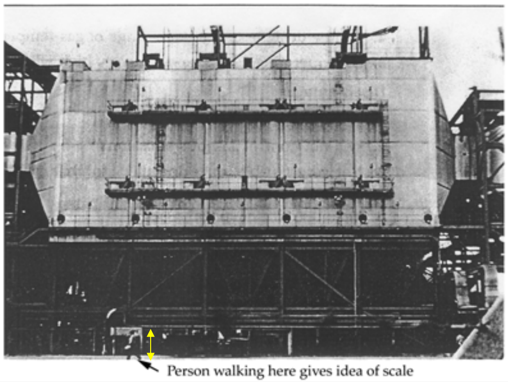
Electrostatic Precipitators

(Mihelcic & Zimmerman, Section 12.8.4; Mines & Lackey, Section 11.5.2 + much added material)

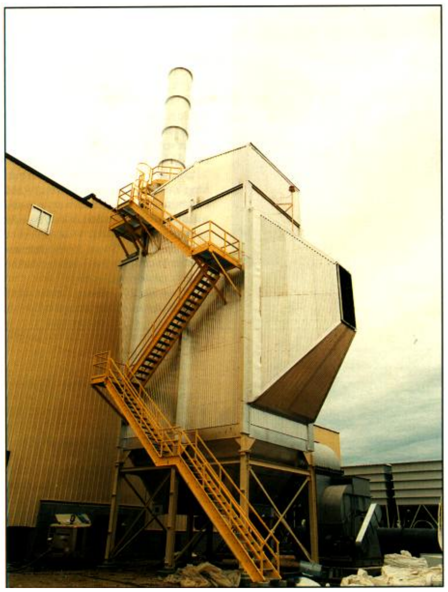
An ESP installed on a 364 MW coal-fired power plant (the coal has about 15% ash, and the ESP treats roughly one million acfm at 99.6% efficiency; the plate height is 14.5 m with 30 cm spacing, 50 channels, 5 sections in the direction of flow, and 10 bus sections total).



Person walking here gives idea of scale

A couple more pictures of electrostatic precipitators

(http://www.bheltry-spares.com/esp.htm)

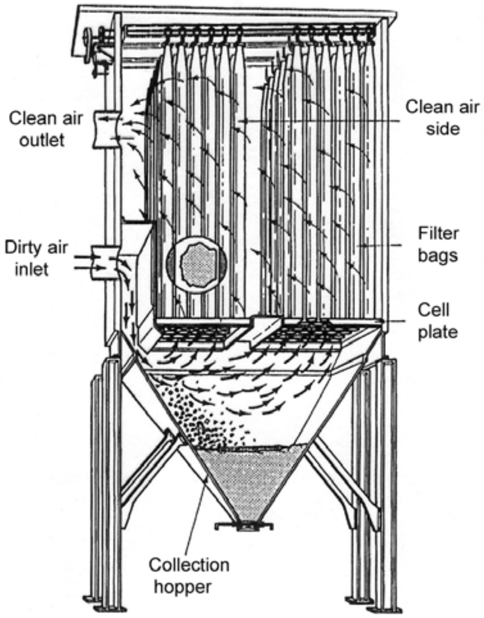


(http://www.ppcesp.com/ppcart.html)

Electrostatic precipitators (ESPs) are major pieces of equipment and are expensive.

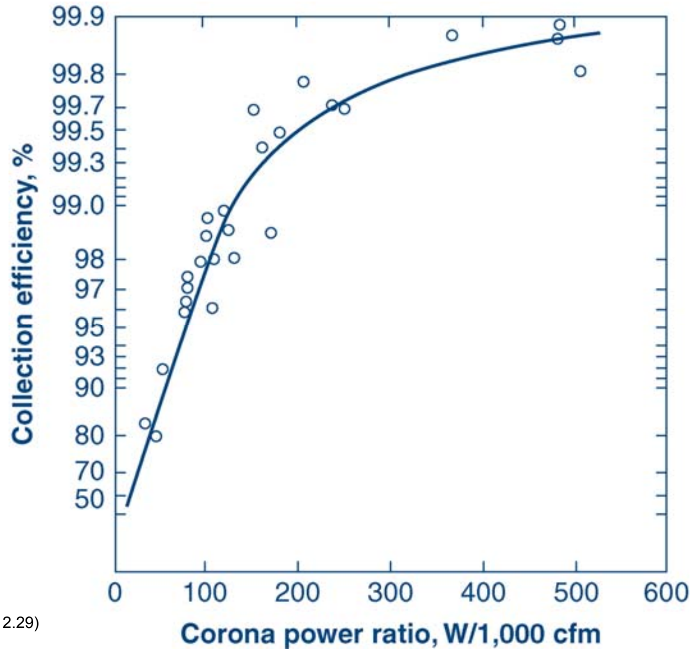
Electrostatic precipitators work better than the alternative, the fabric filter baghouse…

… especially when the gas to be treated and its particles are hot or wet.



Typical simple fabric filter baghouse
(*Source*: Wheelabrator Pollution Control)

Typical efficiency of an electrostatic precipitator as a function of the corona power ratio, power (Watts) consumed divided by the airflow in cubic feet per minute (cfm).



(*Source*:
Mihelcic & Zimmerman, Figure 12.29)

Comparison:
CYCLONES versus ELECTROSTATIC PRECIPITATORS

Cyclones and electrostatic precipitators are two different types of equipment, each capable of removing particles from an air stream. When the decision arises regarding which type to adopt in a specific situation, one needs to know the advantages and disadvantages of each type of equipment.

CYCLONES:

Advantages:

Low capital cost
  (= relatively cheap to buy and install)
Ability to operate at high temperatures
Low maintenance requirements
  (absence of moving parts)

Disadvantages:

Relatively low efficiency
  (especially for the smaller particles)
Limited to dry particles
  (= not operating well on mist)
High operating cost
  (= expensive to run, because of pressure loss)

ELECTROSTATIC PRECIPITATORS:

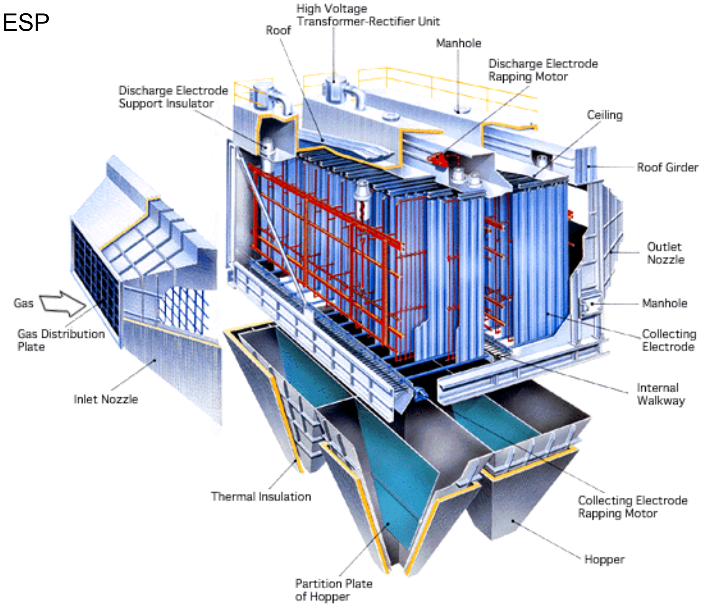
Advantages:

Low operating cost
  (except at very high efficiencies)
Very high efficiency, even for smaller particles
Ability to handle very large gas flow rates
  with low pressure losses
Ability to remove dry as well as wet particles
  (= mist ok)
Temperature flexibility in design

Disadvantages:

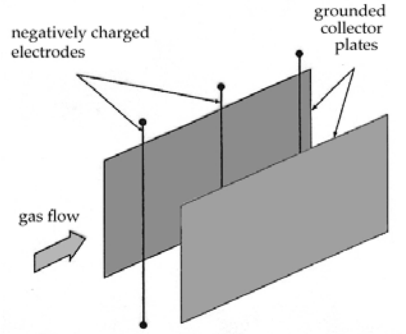
High capital cost
  (= expensive to purchase and install)
Taking a lot of space
Not flexible once installed
Failure to operate on particles with
  high electrical resistivity

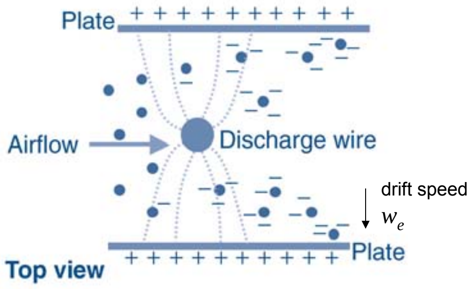
Inside an ESP



(http://www.qrbiz.com/product/1472881/Electrostatic-Precipitator.html)

At the core
of the apparatus



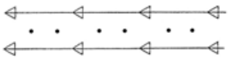


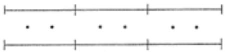
Principle: Electrodes at high voltage create a corona effect (ionized atmosphere) surrounding them. This charges the passing particles. Once charged, particles are subject to a transverse electrostatic force that pulls them toward the collecting plates. Plates are periodically "rapped" (vibrated) to make the collected particles fall down into a receiver basket.

Various types of
charging electrodes
and collecting plates

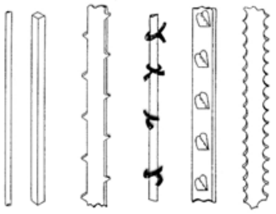
The baffles along the collecting plates are there to catch better the drifting particles.

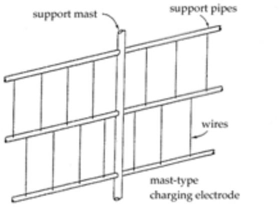
Note the indentations and sharp corners on some of the electrodes. These are to enhance the corona effect.

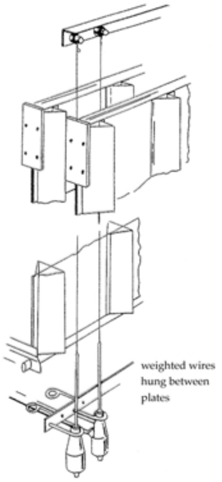

Opzel plates


baffle plates


other type of baffle plates


various types of charging electrodes





Drift speed

The particle drift speed (w_e) results from a balance between the electrostatic force due to the charge (F_e) and the resisting drag force (F_d) exerted by the air due the relative motion between air and particle.

For the drag force, we assume that the particles are very small. (The purpose of an ESP is precisely to catch very small particles!). So, we use Stokes' Law with the Cunningham Slip factor correction (refer to slide in lecture on Transport Phenomena).

$$F_e = \text{electrostatic force} = \text{charge} \times \text{electric field} = qE$$

$$F_d = \text{drag force} = \frac{3\pi\mu_f d_p w_e}{C_c}$$

$$F_d = F_e \quad \Rightarrow \quad \frac{3\pi\mu_f d_p w_e}{C_c} = qE \quad \Rightarrow \boxed{w_e = \frac{C_c qE}{3\pi\mu_f d_p}}$$

where

q = charge acquired by each particle

E = electrical field = voltage difference divided by electrode-plate distance d

C_c = Cunnigham slip factor (to be obtained from graph or formula)

μ_f = fluid viscosity = 1.81 x 10^{-5} kg/m.s for air at ambient temperature

d_p = particle diameter

The charge q acquired by a particle is a certain number times the charge of the electron, which is 1.6 x 10^{-19} C.

So, for example, if a particle acquires 12 electrons, its charge is:

$$q = 12 \times 1.6 \times 10^{-19}\ \text{C} = 1.92 \times 10^{-18}\ \text{C}.$$

The number of electrons acquired depends on the intensity of the corona generated around the electrodes, and this is proportional to the electrical field E. Thus, q is proportional to E, making the electrical force qE proportional to E^2.

It follows that the drift speed w_e, too, is proportional to the square of the electrical field. This is a useful amplification of the effect.

A rule to determine the charge acquired by a particle is:

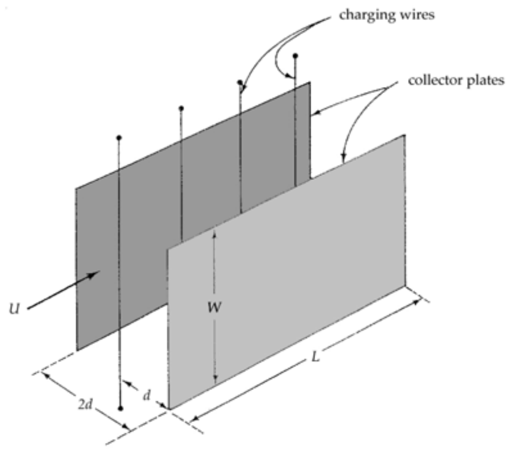
$$q = \pi d_p^2 \varepsilon_0 \frac{3\varepsilon}{2+\varepsilon} E_{ch}$$

where

ε_0 = 8.85 x 10^{-12} C/V.m = permittivity of vacuum

$\varepsilon \approx 3.7$ = dielectric constant for the particle relative to vacuum

E_{ch} = charging field strength (in V/m), different from collecting.



Nomenclature:

U = speed of air flow
d = electrode-plate distance
   = half of plate separation distance
W = plate width (height)
L = plate length

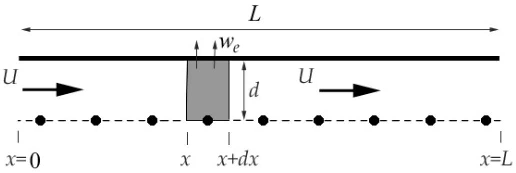
Budget for an interval (x, $x+dx$) along the flow, and between electrode and plate (distance d) and for the full width W of the plate:

$$V\cancel{\frac{dC}{dt}} = Q_{upstream}C_{upstream} - Q_{downstream}C_{downstream} - Q_{drift}C_{drift}$$

steady state

where each volumetric flowrate Q is the product of a velocity with the respective cross-sectional area:

$$Q_{upstream} = UWd$$
$$Q_{downstream} = Q_{upstream} = UWd$$
$$Q_{drift} = w_e W dx$$



The budget then becomes:

$$0 = (UWd)C(x) - (UWd)C(x+dx) - (w_e W dx)C\left(x + \frac{dx}{2}\right)$$

This budget equation can be rewritten as

$$(Ud)\frac{C(x+dx)-C(x)}{dx}=-w_e C\left(x+\frac{dx}{2}\right)$$

In the limit of $dx \to 0$, we obtain the differential equation

$$Ud\,\frac{dC}{dx}=-\,w_e\,C(x)\quad\Rightarrow\quad\frac{dC}{dx}=-\frac{w_e}{Ud}\,C$$

The solution of which is

$$C(x)=C(x=0)\,e^{-w_e x/Ud}$$

With $C(x=0)=C_{in}$ and
writing the solution for the end point $x = L$ where $C(x = L) = C_{out}$,
we obtain

$$C(x=L)=C(x=0)\,e^{-w_e L/Ud}\quad\Rightarrow\quad C_{out}=C_{in}\;e^{-w_e L/Ud}$$

Efficiency

The efficiency η is defined as the percentage of removal.
We find it to be:

$$\eta=\frac{\text{amount removed}}{\text{amount entering}}=\frac{C_{in}-C_{out}}{C_{in}}=1-\frac{C_{out}}{C_{in}}$$

$$=1-\exp\left(-\frac{w_e\,L}{U\,d}\right)$$

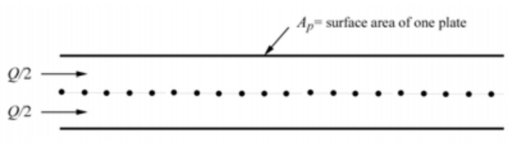
Since the flow speed U is the volumetric flow Q of air divided by the cross-sectional area Wd, we can also write the efficiency as:

$$\eta=1-\exp\left(-\frac{w_e WL}{Q}\right)=1-\exp\left(-\frac{w_e A}{Q}\right)$$

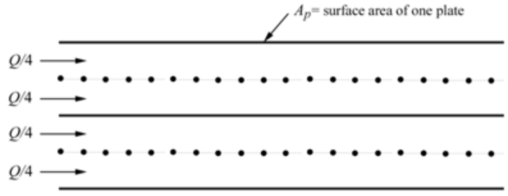
where $A=WL$ is the collecting plate area.

Dividing the total collecting area in a set of plates

$$\eta = 1 - \exp\left(-\frac{w_e A_p}{Q/2}\right)$$
$$= 1 - \exp\left(-\frac{w_e (2A_p)}{Q}\right)$$
$$= 1 - \exp\left(-\frac{w_e A}{Q}\right)$$



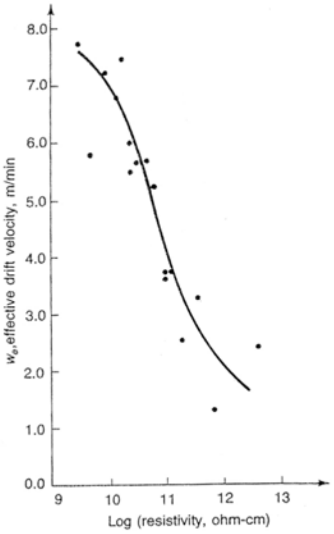
$$\eta = 1 - \exp\left(-\frac{w_e A_p}{Q/4}\right)$$
$$= 1 - \exp\left(-\frac{w_e (4A_p)}{Q}\right)$$
$$= 1 - \exp\left(-\frac{w_e A}{Q}\right)$$



etc. with more plates. Rule is that A in the formula stands for the total plate collecting area.

Effect of fly-ash resistivity on effective drift velocity in an electrostatic precipitator

Particles of high electrical resistivity lose their charge slowly after hitting the collecting plate. This creates an electrical shield on the plates that lowers the ambient electric field. As a result, particles of high electrical resistivity are harder to collect.



SOURCE: Adapted from White, "Control of Particulates by Electrostatic Precipitation," *Handbook of Air Pollution Technology*. Copyright © 1984 by John Wiley & Sons, Inc.

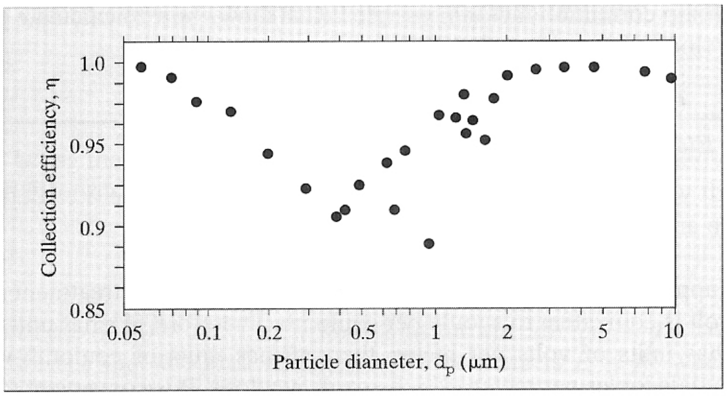


Figure 7.C.4 Measured collection efficiency as a function of particle size for an electrostatic precipitator installed on a pulverized coal boiler. (Reprinted with permission of the Air & Waste Management Association from J.D. McCain et al. [1975].)

(Nazaroff & Alvarez-Cohen, Figure 7.C.4)

Larger particles are removed more efficiently because they acquire a greater electric charge, whereas smaller particles, too, are removed more efficiently because they are subjected to less drag and thus drift more easily, leaving intermediate particles as those that are less efficiently collected. Nonetheless, efficiency easily exceeds 90% for all particles.

An example

Design requirement Device must achieve an efficiency of 99%

Given situation

Airflow Q = 2,000 m^3/min
Particle diameter d_p = 1 μm
Average particle charge q = 10 electron charges
Electric field E = 50,000 V/m
Each plate has dimensions 6 m by 3 m.

Solution

One-micron particles are quite small. So, we include the correction due to the Cunningham slip factor:

$$C_c = 1 + \frac{\lambda_g}{d_p}\left[2.51 + 0.80\exp\left(-\frac{0.55 d_p}{\lambda_g}\right)\right]$$

With λ = 0.066 μm and d_p = 1 μm, we get C_c = 1.166.

Next, we calculate the electric charge on each particle. It is

q = 10 e = 10 x 1.6 10^{-19} C = 1.6 x 10^{-18} C

The drift speed can now be estimated:

$$w_e = \frac{qEC_c}{3\pi\mu\, d_p} = \frac{(1.6\times10^{-18}\,\mathrm{C})(5\times10^{4}\,\mathrm{V/m})(1.166)}{(3\pi)(1.81\times10^{-5}\,\mathrm{kg/m.s})(10^{-6}\,\mathrm{m})} = 5.47\times10^{-4}\ \mathrm{m/s}$$

(Note how small it actually is.)

For an efficiency of 99% (η = 0.99), we must have

$$\exp\left(-\frac{A\,w_e}{Q}\right) = 1 - 0.99 = 0.01 \ \Rightarrow\ \frac{A\,w_e}{Q} = 4.61$$

With Q given (= 2000 m^3/min = 33.33 m^3/s) and w_e already determined, we can deduce the total collecting area A:

$$A = \frac{(4.61)\,(33.33\,\mathrm{m}^3/\mathrm{s})}{(5.47\times10^{-4}\ \mathrm{m/s})} = 280{,}632\,\mathrm{m}^2$$

Since a single plate offers a collecting area of 2 x 6 x 3 = 36 m^2 (counting both sides), the required number of plates is

$$n = \frac{280{,}632\,\mathrm{m}^2}{36\,\mathrm{m}^2} + 1 = 7{,}780$$

(*Note*: Need to add 1 because the two terminal plates each offer only a single collecting side.)