Lesson 4
INDUSTRIAL EMISSION REDUCTION

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4.1. INTRODUCTION. CONCEPTS

Industrial sources can emit significant amounts of **particulate matter** and **pollutant gases** into the atmosphere. In order to attain industrial source emission standards as well as to improve and protect air quality, these emissions must be reduced by using different **control devices**.

"Gas emissions at a manufacturing complex in Toronto, Canada" by United Nations licensed under CC BY-NC-ND 2.0

Almost all industrial processes consist of a sequence of interconnected devices for the **conversion of materials and energy.** The emission of pollutants from industrial processes depends on:

- Raw materials
- Types of conversion: physical, chemical and/or biological
- Design of the equipment

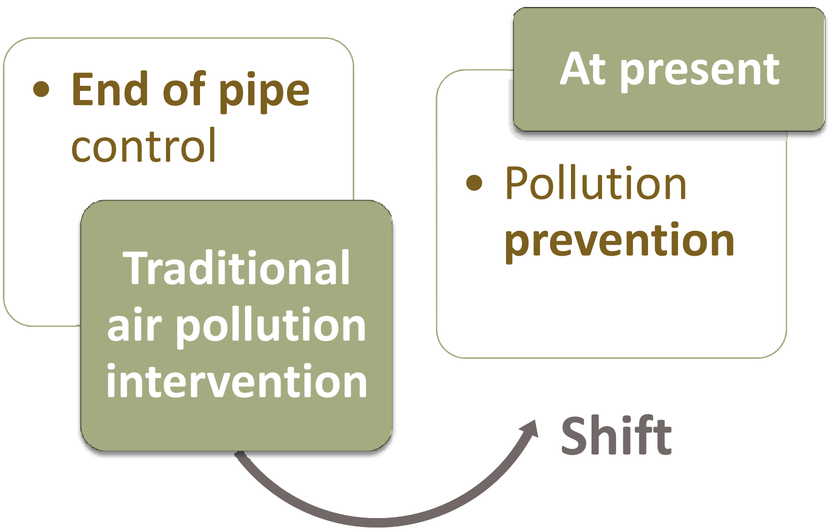
None of these processes generates only the intended products; there is always a generation of sub-products, which can be pollutants and wastes. In some processes and plants the generation of sub-products is higher than the generation that will result if the **Best Available Techniques** (BAT) were used.

BAT means the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole. *Directive 2008/1/EC concerning integrated pollution prevention and control*

The BAT reference documents are called **BREF**s. BREFs are drawn up for defined activities and describing applied techniques, present emissions and consumption levels, techniques considered for the determination of BATs as well as any emerging techniques.

Control strategies

In most cases, air pollution control equipment is installed at industrial sources to reduce emission in order to meet regulations. However, **it is possible** (**and desirable**) to reduce emissions by other methods.



1. Pollution prevention →

2. Removal pollutants (end of pipe control)

3. Intervention at the point of release

The best procedure is **intervention at the source of generation**.

- **Changes in the raw materials**

  e.g. use of low sulfur fuel or natural gas instead of high sulfur fuel by electric utilities

- **Process modifications**

  e.g. Painting operations in automobile industry: substitution of water based paints for oil based paints to reduce VOC and other hazardous air pollutants' emissions

- **Operational changes in the pollution-producing process.**

  e.g. maintaining a good housekeeping

These modifications involve the greatest investments but result in the most rewards.

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1. Pollution prevention

2. Removal pollutants (end of pipe control) →

3. Intervention at the point of release

In many situations sufficient control cannot be obtained by material or process change. In cases such as these, the levels of the pollutants of concern must be reduced to allowable values before they are released into the atmosphere **by control equipment.**

e.g. electrofilters, washers,…

This is known as '**end-of-pipe pollution control**' or '**downstream pollution control**'.

The type of technology applied depends on the characteristics of the pollutants and the substance in which they reside.

1. Pollution prevention

2. Removal pollutants (end of pipe control)

3. Intervention at the point of release

"Four smokestacks at the Northport Power Station released under public domain in English Wikipedia

→ This includes enhancing dispersion at the point of release or as the pollutant is transported into the environment.

e.g. installation of ***tall discharge stacks*** *to disperse/dilute pollutants to tolerable levels or rely upon the* ***mixing capacity*** *of the atmosphere*

Selection of the control device

- ✓ The control device or system must be specific for the pollutant of concern.
- ✓ Eliminating or reducing pollutant concentrations in the waste stream begins with an assessment of the characteristics of **each pollutant and the carrier gas** and matching these characteristics to the appropriate treatment technology.
- ✓ It is generally determined by the phase of the pollutant: **gas-phase** and **particle-phase** (solid-phase or liquid-phase).

The processes and devices employed to collect particles depend on their **physical properties** (size distribution and density), whereas the processes and devices to reduce the concentration of the gaseous compounds depend on their **chemical properties**.

Emissions characterization

The separation or depuration efficiency and/or the concentration the pollutants in the exhaust gases are not useful for the characterization or the analysis of the emission of air pollutants. The most important parameter determining the emissions of industrial sources are Emission Factors (EF).

EF is the average emission rate of a given pollutant from a given source relative to the intensity of a specific activity

EF are usually expressed as the weight of pollutant divided by the unit weight, volume, distance, or duration of the activity that emits the pollutant.

$$EF_{pollutant\ i} = \frac{emission_{pollutant\ i}}{activity\ rate}$$

The use of emission factors is straightforward when the relationship between process data and emissions is direct (**controlled emissions**). Note, however, that emission factors may be developed assuming no control device is in place. These are referred as **fugitive, uncontrolled** or **diffuse emissions**.

"Fugitive emissions at a Power Station" by Mriya licensed under CC BY-SA 3.0

Separation of PM

The performance of particulate matter pollution control equipment is often judged in terms of collection efficiency.

GLOBAL SEPARATION EFFICIENCY (Φ_R or η_0)
indicates what fraction of the total particle weight will be removed from the entire fraction.

$$\Phi_R = \eta_0 = \frac{weight_{in} - weight_{out}}{weight_{in}} = 1 - \frac{weight_{out}}{weight_{in}}$$

Where: $weight_{in}$ = entering loading or concentration [$M \cdot L^{-3}$]
$weight_{out}$ = leaving loading or concentration [$M \cdot L^{-3}$]

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Global separation efficiency is a generalized parameter employed to indicate the performance level of a gas cleaning device. However, the efficiency of particle removal is a function of the particle size distribution of the particles to be collected.

FRACTIONAL SEPARATION EFFICIENCY (Φ_F or η_d)
is the collection efficiency in an interval of particle size.

$$\Phi_F = \eta_d = \frac{(weight)\Delta d_{in} - (weight)\Delta d_{out}}{(weight)\Delta d_{in}} = 1 - \frac{(weight)\Delta d_{out}}{(weight)\Delta d_{in}}$$

Where: $(weight)\ \Delta d_{in}$ and $(weight)\ \Delta d_{out}$ = entering and leaving loading or concentration of particles in the size range d_1- d_2 [$M \cdot L^{-3}$]

The fractional collection efficiency is a function of:

- Type of equipment and of design variations (geometry, size, …) and operating conditions for a given type.
- Type of dust (shape, density), loading of the emission and the particle size distribution (percentage by mass of a collection of particles).

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4.2. PARTICULATE MATTER CONTROL EQUIPMENT

A number of devices that differ widely in effectiveness, complexity and cost have been developed for this purpose. They are classified into two groups:

- **Dry collectors**
- **Wet collectors**

"Collection electrode of electrostatic precipitator in waste incineration plant"
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4.2.1. Dry collectors

Dry collectors remove dust particles by passing the dust-laden gas stream through a zone in which the particles come under the influence of some kind of force. Agents are not added. Collected dust can be **eliminated directly.**

The separation of particulate matter from a gas is accomplished by the action of three **forces**. According to these forces the control systems are divided into three types:

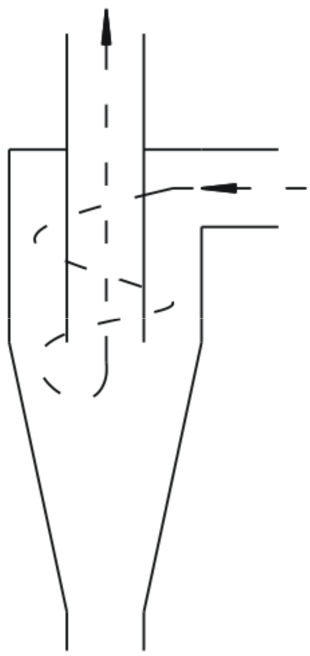
	Forces
Cyclones	Mass-forces or inertia
Bag filters	Surface forces or adhesion
Electrostatic precipitators (ESP)	Electrical forces

4.2.1.1.Cyclones

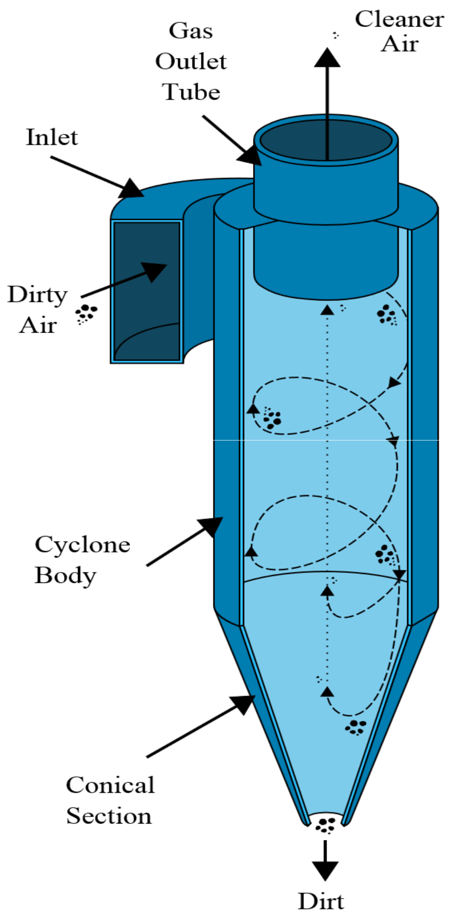
Cyclone separators employ the **centrifugal force (inertia)** generated by a spinning gas stream to separate the particulate matter from the carrier gas.

Elements

They have a distinctive and easily recognized form. They are composed of an inlet chamber, cyclone body, dust discharge system and outlet.



“Cyclone separator” by S. Enz licensed under Public Domain



"Cyclone separator" by Cburnett licensed under CC BY-SA 3.0

Operation

Typically, the particle-laden gas enters tangentially near the top of the cyclone. The gas flow is forced into a downward spiral simply because of the cyclone's shape and the tangential entry. Centrifugal force cause particles to move outward, collide with the outer wall, and slide downward to the bottom of the device.

Near the bottom of the cyclone, the air reverses its downward spiral and moves upward in a smaller inner spiral. The cleaned gas exists from the top from a *vortex-finder* tube, and the particles exit from the bottom through a pipe to the storage hopper.

Classification

Cyclones are typically classified into four types, depending on how the **gas stream is introduced** into the device and how the collected dust is **discharged**.

- Tangential inlet, axial discharge and output
- Tangential inlet and peripheral discharge
- Axial inlet and axial discharge
- Axial inlet and peripheral discharge

They can also be classified by the chamber's morphology: **cylinder** or **cone**. Most of them are conical.

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Advantages

- Continuous separators
- Simple design and reliability
- Low capital costs and low operating costs
- Ability to operate at high P (1 kPa-10 MPa) and T (>1000 ºC)
- Relatively small space requirements

Disadvantages

- Low-efficiency collectors as they are not effective removing particles sizes down to 5 µm. Therefore, cyclones are usually employed as pre-cleaners before the gas passes through final control devices.
- Unable to tackle sticky or tacky materials

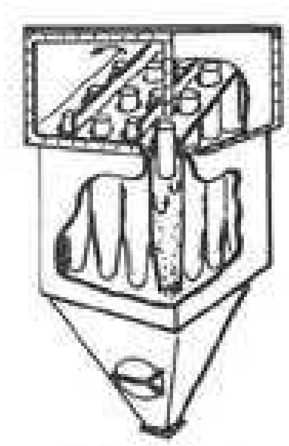
The particle removal efficiency of a cyclone depends to a great extent upon the cyclone´s dimensions, particularly, upon the **diameter** and the **length of the body**.

↑ length ↑ vortex revolutions ↑ chances PM collection	↓ diameter ↓ radius of the path of travel ↑ collection efficiency small particles ↓throughput (Q)

To effectively remove particles having smaller diameters multiple cyclones can be used, either **in series** or **in parallel.**

A **multicyclone** consists of a number of small-diameter cyclones in parallel and having a common gas inlet and outlet

Multicyclones operate on the same principle as cyclones but they are more efficient than single common cyclones because they are longer and smaller in diameter.



“Multicyclone” by US Department of Labor licensed under Public Domain

Design

Extensive work has been done to determine in what manner dimensions of cyclones affect performance.

The ***optimal*** **dimensions** for cyclones were originally determined in some classic works on the topic (still in use today).

All dimensions are related to the **body diameter of the cyclone** (D_c).

In cyclones, collection efficiency generally increases as the pressure drop increases. The small **openings** (S_{inlet}) that create high inlet pressure produce a high **inlet gas velocity** (u_c) and this higher velocity results in greater centrifugal force on the particles and thus greater collection efficiency.

Inlet gas velocity in conventional cyclones ranges from **6-20 m·s^{-1}**.

Lapple developed a semi-empirical relationship to calculate the "**50% cut diameter**", which is the diameter of particles collected with 50% efficiency (***dp$_c$*** or ***dp$_{0.5}$***).

$$dp_c = \sqrt{\frac{9\mu b}{2\,\pi\,N u_c\,(\rho_p - \rho_g)}}$$

Where:
μ = gas viscosity [M· L^{-1}·T^{-1}]
b = width of inlet = W [L]
H = height of inlet [L]
N = effective turns or revolutions [=]
u_c = inlet gas velocity [L·T^{-1}]
ρ_p = density of the particle [M·L^{-3}]
ρ_g = density of the gas [M·L^{-3}]

The inlet gas velocity is:

$$u_c = \frac{Q}{WH}$$

The **number of effective turns** (*N*) in the main vortex of the cyclone can be approximated:

$$N = \frac{t_r \, u_c}{\pi \, D_c} = \frac{\left(\frac{V_i}{Q}\right) \, u_c}{\pi \, D_c}$$

t_r= residence time of the gas at the device [T]
D_c = cyclone body diameter [L]
V_i = internal volume (cylinder's volume + cone's volume) [L^3]
Q = flow rate [$L^3 \cdot T^{-1}$]

Lapple developed a general curve for standard conventional cyclones to predict the collection efficiency for any particle size.

Grove then fitted an algebraic equation to the curve, which makes Lapple's approach more precise and more convenient to apply. The efficiency of collection of any size of particle is:

$$\eta = \frac{dp^2}{dp^2 + dp_c^2}$$

where:
η = collection efficiency of particles in the *x*-th size range [=]
dp_c = diameter of particles collected with 50% efficiency = $dp_{0.5}$ [L]
dp = diameter of the *x*-th particle size range [L]

4.2.1.2. Bag filters

Bag filters consist of filters that allow the passage of the gas but retain particulate material. The collected particles are then removed from the filter by a cleaning system.

Mechanisms

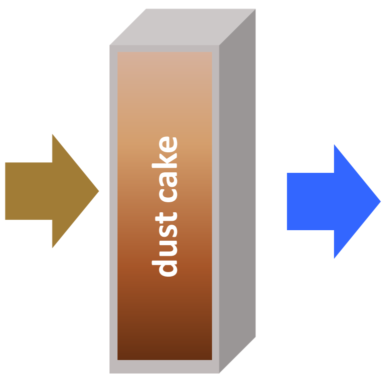
Basically, these particles are trapped through a combination of the following four mechanisms:

1. Diffusion caused by Brownian movement
2. Impactation
3. Interception
4. Electrostatics

Process

Two main features determine how particles are collected on the filter:

- With an unused or recently cleaned bag, particles are collected primarily by impaction or direct interception onto the fibers of the filter fabric itself. A layer of particles continues to build up on the filter surface. Continued filtration builds a dust cake on the fabric surface which, in turn, increases the particle capture. This **dust layer** or ***cake*** replaces the fabric as a filtering medium and is actually more efficient than the uncoated filter.



- As the dust cake accumulates on the filter, the removal efficiency is expected to increase; on the other hand, when the dust cake buildup reaches a thickness that increases the **pressure drop** across the filter. When the dust deposit becomes so heavy that the pressure necessary to force the gas through the filter becomes excessive (1000-2500 Pa), the dust must be removed by some means.

Bag filter by Patirslm licensed under CC BY-SA 4.0

Design

There are a range of basic design geometries of surface filters: bags, sacks and cartridge filters.

Filters used in industry are usually formed into cylindrical tubes and hang in multiple rows to provide large surface areas for gas passage The housing is frequently referred to as **baghouse.** The dirty gas enters the bag at the bottom and passes through the filter, while the particulate matter is deposited on the surface of the filter forming a dust layer. When dust layers build up to a sufficient thickness, bag filters are shaken and the dust falls into a hopper located below the bags. The baghouse is enclosed by sheet metal to protect the bags from environmental conditions.

“Baghouse dust collector for asphalt plants ”by Cornhorn licensed under CC BY-SA 3.0

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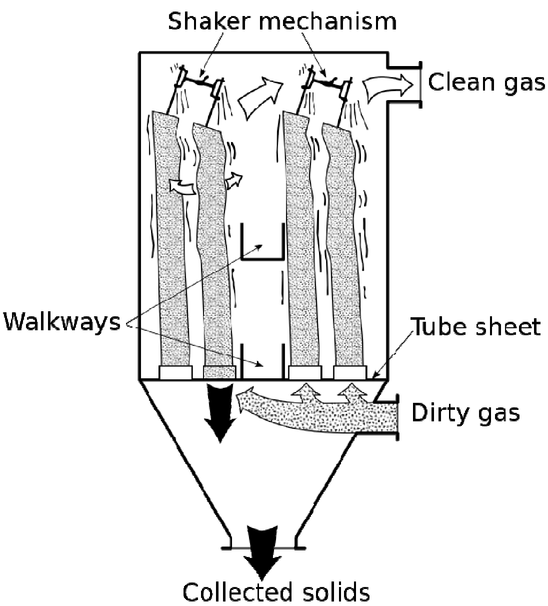
Bag cleaning

Two basic sequences are used for cleaning: intermittent cleaning and continuous cleaning.

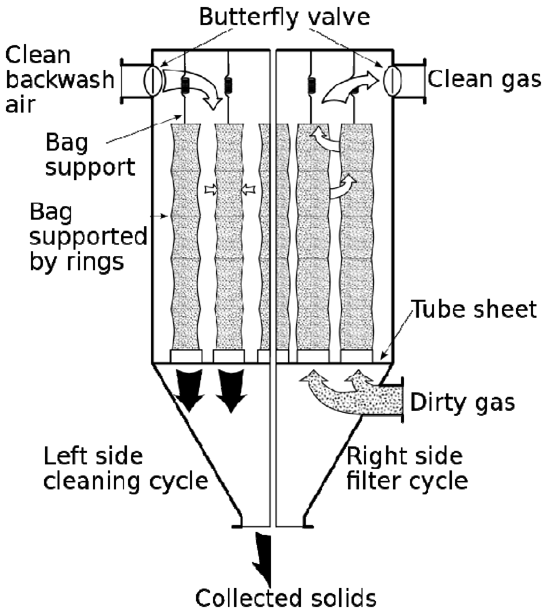
- **Intermittently cleaned baghouses** consist of a number of compartments. One compartment at a time is removed from service and cleaned on a regular rotational basis.
- **Continuously cleaned baghouses** constantly remain on-line for filtering. The filtering process is momentarily interrupted by a blast of compressed air that cleans the bag.

Frequency of bag cleaning depends on the type of dust, the concentration and the pressure drop.

Cleaning mechanisms



"Mechanical shaker" by Goran Tek licensed under CC BY-SA 3.0



"Reverse air" by Goran Tek licensed under CC BY-SA 3.0

Filtering media

The filter is constructed of materials compatible with the carrier gas and the particulate matter. The choice of fabric is based on the following factors:

- Temperature of the carrier gas
- Physical and chemical characteristics of the particulate matter
- Physical and chemical characteristics of the carrier gas

Some filters are made from cheap natural fibers such as cotton or wool, but they have temperature limitations and only average abrasion resistance. Synthetic fibers such as nylon, orlon or polyester have slightly different higher temperature limitations and chemical resistances.

Advantages

- High collection efficiency (99.9%) over a broad range of particles.
- Extreme flexibility in design.
- Simple and reliable operation.
- Dry separation of dust; this can be recirculated back for reuse

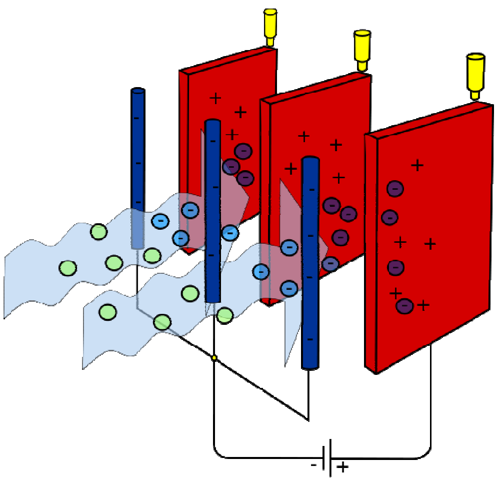
Disadvantages

- High operating costs derived from power requirements.
- Space requirements
- Possibility of explosion or fire

As they are one of the most efficient and cost effective types of dust collectors, they are used extensively for the control submicrometric particles in industrial applications.

4.2.1.3. Electrostatic precipitators

Particle collection by electrostatic precipitators (ESP) is based on the mutual attraction between particles of one **electrical charge** and a collection electrode of opposite polarity.



“Electrostatic precipitator” by E.Mason licensed under CC BY-SA 3.0

Typical ESPs have wires called **discharge electrodes**, which are evenly spaced between large plates called **collection electrodes**, which are grounded.

"Electrodes inside the electrostatic precipitator" by LukaszKatlewa licensed under CC BY-SA 3.0

Components

Essential components

- ✓ Discharge electrodes
- ✓ Collection electrodes
- ✓ Power supply unit to provide electric field between the discharge and collection electrodes.

External complementary elements

- ✓ Gas moving blowers
- ✓ Means, such as rappers, for removing the collected particles.
- ✓ Hoppers to collect and temporary store the dust removed
- ✓ Shell to support the ESP components and enclose the unit

Process

1. A negative current is applied to the discharge electrode creating a negative electric field.
2. Contaminated gases flow through the passage formed by the discharge and collecting electrodes.
3. As the e- leave the strong electrical field area around the discharge electrode, they collide with and impart a negative charge to the gas molecules, creating their ionization.
4. These negative ions move toward the collection electrode.
5. The dust particles travelling along in the gas stream encounter across in their path these negative ions and they receive a charge.
6. Once charged, the particles are attracted to the positively charged electrode and they adhere to it.
7. When the accumulated dust layer is relatively thick, the collected particles are removed by rapping the collecting electrodes.

Classification

ESPs can be grouped according to a number of distinguishing features in their design.

- Structural design of the electrodes: Tubular ESPs
  Plate ESPs
- Method of charging: Single-stage ESPs
  Two-stage ESPs
- Voltage: High-voltage ESPs (50-70 kV)
  Low-voltage ESPs (12-13 kV)
- Temperature of operation: Cold-side ESPs (200 ^{o}C)
  Hot-side ESPs (300 ^{o}C)

Disadvantages

- Initial costs are the higher than any particulate collection system
- A large amount of space is required for their installation

Advantages

- Continuous operation
- Capacity to handle large gas volumes
- High collection efficiencies even for small particles
- Low energy consumption and operating costs
- Ability to operate with a wide range of inlet temperatures, pressures, dust volumes and acid conditions.
- Valuable materials can be recovered

Application

Wide use in industry, especially in electrical power generation field

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One property of the particles that is extremely important in ESPs operation is the particle's electrical resistivity.

> **Resistivity** is the electrical resistance of a dust sample 1 cm^2 in cross-sectional area and 1 cm thick

Resistivity levels are generally broken down into three categories:

- **Low resistivity** $< 10^{4}\,\Omega\cdot cm$
- **Medium resistivity** $10^{4}-10^{10}\,\Omega\cdot cm$
- **High resistivity** $> 10^{10}\,\Omega\cdot cm$

ESPs are more effective in collecting particles in the medium resistivity range. Since many industrial particles do not fall within this range, it is often necessary to change operating conditions.

Design

Various equations have been proposed that relate the collection efficiency of an electrostatic precipitator to operating parameters. One of the expressions frequently quoted is Deutsch-Anderson equation:

$$\eta = 1 - e^{\frac{-w\,A}{Q}}$$

where:

η = global or overall efficiency of the electrostatic precipitator [=]
w = drift velocity or migration velocity of the particles [$L \cdot T^{-1}$]
A= area of the collection electrodes [L^2]
Q = volume flow rate [$L^3 \cdot T^{-1}$]

4.2.2. Wet collectors

Wet collectors or **scrubbers** rely on a liquid spray to remove dust particles from a gas stream. They are used where the particles cannot be removed easily in a dry form.

Scrubbers can be designed to collect particulate matter and gaseous pollutants. Scrubbers remove particles by *capturing* them in liquid droplets, whereas they remove gases by *dissolving* or them into the liquid. In any case, droplets that are in the gas must be separated from the exhaust gas stream by means of another device. Also, the scrubbing liquid must be treated prior to any ultimate discharge.

There are some important considerations regarding the use of these devices.

- It involves the humidification of the gas stream
- The scrubbing liquid should be treated before it is recycled or disposed of.
- They are not suitable for the removal of particles $d \leq 20\ \mu m$

There are multiple designs of scrubbing systems, all designed to provide good contact between the liquid and the dirty gas stream, with the following two being the most common:

Wash towers

Venturi scrubbers

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Advantages

- Remove both gases and particles
- Small space requirements
- Low installation costs
- Ability to handle high temperatures and moisture
- No secondary dust sources

Disadvantages

- Water disposal problems. Need for treatment of spent liquid to meet wastewater regulations.
- Need of moist removal to obtain high efficiencies
- High power requirements (Venturi scrubbers)
- Corrosion problems

4.2.2.1. Wash towers

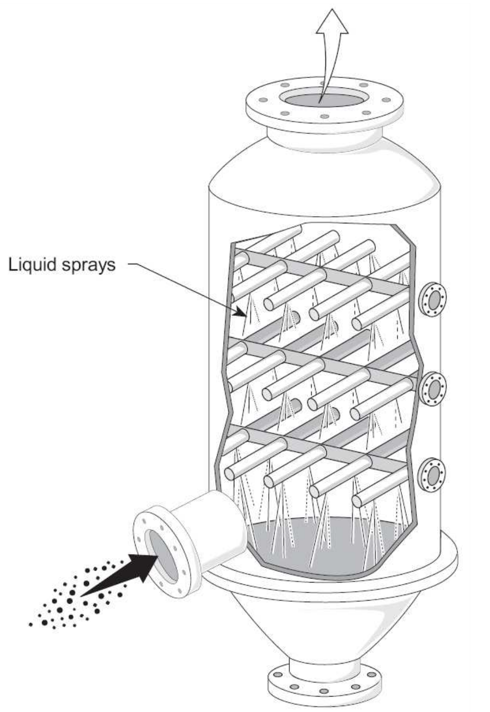
One of the simplest devices for wet collection of particulate matter is the spray tower.

Process

Washing liquid droplets are sprayed throughout the dirty gas so that contact is made between droplets and particles. The contact mechanism can be either inertial impingement or direct interception during the gravitational settling. After that, the liquid droplets containing the particles settle by gravity to the bottom of the tower where they are collected. These particles must be separated by means of another device.

Spray towers consist of empty cylindrical vessels made of steel or plastic and nozzles that the spray the scrubbing liquid.

In these scrubbers the polluted, dirty gas enters the bottom of the tower and flows upward, while the liquid is sprayed downward from one or more levels. This flow of dirty gas and liquid in opposite directions is called **countercurrent flow**.



Countercurrent-flow spray tower by BetacommandBot licensed under Pubic Domain

The efficiency of spray towers depends on the droplet size, flow velocity and droplet velocity. Thus, many nozzles are placed across the tower at different heights to form a high number of fine droplets for impacting particles.

Application

Spray towers are inexpensive low-energy scrubbers. Their collection efficiency for small particles is limited, but they are adequate for collection of coarse particles (> 10 µm). Thus, they are used for gas conditioning (cooling or humidifying) or first-stage particle removal (pretreatment).

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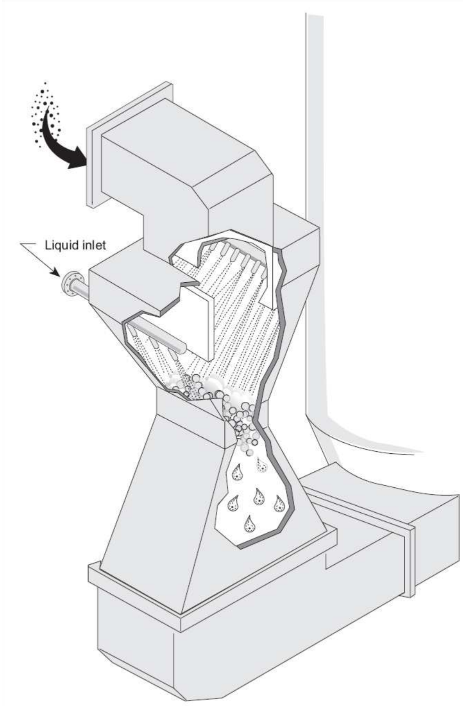
4.2.2.2. Venturi scrubbers

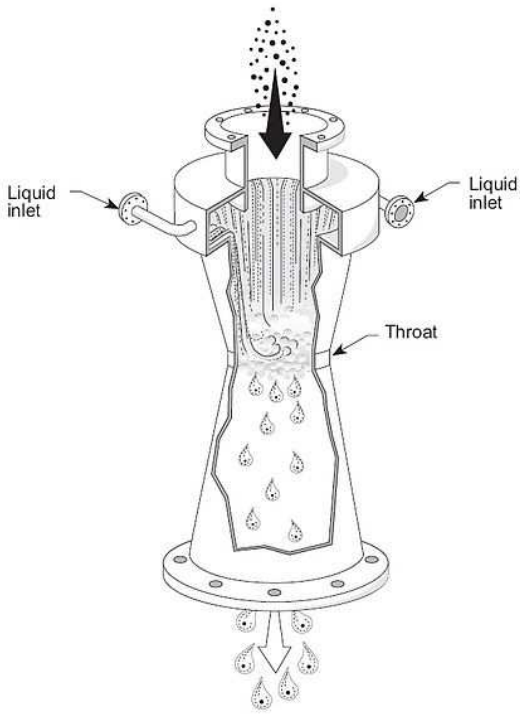
Venturi washers are designed to use the energy of the dirty gas stream to atomize the scrubbing liquid.

The dust-laden gas enters through a flow channel that converges to a narrow throat section where, as the area decreases it is accelerated (50-100 $m \cdot s^{-1}$). Scrubbing liquid is injected radially into this converging section as a high number of very tiny droplets into the incoming dirty gas gas. Particle collection occurs in the throat section as the gas mixes with the tiny liquid droplets.

Venturis are capable of achieving the highest collection efficiency of any wet scrubbing systems High efficiency removal of small PM (d <1 µm).

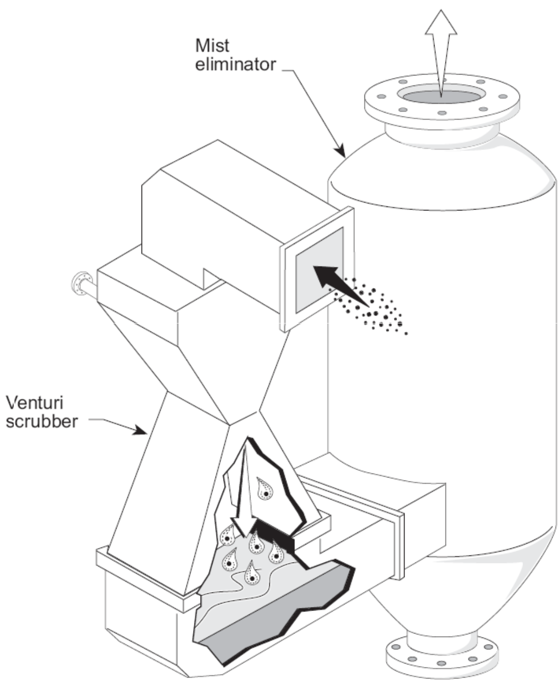


Venturi washer (1) by BetacommandBot licensed under Pubic Domain via Wikimedia commons



Venturi configuration by BetacommandBot licensed under Pubic Domain

All Venturi scrubbers require a separator as the high velocity of the gas through the scrubber will have a tendency to exhaust the dust-laden droplets with the clean gas stream. A common system is a cyclone separator connected to the Venturi.



Venturi scrubber and a cyclone in series by BetacommandBot licensed under Pubic Domain

4.3. GASEOUS POLLUTANT CONTROL EQUIPMENT

Generally, the concentrations of gaseous pollutants in gas mixtures are relatively low. The reduction of these concentrations to desirable levels can be accomplished by several methods:

Physical	Adsorbed on the surface of a selective solid adsorber
	Absorbed by liquid solvents
	Converted into a liquid
Chemical	Oxidized or reduced to another chemical form
Biological	Transformed by microorganisms

The use of a particular method depends on the properties of both the pollutant and the exhaust gas.

4.3.1. Adsorption

Adsorption is a mass transfer process in which certain gases are selectively removed from the gas stream because they adhere to the surface of a **solid**. The solid-adsorbing medium is termed **adsorbent** while the gas adsorbed is called **adsorbate.**

Classification

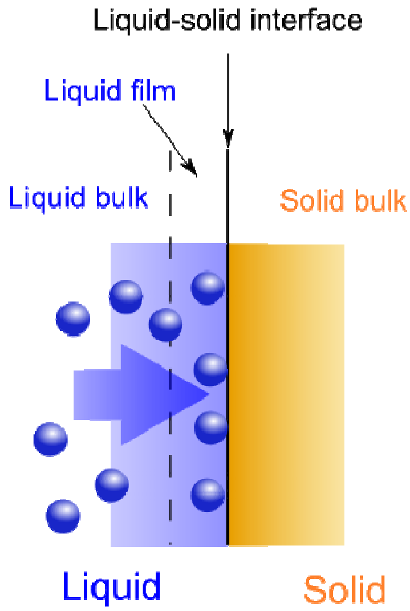
Adsorption can be strictly a surface phenomenon with only intermolecular or Van der Waals-type forces involved (**physical adsorption**), or it may be combined with a chemical reaction once the gas and adsorbent are in intimate contact (**chemisorption**). Physisorption is **reversible** whereas chemisorption is **irreversible**, thus, the adsorbed gas and the adsorbent can not be recovered.

Process

The air stream carrying the pollutants is brought into contact with the adsorbent. The pollutant molecules diffuse into the pores of the absorbent where they are adsorbed.

The strength of the attractive forces depends on the chemical structure of both the gas molecule and the solid.

The adsorption process is exothermic. Thus, the cooler the gas, the more effective the adsorption process.



Adsorption process by Aushulz licensed under CC BY-SA 3.0

Adsorbents

Solid materials used as adsorbents are be very porous with an extremely large internal surface area. This characteristic, the ↑ surface-to-volume ratio, enables them to hold large volumes of pollutants.

Several materials are used as adsorbing agents: activated carbon, aluminum oxide, silica gel and alumina silicates.

Activated carbon by Ravedave licensed under CC BY 2.5

Silica gel by Henningklevjer licensed under CC BY-SA 2.5

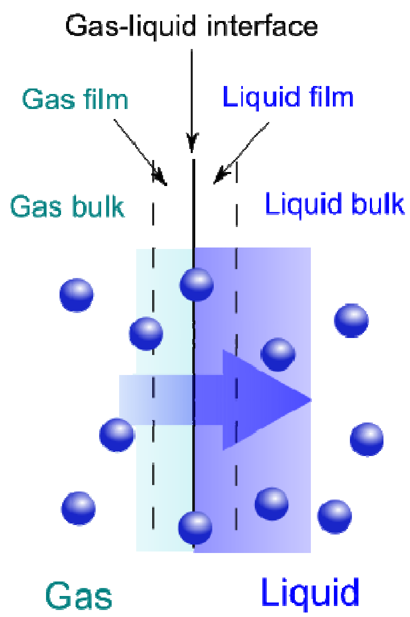
A variety of configurations are used to bring a polluted airstream into contact with the adsorbent. The most common industrial configuration is to pass the airstream down through a **bed of adsorbent material**. As the contaminant-laden airstream passes through the bed, it becomes saturated or *filled* with these gases. When this happens, to continue to be effective, the adsorbent is replaced or the pollutants are desorbed. The most common way to desorb the gases is injecting steam.

Application

In addition to dehumidifying air and other gases, adsorption is useful in removing odors and pollutants (VOCs, CS_2, COS,...) from industrial gases as well as recovering of valuable solvent vapors from air and other gases.

4.3.2. Absorption

Absorption is a process that refers to the transfer of a gaseous pollutant from a gas phase into a **liquid phase**. The liquid into which the pollutant is absorbed is the **absorbent** and the gaseous pollutant being absorbed is the solute or **absorbate.**



Absorption process by Aushulz licensed under CC BY-SA 3.0

Classification

The absorption process can also be categorized as **physical** (absorbed compound dissolves in the liquid without reacting) or **chemical** (absorbed compound and the liquid react).

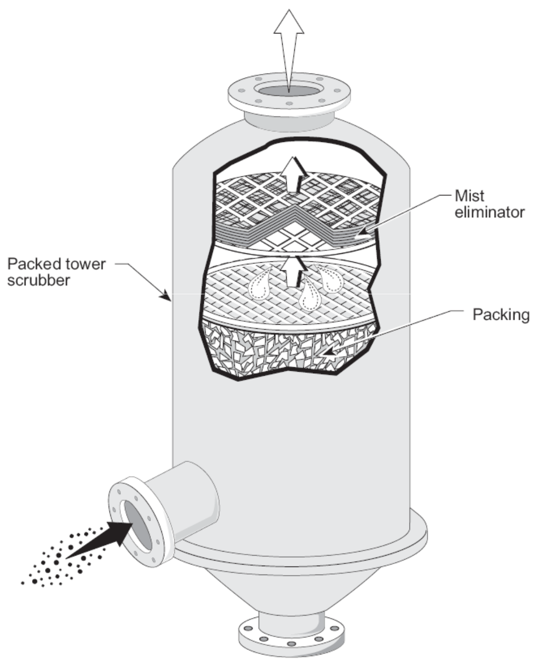
Good **gas-to-liquid contact** is essential to obtain high efficiency removal in absorbers. Thus, the wet scrubbers are designed to get as much mixing between the gas and liquid as possible with a minimum of gas pressure drop. This can be done by forcing the gas stream through a pool of liquid, spraying it with the liquid, or by some other contact method. A number of designs are used to remove gaseous pollutants with **packed towers** and **plate towers** being the most common.

In **packed towers** liquid is poured over a packing material contained between support trays.

A liquid film coats the packing through which the exhaust gas stream is forced.

Pollutants are collected as they pass through the packing, which provides a large contact area between the gas and the liquid phase.

The most common design flow configuration is countercurrent.



Packed tower by BetacommandBot licensed under Public Domain

A **plate tower** is a vertical column with one or more plates mounted horizontally inside.

The dirty gas enters at the bottom and flows upward, passing through openings in the plates. Liquid enters at the top of the tower, travelling across each plate to a down-comer. Pollutant collection occurs at each plate as the dirty gas contacts and then atomizes the liquid flowing over each plate.

The **scrubbing liquid** is chosen with specific reference to the gas being removed. The liquid used most often is water since it is inexpensive and can dissolve a number of pollutants. Some other solvents commonly used in absorption devices are monoethanolamine, diethanolamine, alkaline and acid solutions.

4.3.3. Condensation

Condensation is the process of **converting gaseous vapors into liquid droplets**. This separation technique is applied to gaseous mixtures containing at least one gas with a higher boiling point than the others.

A compound condenses when its partial pressure increases up to the point equal or greater than its vapor pressure at a given temperature. The higher (lower) the vapor pressure of a compound at a given temperature, the higher (lower) the volatility and the lower (higher) the boiling point of the compound, the longer (shorter) they stay in the gas phase at a given temperature and the lower (higher) the temperature required for its saturation, that is, its condensation.

The conversion from gas phase to liquid phase is usually achieved by **reducing the temperature** of the pollutant-laden gas stream until liquid droplets form or by **increasing its pressure.**

Classification

Condensers fall into two basic categories:

- Contact condensers
- Surface condensers


Surface condenser by M-I Nguyen licensed under CC BY 2.5

4.3.4. Oxidation-reduction

Gaseous pollutants can be transformed into inert or lower-hazard compounds by oxidation and reduction.

In **oxidation**, pollutants react with oxygen, whereas, in **reduction**, pollutants combine with carbon, carbon monoxide or hydrogen.

A widely used system for the control of organic gaseous emissions is **oxidation of the combustible components** to water and carbon dioxide (**combustion**). Reduction is applied to transform nitrogen oxides to nitrogen.

These two processes are carried out in units which are very similar to the ones employed by chemical industry.

Combustion

It is used to control combustible gases emitted from various industries, such as hydrocarbons, other organic vapors and S, Cl and F.

Depending on the compound to be oxidized, three kinds of combustion equipment are used:

- **Flares.** All waste gases are burned directly in a combustor with the aid of an additional fuel such as natural gas or oil.
- **Thermal oxidizers** use a flame in a chamber to convert combustible material to carbon dioxide and water at 700-1000 °C.
- **Catalytic oxidizers.** After passing through the flame area, the gases pass over a catalyst bed that promotes an oxidation at lower temperature than is necessary in thermal oxidizers: 400-500 °C.

4.3.5. Biofiltration

Waste gases with low-to-moderate concentrations of biodegradable pollutants may be treated with biological systems. These systems are based on the absorption of the pollutants into a liquid phase and the subsequent degradation by microorganisms into less harmful and simpler compounds such as CH_4 (if anaerobic) CO_2 (if aerobic) and water.

Biofilter by Llucas licensed under CC BY-SA 3.0

Classification

According to how the gas interfaces with the microorganisms, the systems are classified into three basic types:

- **Biofilters.** The gas containing pollutants is passed through a filter medium where microorganisms are grown. The gas phase is stationary.
- **Bioscrubbers.** Pollutants are biologically degraded by the microorganisms suspended in a washing liquid. The gas moves through the biologically active media.
- **Combinations** of biofilters and bioscrubbers.

The **applicability** and **efficiency** of biofiltration depend on:

- The water solubility and biodegradability of the compounds
- The presence of inhibiting compounds in the waste gas.
- The potential threat of the products of the biodegradation both for the biological system and for the environment.

Application

These biological systems are mainly used for removal of odors and destruction of organic compounds such as VOCs. Microorganisms use these pollutants as energy or as a carbon source.

In addition to a wide array of organic compounds, biological systems remove successfully inorganic compounds such as ammonia and hydrogen sulfide.

Advantages and disadvantages

All three types of biological systems have relatively low operating costs, since they are habitually operated near ambient temperature and pressure conditions.

However, care must be taken in maintaining the optimal environmental conditions for the growth of the microorganisms. This includes humidification, cooling, addition of nutrients, and extraction of inhibiting substances, among others. Thus, other costs include amendants and humidification.