applications of high efficiency cyclones:

BurnerMax
Fluidized bed furnace
High efficiency cyclones operating at 400 C
Flue Gas Cleaning – The state of the art

Project 1996 / 97
30 year old Büttner solid fired wood chip dryer equipped with low efficiency cyclone. Emission > 650 mg / Nm$^3$

Solution:

Step 1 = retrofitting of high efficiency cyclones

Reduction of emission to < 100 mg / Nm$^3$

First idea of agglomeration spray in 1997

Step 2 = installation of THERMAX agglomeration sprays upstream of cyclones

Reduction of emission to < 20 mg / Nm$^3$
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High efficiency cyclone plant with fully evaporative fine agglomeration sprays (Installation 1997)

Efficiency > 99 %

Emission < 20 mg / Nm³
Flue Gas Cleaning – The state of the art

What is the agglomeration spray?

- Water spray with very fine droplets
- Fully evaporative (dry system)
- Droplets capture small particles
- and agglomerate them
- Larger particles are easily collected

Typical water consumption
30 liter / t steam generation
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Case study:

Wet scrubber installed at a 130 t/h JTA water-tube boiler

Inlet conditions:

• 5000 mg / Nm$^3$
• 5 % (250 mg / Nm$^3$) < 5 micron
• Emission > 300 mg / Nm$^3$
• Required 120 mg / Nm$^3$
Flue Gas Cleaning – The state of the art

Solution: Installation of 3 horizontal “spraytrees”

- Water consumption minimal.
- Fully evaporative
- Final emission < 100 mg / Nm³
Current *CyDesign* specifications for advanced cyclone technology:

Integrated cyclone system with fully evaporative agglomeration water spray (20 l / h per cyclone)

To provide a robust, economic, low maintenance, very high performance, flue gas cleaning system
Cyclone parts are manufactured to high precision as erosion & corrosion resistant castings.

Cyclone vortex blade ring with pressure recovery.

Wax dies

Castings
Cyclone Separator - Cheap

Dirty gas

Cleaned gas

Does NOT produce hazardous materials like other

Dust discharge
Multiple Cyclones (Multi clone)

Smaller Particles Need Lower Air Flow Rate To Separate.

Multiple Cyclones Allow Lower Air Flow Rate, Capture Particles to 2 microns
Air Filtration
Q: How does efficiency change with respect to $d_p$?
   a. Efficiency goes up as $d_p$ decreases
   b. Efficiency goes down as $d_p$ decreases
Q: How does efficiency change with respect to $d_p$?

a. Efficiency goes up as $d_p$ decreases

b. Efficiency goes down as $d_p$ decreases
Interception

Gas streamlines

Interception

Center line

Cross section of fiber

Fat Man’s Misery, Mammoth Cave NP
Filter efficiency for individual mechanism and combined mechanisms

<table>
<thead>
<tr>
<th>dp (μm)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- Interception
- Impaction
- Diffusion
- Gravitation
- Total
Q: Do filters function just as a strainer, collecting particles larger than the strainer spacing?

a: yes
b: no

Fiber filter
Drag Model

\[ \Delta P = \Delta P_f + \Delta P_p (\Delta P_s) \]

\[ = K_1 V + K_2 (LVt)V \]

Areal Dust Density

\[ W = LVt \]

Filter drag

\[ S = \frac{\Delta P}{V} \]

\[ \Rightarrow S = K_1 e + K_2 W_s \]

\[ K_e \text{ & } K_s \text{ to be determined empirically} \]

\[ DP_f: \text{ fabric pressure drop} \]
\[ DP_p: \text{ particle layer pressure drop} \]
\[ DP_s: \text{ structure pressure drop} \]

**Q: What is the pressure drop after 100 minutes of operation?**

L = 5 g/m³ and V = 0.9 m/min.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>ΔP, Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>380</td>
</tr>
<tr>
<td>10</td>
<td>505</td>
</tr>
<tr>
<td>20</td>
<td>610</td>
</tr>
<tr>
<td>30</td>
<td>690</td>
</tr>
<tr>
<td>60</td>
<td>990</td>
</tr>
</tbody>
</table>
Case A: Pore blocking
Case B: Pore plugging
Case C1: Pore narrowing
Case C2: Pore narrowing w/lost pore
Case D: Pore bridging
Air Filtration

- Impaction
- Diffusion
- Straining (Interception)
- Electrostatics
Air Filter

- High removal efficiency for < 5 μm particles
Cleaned gas

Dirty gas

Baghouse Filter – only one to remove hazardous fine particles

Dust discharge

Bags
Advantages/Disadvantages

• Very high collection efficiencies
• Pressure drop reasonably low (at beginning of operation, must be cleaned periodically to reduce)
• Can’t handle high T flows or moist environments
Fabric Filters / Baghouses

Advantages: Good efficiency for various sizes of particles

Disadvantages: Not to be used around corrosive substances, explosive gases, or sticky and wet particles
**DESIGN OF FABRIC FILTERS**

- The equation for fabric filters is based on Darcy’s law for flow through porous media.
- Fabric filtration can be represented by the following equation:
  \[ S = K_e + K_s W \]
  Where,
  \( S \) = filter drag, N-min/m\(^3\)
  \( K_e \) = extrapolated clean filter drag, N-min/m\(^3\)
  \( K_s \) = slope constant. Varies with the dust, gas and fabric, N-min/kg-m
  \( W \) = Areal dust density = LVt, where
  \( L \) = dust loading (g/m\(^3\)), \( V \) = velocity (m/s)
- Both \( K_e \) and \( K_s \) are determined empirically from pilot tests.
Fabric Filters

\[ \Delta P = \Delta P_f + \Delta P_p + \Delta P_s \]

\( \Delta P \)  Total pressure drop

\( \Delta P_f \)  Pressure drop due to the fabric

\( \Delta P_p \)  Pressure drop due to the particulate layer

\( \Delta P_s \)  Pressure drop due to the bag house structure
ADVANTAGES OF FABRIC FILTERS

- Very high collection efficiency
- They can operate over a wide range of volumetric flow rates
- The pressure drops are reasonably low.
- Fabric Filter houses are modular in design, and can be pre-assembled at the factory
FABRIC FILTERS (CONTD.)

- Disadvantages of Fabric Filters
  - Fabric Filters require a large floor area.
  - The fabric is damaged at high temperature.
  - Ordinary fabrics cannot handle corrosive gases.
  - Fabric Filters cannot handle moist gas streams.
  - A fabric filtration unit is a potential fire hazard.
DESIGN OF FABRIC FILTERS

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  - \( W \) = areal dust density = \( L V t \), where
    - \( L \) = dust loading (g/m³), \( V \) = velocity (m/s)
- Both \( K_e \) and \( K_s \) are determined empirically from pilot tests.
Fabric Filters

$$\Delta P = \Delta P_f + \Delta P_p + \Delta P_s$$

$\Delta P$ $\longrightarrow$ Total pressure drop

$\Delta P_f$ $\longrightarrow$ Pressure drop due to the fabric

$\Delta P_p$ $\longrightarrow$ Pressure drop due to the particulate layer

$\Delta P_s$ $\longrightarrow$ Pressure drop due to the bag house structure
Darcy’s equation

\[ \Delta P_f = \frac{D_f \mu V}{60 K_f} \]
\[ \Delta P_p = \frac{D_p \mu V}{60 K_p} \]

\[ \Delta P_f \] Pressure drop N/m²
\[ \Delta P_p \] Pressure drop N/m²
\[ D_f \] Depth of filter in the direction of flow (m)
\[ D_p \] Depth of particulate layer in the direction of flow (m)
\[ \mu \] Gas viscosity kg/m·s
\[ V \] Superficial filtering velocity m/min
\[ K_f, K_p \] Permeability (filter & particulate layer m²)
\[ 60 \] Conversion factor s/min
\[ V = Q/A \]
\[ Q \] Volumetric gas flow rate m³/min
\[ A \] Cloth area m²
Dust Layer

\[ D_p = \frac{LVt}{\rho_L} \]

- \( L \) Dust loading \( \text{kg/m}^3 \)
- \( t \) time of operation \( \text{min} \)
- \( \rho_L \) Bulk density of the particulate layer \( \text{kg/m}^3 \)

\[ \Delta P = \Delta P_f + \Delta P_p \]

\[ \Delta P = \left( \frac{D_f\mu}{60K_f} \right)V + \left( \frac{\mu}{60K_p\rho_l} \right)LVt \ V \]

\[ \frac{\Delta P}{V} = k_1 + k_2 (LVt) \]

Filter Drag \( S = \Delta P/V \)

Areal dust density \( W = LVt \)

\( S = k_1 + k_2 W \)
Composite Minimum Efficiency Curve

AmAir® 62 Plus filters are classified UL Class 2. Testing was performed according to U.L. Standard 900 and CAN 4-S111.

Recommended Final Resistance - 1.0 in. W.G.
Rated Filter Face Velocity - 500 FPM
Continuous Operating Temperature Limit - 200°F (93°C)
Initial Resistance vs. Filter Face Velocity

Initial Resistance (In. Wg.)

Filter Face Velocity (FPM)

1" Filter
2" Filter
4" Filter
Wet Particle Scrubbers

- Particulate control by impaction, interception with water droplets
- Can clean both gas and particle phases
- High operating costs, high corrosion potential
Baghouse Filters

- Particulate control by impaction, interception, diffusion on fabric & dust layer
Baghouses

- Fabric filtration – vacuum cleaner
- High removal efficiency for small particles
- Not good for wet or high temperature streams
- Uses fabric bags to filter out PM
- Inexpensive to operate (process based)
- Bags cleaned by periodic shaking or air pulse
- Creates solid-waste stream
Pulse-Air-Jet Type Baghouse
Fabric Filter (Baghouse)

- Same Principle As Home Vacuum Cleaner
- Air Can Be Blown Through Or Pulled Through
- Bag Material Varies According To Exhaust Character
## Table 8.2 Filter Bag Design Factors.

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Type Yarn</th>
<th>Maximum Temperature, °F</th>
<th>Acid Resistance</th>
<th>Flouride Resistance</th>
<th>Alkali Resistance</th>
<th>Flex Abrasion Resistance</th>
<th>Tensile Strength, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>Staple</td>
<td>180 225</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Very Good</td>
<td>70,000</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>Filament Spun</td>
<td>190 200</td>
<td>Good to Excellent</td>
<td>Poor</td>
<td>Fair to Excellent</td>
<td>Good to Excellent</td>
<td>110,000</td>
</tr>
<tr>
<td>Wool</td>
<td>Staple</td>
<td>200-215 250</td>
<td>Very Good</td>
<td>Poor to Fair</td>
<td>Poor</td>
<td>Fair</td>
<td>25,000</td>
</tr>
<tr>
<td>Nylon</td>
<td>Filament Spun</td>
<td>200-225 250</td>
<td>Poor to Fair</td>
<td>Poor</td>
<td>Good to Excellent</td>
<td>Excellent</td>
<td>80,000</td>
</tr>
<tr>
<td>Orlon®</td>
<td>Spun</td>
<td>240 260</td>
<td>Good to Excellent</td>
<td>Poor to Fair</td>
<td>Fair to Good</td>
<td>Good</td>
<td>75,000</td>
</tr>
<tr>
<td>Acrylic</td>
<td>Filament Spun</td>
<td>260 280</td>
<td>Good</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
<td>40,000</td>
</tr>
<tr>
<td>Dacron®</td>
<td>Filament Spun</td>
<td>275 325</td>
<td>Good</td>
<td>Poor to Fair</td>
<td>Good</td>
<td>Very Good</td>
<td>80,000</td>
</tr>
<tr>
<td>Nomex®</td>
<td>Filament Spun</td>
<td>400 425</td>
<td>Poor to Good</td>
<td>Good</td>
<td>Good to Excellent</td>
<td>Good to Excellent</td>
<td>80,000</td>
</tr>
<tr>
<td>Teflon®</td>
<td>Filament Spun</td>
<td>400-450 500</td>
<td>Excellent</td>
<td>Poor to Fair</td>
<td>Excellent</td>
<td>Poor to Fair</td>
<td>20,000</td>
</tr>
<tr>
<td>Fiberglas®</td>
<td>Filament Spun, Bulked</td>
<td>500 550</td>
<td>Fair to Good</td>
<td>Poor</td>
<td>Fair to Good</td>
<td>Fair</td>
<td>200,000</td>
</tr>
</tbody>
</table>

*Principle sources: Walling (1970) and Pring (1972).*
About Baghouses

Efficiency Up To 97+%  
(Cyclone Efficiency 70-90%)  
Can Capture Smaller Particles Than A Cyclone  
More Complex, Cost More To Maintain Than Cyclones
Types of Baghouses

• The three common types of baghouses based on cleaning methods
  a. Reverse-air
  b. Shaker
  c. Pulse-jet
MIGRATION VELOCITY

\[ W = \frac{q \times E_p \times C}{6\pi r \mu} \]

Where,

- \( q \) = charge (coulombs)
- \( E_p \) = collection field intensity (volts/m)
- \( r \) = particle radius (m)
- \( \mu \) = dynamic viscosity of gas (Pa·s)
- \( c \) = cunningham correction factor
Cunningham correction factor

\[ c = 1 + \frac{6.21 \times 10^{-4}(T)}{d_p} \]

where,

\[ T = \text{absolute temperature (°k)} \]
\[ d_p = \text{diameter of particle (μm)} \]
• **Advantages of Electrostatic Precipitators**
  
  Electrostatic precipitators are capable very high efficiency, generally of the order of 99.5-99.9%.
  
  Since the electrostatic precipitators act on the particles and not on the air, they can handle higher loads with lower pressure drops.
  
  They can operate at higher temperatures.
  
  The operating costs are generally low.

• **Disadvantages of Electrostatic Precipitators**

  The initial capital costs are high.
  
  Although they can be designed for a variety of operating conditions, they are not very flexible to changes in the operating conditions, once installed.
  
  Particulate with high resistivity may go uncollected.
Note about pulse-jets

- blast of compressed clean air flows briefly into the bags, while they are still filtering dusty air, knocking off some dust

- bottom of the bag is closed and filtration can occur on this surface - need to account for in area calculations
Q: What is one of the parameters that affect our decision on the number of compartments to be used?
   a. fabric type
   b. time required to clean a compartment
   c. temperature and RH

Table 6.3  Number of Compartments as a Function of Net Cloth Area

<table>
<thead>
<tr>
<th>Net Cloth Area, ft²</th>
<th>Number of Compartments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–4000</td>
<td>2</td>
</tr>
<tr>
<td>4000–12,000</td>
<td>3</td>
</tr>
<tr>
<td>12,000–25,000</td>
<td>4–5</td>
</tr>
<tr>
<td>25,000–40,000</td>
<td>6–7</td>
</tr>
<tr>
<td>40,000–60,000</td>
<td>8–10</td>
</tr>
<tr>
<td>60,000–80,000</td>
<td>11–13</td>
</tr>
<tr>
<td>80,000–110,000</td>
<td>14–16</td>
</tr>
<tr>
<td>110,000–150,000</td>
<td>17–20</td>
</tr>
<tr>
<td>&gt;150,000</td>
<td>&gt;20</td>
</tr>
</tbody>
</table>
Parallel Flow Operation

How do you determine when to clean?
Design procedure for baghouses

- Identify filter velocity (V) for dust that you are trying to treat
- Estimate net cloth area $A = Q/V$
- Remember to add area at bottom of filter if you are using pulse-jet
- Estimate number of compartments using table
- Not needed for pulse-jet
- May need to develop filter-drag model to understand relationship between pressure drop $\Delta P$, filtering velocity $V$
- For estimating how long you can run
Electrostatic Precipitator (ESP)

- High Efficiency
- Able to Handle Large Air Flow Rates
- Or Can Be Very Small (Smoke Eaters In Bars and Restaurants)
Type 4: Electrostatic Precipitators

Types include:

• Dry, negatively charged

• Wet-walled, negatively charged

• Two-stage, positively charged
Electrostatic Precipitators

Advantages: Good efficiency

Disadvantages: Dependent upon resistivity of PM, cannot be used around explosive gases
DESIGN OF ELECTROSTATIC PRECIPITATORS

The efficiency of removal of particles by an Electrostatic Precipitator is given by

\[ \eta = 1 - e^{\left(-\frac{wA}{Q}\right)} \]

\(\eta\) = fractional collection efficiency
\(w\) = drift velocity, m/min.
\(A\) = available collection area, m\(^2\)
\(Q\) = volumetric flow rate m\(^3\)/min
http://www.ppcbio.com/ppcdespwhatish.htm
Electrostatic Precipitator Drawing

- Clean gas out
- Rappers
- Flue gas in
- Discharge electrodes
- Hoppers
How An ESP Operates
ESP\textsuperscript{s}

- Electrostatic precipitator
- More expensive to install,
- Electricity is major operating cost
- Higher particulate efficiency than cyclones
- Can be dry or wet
- Plates cleaned by rapping
- Creates solid-waste stream
- Picture on next slide
Electrostatic Precipitator Concept
Electrostatic Precipitator
Electrostatic Precipitator — static plates collect particles

Cleaned gas

Electrodes

Dust discharge

Dirty gas
Principle

High-Voltage Charges Wires
Gases Are Ionized
Particles Become Charged
Collection Plates (Opposite Charge) Attract Particles
Rapper Knocks Plates So That The Collected Dust Layer Falls Into Hoppers
Wet Type

- Venturi
- Static packed
- Moving bed
- Tray tower
- Spray towers
Scrubbers

- Gas Contacts A Liquid Stream
- Particles Are Entrained In The Liquid
- May Also Be A Chemical Reaction
- Example: Limestone Slurry With Coal Power Plant Flue Gas
Scrubbers

Advantages: Good efficiency, can collect (potentially explosive) gaseous pollutants as well as PM, small size

Disadvantages: Requires a lot of water, generates waste stream
SCRUBBER

- **Efficiency**
  \[ \eta = 1 - \exp(-KR\sqrt{\psi}) \]
  where,
  - \( k \) = Scrubber coefficient (m\(^3\) of gas / m\(^3\) of liquid)
  - \( R \) = Liquid-to-gas flow rate (\( Q_L/Q_G \))
  - \( \psi \) = internal impaction parameter

- **Internal impaction parameter**
  \[ \psi = \frac{c \rho_p V_g (d_p)^2}{18 d_d \mu} \]
  where,
  - \( c \) = cunningham correction factor
  - \( \rho_p \) = particle density (kg/m\(^3\))
  - \( V_g \) = speed of gas at throat (m/sec)
  - \( d_p \) = diameter of particle (m)
  - \( d_d \) = diameter of droplet (m)
  - \( \mu \) = dynamic viscosity of gas, (Pa-S)
Advantages of Wet Scrubbers
Wet Scrubbers can handle incoming streams at high temperature, thus removing the need for temperature control equipment.

- Wet scrubbers can handle high particle loading.
- Loading fluctuations do not affect the removal efficiency.
- They can handle explosive gases with little risk.
- Gas adsorption and dust collection are handled in one unit.
- Corrosive gases and dusts are neutralized.

Disadvantages of Wet Scrubbers
- High potential for corrosive problems
- Effluent scrubbing liquid poses a water pollution problem.
Venturi Scrubber

- High intensity contact between water and gas => high pressure drop
- Venturi action modified spray tower
- High removal efficiency for small particles
- Creates water pollution stream
- Can also absorb some gaseous pollutants ($\text{SO}_2$)
Venturi Scrubber

Detail illustrates cloud atomization from high velocity gas stream shearing liquid at throat.
Typical Venturi Scrubber with a cyclone separation configuration.
Vertical Venturi Scrubber
Packed Bed Scrubber
Dry Scrubber System

http://www.fkinc.com/dirctspraydry.htm#topca
Tower Scrubber
Spray Towers

- Water or other liquid “washes out” PM
- Less expensive than ESP but more than cyclone, still low pressure drop
- Variety of configurations
- Higher efficiency than cyclones
- Creates water pollution stream
- Can also absorb some gaseous pollutants (SO$_2$)
Spray Tower

Figure 4b  Adapted from Calvert (1977).

Preformed-spray scrubber recovers particles or gases on liquid droplets atomized by spray nozzles.
Types Of Scrubber

Tray Tower Scrubbers
- Impingement Tray
- Sieve Tray

Packed Bed Scrubbers
- Cylinder Filled with Media
  Which Promotes Gas-Liquid Contact
Types Of Scrubber

Fiber Bed Scrubber

Vertical Mesh Pads Of Interlaced Fibers Promote Gas-Liquid Contact

Spray Tower Scrubber

Nozzles Spray Liquid Across the Inlet Gas Flow Path
Gaseous Pollutant Control

• Absorption

• Adsorption

• Combustion
Control of Air Pollutants

Gaseous pollutants - Combustion

- 3 types of combustion systems commonly utilised for pollution control
  - direct flame,
  - thermal, and
  - catalytic incineration systems
Gaseous pollutants - Adsorption

- Physical adsorption to solid surfaces
- Reversible - adsorbate removed from the adsorbent by increasing temp. or lowering pressure
- Widely used for solvent recovery in dry cleaning, metal degreasing operations, surface coating, and rayon, plastic, and rubber processing
Gaseous pollutants - Adsorption

- limited use in solving ambient air pollution problems – with its main use involved in the reduction of odour
- Adsorbents with large surface area to volume ratio (activated carbon) preferred agents for gaseous pollutant control
- Efficiencies to 99%
Carbon Adsorption

- Will do demonstration shortly
- Good for organics (VOCs)
- Both VOCs and carbon can be recovered when carbon is regenerated (steam stripping)
- Physical capture
  - Adsorption
  - Absorption
Carbon Adsorber for VOC Abatement from Paint Shop Process

Process Air (Dirty)

Clean Air

Sacrificial Carbon Bed

Cooling Out
Desorption In
Desorption Out

Honeycomb Cassette
Fig. 13.2. Schematic of molecular screening and adsorbate migration in micropores of activated carbon. (Courtesy Calgon Corp., Activated Carbon Div.)
Gaseous pollutants - Absorption

- Scrubbers remove gases by chemical absorption in a medium that may be a liquid or a liquid-solid slurry
- Water is the most commonly used scrubbing medium
- Additives commonly employed to increase chemical reactivity and absorption capacity
Pollutants Of Interest

- Volatile Organic Compounds (VOC)
- Nitrogen Oxides (NOx)
- Sulfur Oxides (SOx)
Example Sources Of Gaseous Pollutants

- Surface Coating Processes
- Printing
- Combustion (Boilers)
- Dry Cleaning
- Bakeries
Mechanical Control

- For Burners, Air/Fuel Ratio Control, Called Low-NOx Burners.
- For Dry Cleaners And Similar Processes Using Solvent In Closed Vessels, Refrigerated Condensers.
Chemical Control

- Flue Gas Control
- Solvent Destruction
Flue Gas Control

To Reduce Emissions of NOx From Burners:
Break NOx into O2 And N2 with a catalyst.
Same Process as in automobiles.
Controlling Gaseous Pollutants: $\text{SO}_2$ & $\text{NO}_x$

- Modify Process (recall 3P’s)
  - Switch to low-sulfur coals
  - Desulfurize coal (washing, gasification)
- Increase efficiency
  - Low-$\text{NO}_x$ burners
- Recover and Reuse (heat)
  - Staged combustion
  - Flue-gas recirculation
Controlling Gaseous Pollutants: CO & VOCs

- Wet/dry scrubbers
  - Absorbers
  - NO$_x$ and SO$_x$ included
- Proper operating conditions
- Thermal and catalytic oxidation
  - Chemical
  - Carbon adsorption
  - Physical
VOC / CO Process Control

• Keep combustion HOT

○ Reuse & recycle heat

• Control cold start-ups, shut-downs, wet inputs

○ wood-fired, chemical incinerators, boilers

• Increase residence time of gas in combustor

• Unfortunately, things that reduce NO\textsubscript{x} tend to increase VOC’s

○ Atmosphere in air combustion 78% N\textsubscript{2}
VOC INCINERATORS

- **Principle**
  - VOC incinerators thermally oxidize the effluent stream, in the presence of excess air.
  - The complete oxidation of the VOC results in the formation of carbon monoxide and water. The reaction proceeds as follows:
    \[ C_xH_y + (x + y/4)O_2 \rightarrow xCO_2 + (y/2)H_2O \]

- **Operation**
  The most important parameters in the design and operation of an incineration system are what are called the 'three T's' - Temperature, Turbulence, and residence Time.
Scrubbers / Absorbers

- SO₂ removal: “FGD” (flue gas desulfurization)
  - Lime/soda ash/citrate absorbing solutions
  - Can create useable by-product OR solid waste stream
- NOₓ removal—catalytic and non-catalytic
  - Catalyst = facilitates chemical reaction
- Ammonia-absorbing solutions
- Process controls favored over this technology
- CO & CO₂ removal
- Some VOC removal
Flue Gas SOx Control

SOx Forms Sulfuric Acid With Moisture In Air Producing Acid Rain.

Remove From Flue Gas By Chemical Reaction With Limestone
Control Technologies for Nitrogen Oxides

- **Preventive**
  - minimizing operating temperature
  - fuel switching
  - low excess air
  - flue gas recirculation
  - lean combustion
  - staged combustion
  - low Nox burners
  - secondary combustion
  - water/steam injection

- **Post combustion**
  - selective catalytic reduction
  - selective non-catalytic reduction
  - non-selective catalytic reduction
Thermal Oxidizers

For VOC Control

Also Called Afterburners
Thermal Oxidation

- Chemical change = burn
- $\text{CO}_2$ and $\text{H}_2\text{O}$ ideal end products of all processes
- Flares (for emergency purposes)
- Incinerators
  - Direct
  - Catalytic = improve reaction efficiency
  - Recuperative: heat transfer between inlet / exit gas
  - Regenerative: switching ceramic beds that hold heat, release in air stream later to re-use heat
Two Types Of Oxidizer

- Catalytic
- Non-Catalytic
Thermal Oxidizer
(Non-Catalytic)
Catalytic Thermal Oxidizer
Biological Method

- Uses Naturally Occurring Bacteria (Bugs) To Break Down VOC
- “Bugs” Grow On Moist Media And Dirty Gas Is Passed Through. Bugs Digest The VOC.
- Result Is CO2 And H2O
A Bio Filter For VOC Removal
Design procedure for Scrubbers

- Identify type of scrubber
  - Counter current
  - Cross flow
  - Venturi

- Calculate $K_p$, impaction parameter
- Calculate single droplet target efficiency, $\eta_d$
- Calculate Penetration, $P_{td}$
- Collection efficiency is $1 - P_{td}$
Its Raining in Boulder

• Liken particle scrubbers to a good rain storm
• Some particles in air are removed because they are collected on or in raindrops and deposited on ground
Wet Scrubber – Expensive

Remove 98% of SO2 and PM from emissions
Other Technologies

- High-temp ceramic filter
- Operates at $T > 500 \, ^\circ F$ (limit for baghouses)
E-beam flue gas treatment process

(Prof. A. Chmielewski)
Gaseous pollutants – Odour

The main approaches include

• wet scrubbing,
• charcoal filtration and
• incineration
Gas pollutants – Vehicle emissions

- generally involve simple procedures such as maintaining the correct tuning for the engine, or the use of catalytic converters
- catalytic converters use Pt and Pd attached to some form of ceramic material
- extremely high surface area (in hundreds of m$^2$) allows catalytic materials to contact exhaust gases, oxidising them to CO$_2$ and water vapour
Automobile Emission Control System

- Closed loop, electronically controlled carburetor
- Positive crankcase ventilation (PCV) exhaust gas recirculation
- Electronic control unit
- 3-way catalytic converter
- Exhaust oxygen sensors
Gas pollutants – Vehicle emissions

- all the measures which decrease CO and hydrocarbon emissions, increase NO\textsubscript{x} emissions
- measures such as changing engine spark plug timing and reduction of compression ratios allow NO\textsubscript{x} emissions to be lowered without greatly increasing other pollutant emissions
Environnemental friendly technologies (Pollution Prevention)

- Preparation of fuel materials and by-product energy sources (clean coal, RDF, wood, biofuels, etc...)
- Low NOx burner
- Pollution abatement devices (gas):
  - DeNOx
  - DeDiox
  - Acid neutralization
  - Desulfurization
- Filtration of particles:
  - Electrostatic precipitator
  - Baghouse
- Cogeneration (heat and power)
- Use of renewable energy sources
- Promotion of low carbon power generation technologies
Thank You for Your attention!