Gaseous Emission-Control Technologies
(Air-Quality Technology)

(Nazaroff & Alvarez-Cohen, Section 7.C)
(Mihelcic & Zimmerman, Section 12.7)

Two different approaches:

- Pollution Prevention at the source – the better alternative
- Treatment of fumes as they are formed – the classical approach

Table 7.C.2 Treatment Technologies for Gaseous Air Pollutants

Technology	Pollutants[a]	Description and comment
Absorption	H_2S, SO_2, HCl, VOCs	A spray scrubber or packed column maintains a high gas-liquid contact area; especially effective for water-soluble species that can be converted to nonhazardous form in water
Adsorption	VOCs	Contact is promoted between gas and granular sorbent material, such as activated carbon, so that pollutant molecules adhere to surfaces; often the method of choice for controlling nonpolar organics; can be effective when low trace levels of contamination (ppb–ppm) must be achieved; effective in processing large air volumes with dilute contaminants
Incineration	VOCs	Waste gases are burned to convert H to H_2O, C to CO_2; commonly applied for low to medium levels of contamination with pure hydrocarbons or oxygenated organics
Catalytic redox	NO, CO, VOCs	Solid catalyst is used to increase rate of reaction and convert elements to less hazardous forms; common application is the three-way catalyst used in motor vehicles
Condensation	VOCs	Phase change from gas to liquid is caused either by cooling or by increasing pressure; requires high gas-phase concentration of species with significant recovery value and high boiling point; cannot achieve very low gas-phase concentrations, so sometimes used as pretreatment technique
Membrane recovery	VOCs	Organic vapors are separated from air by flowing gas past membranes that are more permeable to organics than to air; advanced, newly emerging technology

[a]Illustrative examples rather than an exhaustive list.

(Nazaroff & Alvarez-Cohen, Table 7.C.2, page 444)

Nazaroff & Alvarez-Cohen, 7.B Air Pollutant Emissions and Controls

Example of steps taken to minimize air pollution from gasoline internal combustion engines

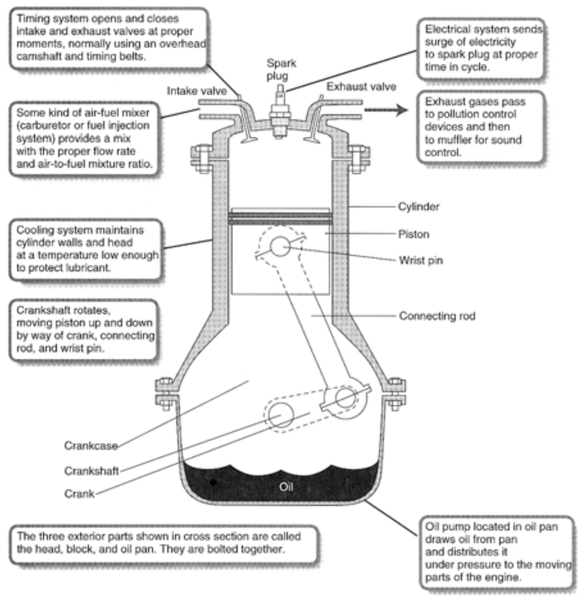
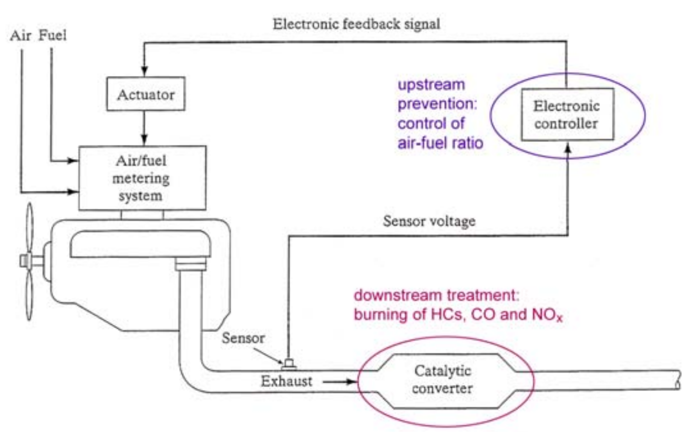


Figure 7.B.10 Simplified schematic of a single cylinder in a motor vehicle engine. (N. de Nevers, *Air Pollution Control Engineering*, McGraw-Hill, New York, 1995; reproduced with permission of The McGraw-Hill Companies.)



For a three-way catalyst to function correctly, the air-to-fuel ratio must be maintained within a very narrow band. To maintain that ratio, a closed-loop control system monitors the composition of exhaust gases and sends corrective signals to the air-to-fuel metering system. (After Powell and Brennan, 1988)

A three-way catalytic converter performs three simultaneous tasks:

1. Oxidation of carbon monoxide (CO) to carbon dioxide

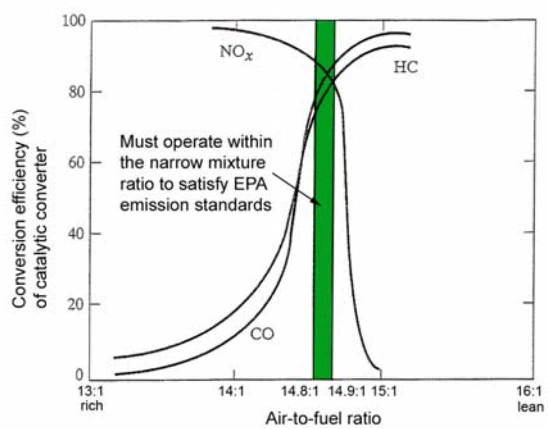
$$2\ CO + O_2 \rightarrow 2\ CO_2$$

2. Oxidation of unburned hydrocarbons (HC) to carbon dioxide and water

$$C_xH_{2y} + [(2x+y)/2]O_2 \rightarrow x\ CO_2 + y\ H_2O$$

3. Reduction of nitrogen oxides to nitrogen and oxygen

$$2NO_x \rightarrow N_2 + x\ O_2$$



In other words: Choose your pollutant!

Techniques to remove particles from an air stream

Table 7.C.1 Control Devices for Capturing Particulate Air Pollutants

Device	Particle size	Collection mechanism and application
Settling chamber	>~20 μm	Separates particles from a gas stream by gravity; used to treat very dirty air streams that contain very coarse particles
Cyclone	>~1 μm	Separates particles by inertia in a vortex flow; common pretreatment process ahead of electrostatic precipitator or fabric filter
Scrubber	>~1 μm	Wet collector; induces collisions between particles and water droplets to remove particles from gas stream by inertia; may be used for combined collection of particles and water-soluble gases
Electrostatic precipitator	All	Creates electrostatic charge on particles so they can be removed by an electric field; high-efficiency device that is used to treat stack gases in industrial processes
Filter	All	Air flow is forced through matrix of fibers, capturing particles by a combination of Brownian motion, physical straining, interception, and impaction; high efficiency possible; applied for treating waste gases and for removing particles from air before use

(Nazaroff & Alvarez-Cohen, Table 7.C.1, page 443)

Cyclone Separators and their Design

(Nazaroff & Alvarez-Cohen, pages 445-447 augmented)
(Mihelcic & Zimmerman, Section 12.8.1)

Low-pressure drop cyclone
at Rochester Asphalt Plant
(Victor, NY)

A cyclone used in a woodshop
(Lebanon, NH)

http://www.jtsystemsinc.com/

Cyclone separators have been used in the United States for about 100 years, and are still one of the most widely used of all industrial gas-cleaning devices. The main reasons for the wide-spread use of cyclones are that they are inexpensive to purchase, they have no moving parts, and they can be constructed to withstand harsh operating conditions.

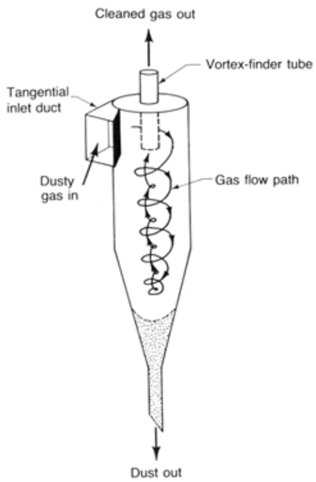
Cyclone Design

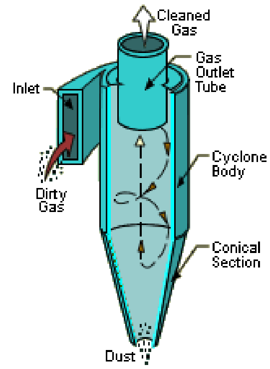
(Adapted from *Air Pollution Control* by C. D. Cooper & F.C . Alley, 1986)

Typically, a particulate-laden gas enters tangentially near the top of the cyclone, as shown schematically in the left figure. The gas flow is forced into a downward spiral simply because of the cyclone's shape and the tangential entry.

Another type of cyclone (a vane-axial cyclone – see right figure) employs an axial inlet with fixed turning vanes to achieve a spiraling flow.

Centrifugal force and inertia cause the particles to move outward, collide with the outer wall, and then slide downward to the bottom of the device. Near the bottom of the cyclone, the gas reverses its downward spiral and moves upward in a smaller inner spiral. The cleaned gas exits from the top through a "vortex-finder" tube, and the particles exit from the bottom of the cyclone through a pipe sealed by a spring-loaded flapper valve or rotary valve.





Advantages of cyclones:

Low capital cost (few parts, easy to assemble)
Ability to operate at high temperatures (all metal parts)
Low maintenance requirements (no moving parts).

Disadvantages of cyclones:

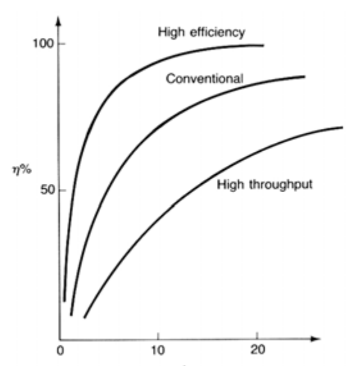
Low collection efficiencies (especially for very small particles)
→ cyclones used almost exclusively for particles > 5 μm.
High operating costs (power required to overcome large pressure drop).

Cyclones by themselves are generally not adequate to meet stringent air pollution regulations, but they serve an important purpose. Their low capital cost and their maintenance-free operation make them ideal for use as pre-cleaners for more expensive final control devices such as baghouses or electrostatic precipitators. In addition to use for pollution control, cyclones are used extensively in process industries. For example, they are used for recovering and recycling certain catalysts in petroleum refineries, for recovering freeze-dried coffee in food processing plants, and for capturing saw dust in a lumber shop.

Cyclones have often been regarded as low-efficiency collectors. However, efficiency varies greatly with particle size and cyclone design. Advanced design work has greatly improved cyclone performance. Some cyclone manufacturers advertise cyclones that have efficiencies greater than 98% for particles larger than 5 microns, and others that routinely achieve efficiencies of 90% for particles larger than 15 – 20 microns.

In general, operating costs increase with efficiency (higher efficiency requires higher inflow pressure), and three categories of cyclones are available: high efficiency, conventional, and high throughput.

Typical efficiency curves for these three types of cyclones are presented in the figure.



Standard Cyclone Dimensions

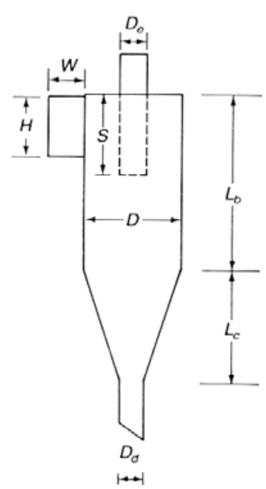
Extensive work has been done to determine in what manner dimensions of cyclones affect performance. In some classic work that is still used today, Shepherd and Lapple (1939, 1940) determined "optimal" dimensions for cyclones. Subsequent investigators reported similar work, and the so-called "standard" cyclones were born.

All dimensions are related to the body diameter of the cyclone so that the results can be applied generally.

The table on the next slide summarizes the dimensions of standard cyclones of the three types mentioned in the previous figure. The side figure illustrates the various dimensions used in the table.

Standard cyclone dimensions

	Cyclone Type					
	High Efficiency		Conventional		High Throughput	
	(1)	(2)	(3)	(4)	(5)	(6)
Body Diameter, D/D	1.0	1.0	1.0	1.0	1.0	1.0
Height of Inlet, H/D	0.5	0.44	0.5	0.5	0.75	0.8
Width of Inlet, W/D	0.2	0.21	0.25	0.25	0.375	0.35
Diameter of Gas Exit, D_e/D	0.5	0.4	0.5	0.5	0.75	0.75
Length of Vortex Finder, S/D	0.5	0.5	0.625	0.6	0.875	0.85
Length of Body, L_b/D	1.5	1.4	2.0	1.75	1.5	1.7
Length of Cone, L_c/D	2.5	2.5	2.0	2.0	2.5	2.0
Diameter of Dust Outlet, D_d/D	0.375	0.4	0.25	0.4	0.375	0.4



SOURCES:
Columns (1) and (5) = Stairmand, 1951; columns (2), (4) and (6) = Swift, 1969; column (3) and sketch = Lapple, 1951.

Cyclone Theory

Collection Efficiency

A very simple model can be used to determine the effects of both cyclone design and operation on collection efficiency.

In this model, gas spins through a number N of revolutions in the outer vortex. The value of N can be approximated as the sum of revolutions inside the body and inside the cone:

$$N = \frac{1}{H}\left(L_b + \frac{L_c}{2}\right)$$

where

N = number of turns inside the device (no units)
H = height of inlet duct (m or ft)
L_b = length of cyclone body (m or ft)
L_c = length (vertical) of cyclone cone (m or ft).

To be collected, particles must strike the wall within the amount of time that the gas travels in the outer vortex. The *gas residence time* in the outer vortex is

$$\Delta t = \text{path length / speed} = \pi\, D\, N / V_i$$

where

Δt = time spent by gas during spiraling descent (sec)
D = cyclone body diameter (m or ft)
V_i = gas inlet velocity (m/s or ft/s) = Q/WH
Q = volumetric inflow (m^3/s or ft^3/s)
H = height of inlet (m or ft)
W = width of inlet (m or ft).

The maximum radial distance traveled by any particle is the width of the inlet duct W. The centrifugal force quickly accelerates the particle to its terminal velocity in the outward (radial) direction, with the opposing drag force equaling the centrifugal force. The terminal velocity that will just allow a particle initially at distance W away from the wall to be collected in time is

$$V_t = W / \Delta t$$

where V_t = particle drift velocity in the radial direction (m/s or ft/s).

The particle drift velocity is a function of particle size.

Assuming Stokes regime flow (drag force = $3\pi\mu d_p V_t$) and spherical particles subjected to a centrifugal force mv^2/r, with m = mass of particle in excess of mass of air displaced, $v = V_i$ of inlet flow, and $r = D/2$, we obtain

$$V_t = \frac{(\rho_p - \rho_a)\, d_p^2\, V_i^2}{9\,\mu\, D}$$

where

V_t = terminal drift transverse velocity (m/s or ft/s)
d_p = diameter of the particle (m or ft)
ρ_p = density of the particle (kg/m^3)
ρ_a = air density (kg/m^3)
μ = air viscosity (kg/m.s).

Substitution of the 2nd equation into the 3rd eliminates Δt. Then, setting the two expressions for V_t equal to each other and rearranging to solve for particle diameter, we obtain

$$d_p = \left[\frac{9\,\mu W}{\pi N V_i (\rho_p - \rho_a)}\right]^{1/2}$$

It is worth noting that in this expression, d_p is the size of the smallest particle that will be collected if it starts at the inside edge of the inlet duct. Thus, in theory, all particles of size d_p or larger should be collected with 100% efficiency.

Note that the units must be consistent in all equations.
One consistent set is m for d_p, R and W; m/s for V_i and V_t; kg/m.s for μ; and kg/m^3 for ρ_p and ρ_a.
An equivalent set in English units is ft for d_p, R and W; ft/sec for V_i and V_t; lbm/ft.sec for μ; and lbm/ft^3 for ρ_p and ρ_a.

The preceding equation shows that, in theory, the smallest diameter of particles collected with 100% efficiency is directly related to gas viscosity and inlet duct width, and inversely related to the number of effective turns, inlet gas velocity, and density difference between the particles and the gas.

In practice, collection efficiency does, in fact, depend on these parameters. However, the model has a major flaw: It predicts that ***all*** particles larger than d_p will be collected with 100% efficiency, which is incorrect. This discrepancy is the result of all our approximations.

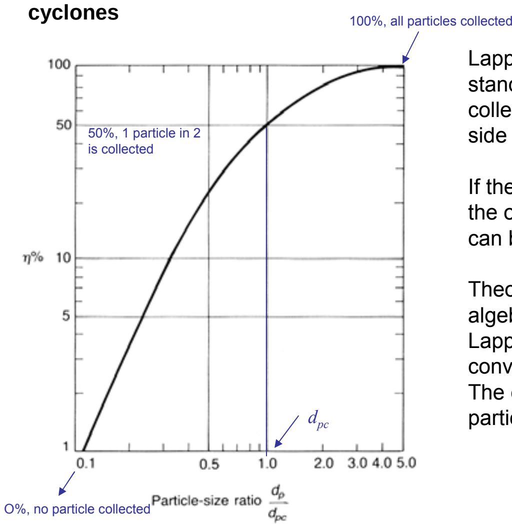
Lapple (1951) developed a semi-empirical relationship to calculate a "50% cut diameter" d_{pc}, which is the diameter of particles collected with 50% efficiency. The expression is

$$d_{pc} = \left[\frac{9 \mu W}{2\pi N V_i (\rho_p - \rho_a)} \right]^{1/2}$$

where d_{pc} = diameter of particle collected with 50% efficiency.

Note the similarity between the last two equations. The only difference is a factor 2 in the denominator.

Particle collection efficiency versus particle size ratio for standard conventional cyclones



Lapple then developed a general curve for standard conventional cyclones to predict the collection efficiency for any particle size (see side figure).

If the size distribution of particles is known, the overall collection efficiency of a cyclone can be predicted by using the figure.

Theodore and DePaola (1980) then fitted an algebraic equation to the curve, which makes Lapple's approach more precise and more convenient for application to computers. The efficiency of collection of any size of particle is given by

$$\eta_j = \frac{1}{1 + (d_{pc}/d_{pj})^2}$$

where

η_j = collection efficiency of particles in the jth size range ($0 < \eta_j < 1$)
d_{pj} = characteristic diameter of the jth particle size range (in μm).

The overall efficiency, called performance, of the cyclone is a weighted average of the collection efficiencies for the various size ranges, namely

$$\eta = \frac{\sum \eta_j m_j}{M}$$

where

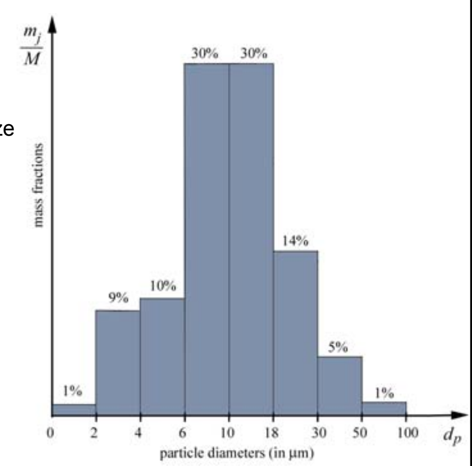
η = overall collection efficiency ($0 < \eta < 1$)
m_j = mass of particles in the jth size range
M = total mass of particles.

Example of Cyclone Analysis

Given:

Conventional type (standard proportions)
D = 1.0 m
Flow rate = Q = 150 m^3/min
Particle density = ρ_p = 1600 kg/m^3
Particle size distribution as follows:

Particle size (d_p)	% mass in that size (m/M)
0-2 μm	1.0%
2-4 μm	9.0%
4-6 μm	10.0%
6-10 μm	30.0%
10-18 μm	30.0%
18-30 μm	14.0%
30-50 μm	5.0%
50-100 μm	1.0%
	100%



Question:

What is the collection efficiency?

Solution

$$N = \frac{1}{H}\left(L_b + \frac{L_c}{2}\right) = 6 \qquad V_i = \frac{Q}{WH} = \frac{Q}{0.125\,D^2} = 1200 \text{ m/min } = 20 \text{ m/s}$$

$$d_{pc} = \sqrt{\frac{9}{2\pi}\frac{\mu W}{NV_i(\rho_p - \rho_a)}} = \sqrt{\frac{9}{2\pi}\frac{0.25\mu D}{6V_i(\rho_p - \rho_a)}} = 5.79 \times 10^{-6}\,\text{m} = 5.79\ \mu\text{m}$$

Size range (in μm)	Average size d_p (in μm)	Collection efficiency η	Mass fraction m/M	Contribution to performance $\eta \times m/M$
0 – 2	1	2.9%	0.01	0.029%
2 – 4	3	21.1%	0.09	1.903%
4 – 6	5	42.7%	0.10	4.268%
6 – 10	8	65.6%	0.30	19.678%
10 – 18	14	85.4%	0.30	25.613%
18 – 30	24	94.5%	0.14	11.953%
30 – 50	40	97.9%	0.05	4.897%
50 - 100	75	99.4%	0.01	0.994%
			1.00	**70.6%**

Two distinct approaches in cyclone analysis

1. *Performance analysis*

The cyclone exists – All dimensions and characteristics are known.
The engineer calculates its collection efficiency (η).

2. *Design analysis*

The cyclone needs to be chosen for a given task.
A target performance (η) is imposed.
Typically, the engineer knows the amount of air flow (Q),
& characteristics of particles (range of d_p's, mass fractions m_j/M).
The engineer needs to determine
the type of cyclone needed (conventional, high-throughput, …)
the required size of the device (diameter D).

Note: Design analysis usually necessitates an iterative approach.
(Successive guesses until the required performance is achieved.)