Chapter 6

Separation of Particles from Gas

- Separation efficiency
- Separation mechanisms
  - *Gravitational settling*
  - *Electrostatic precipitation*
  - *Centrifugal separation*
  - *Filtration*

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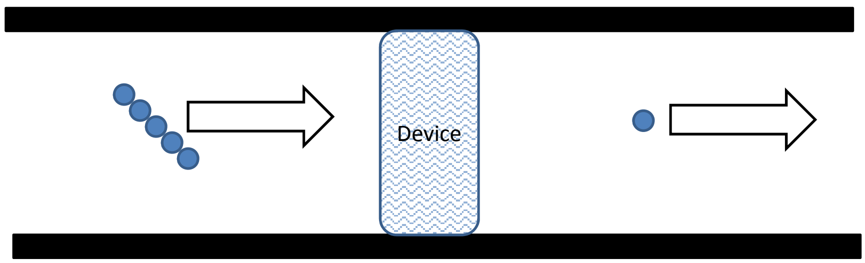
Separation Efficiency

- Consider the simplest case
- 5 particles, same size, going through a filter, 1 made it.



- Penetration efficiency = 1/5 = 20%
- Collection efficiency = 4/5=80%

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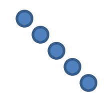
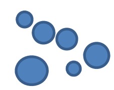
Monodisperse and Polydisperse

- **Monodisperse**: characterized by particles of uniform size in a dispersed phase



- **Polydisperse**: characterized as particles of varied sizes in the dispersed phase of a disperse system



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Monodisperse Particles

- N_i particles, same size d_p, going through a air cleaner,
- N_0 made it.

- Penetration efficiency $$P(d_p) = \frac{N_o}{N_i}$$
- Separation efficiency $$\eta(d_p) = 1 - P(d_p) = \left(1 - \frac{N_o}{N_i}\right)_{d_p}$$

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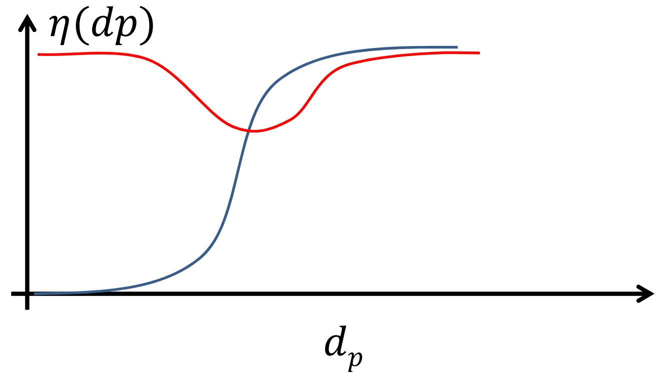
Polydisperse

❑ Size dependent

- Efficiency for each size may be different
- Fractional efficiency or grade efficiency



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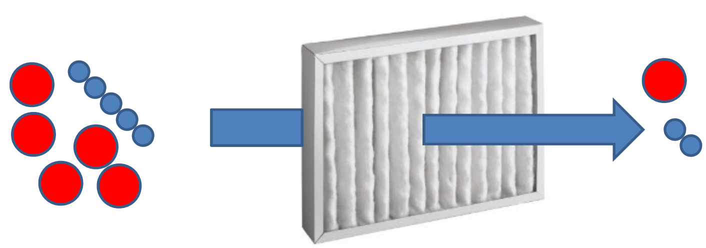
Total number efficiency (polydisperse)

- In: 10 particles (5 of the 10 um, the others 1 um)
- Out: 1 of them 10-um, 2 of them 1-um



- Total number penetration efficiency = 3/10
- Total number collection efficiency = 7/10

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In general

Total number efficiency

$$\eta = \frac{\sum_i \eta(d_p) \mathrm{N_i}(d_p)}{\sum_i \mathrm{N_i}(d_p)} \qquad \eta = \frac{\int_0^\infty \eta(d_p) \mathrm{N_i}(d_p) d(d_p)}{\int_0^\infty \mathrm{N_i}(d_p) d(d_p)}$$

Total mass efficiency from fractional efficiency

$$\eta = \frac{\int_0^\infty \mathrm{m}_{po}(d_p) d(d_p)}{\int_0^\infty \mathrm{m}_{p\mathrm{i}}(d_p) d(d_p)} = \frac{\int_0^\infty \eta(d_p) \mathrm{m}_{p\mathrm{i}}(d_p) d(d_p)}{\int_0^\infty \mathrm{m}_{p\mathrm{i}}(d_p) d(d_p)}$$

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Equipment for particle counting

Scanning mobility particle sizer (SMPS) x-1000 nm

Aerodynamic Particle Sizer (APS 3321), 0.35-20 um

Example (Start with a simple case)

- A particle counter is used to measure the particle number concentration up- and down-stream of a particulate air cleaning device as a function of aerodynamic diameter.
- The up- and down-stream particle number concentrations are

d_p(μm)	Up- N_i	Down- N_o
1	1000	10
5	100	6
10	5	0
20	1	0

- Calculated the fractional efficiency, and
- the total mass efficiency of this air cleaning device.

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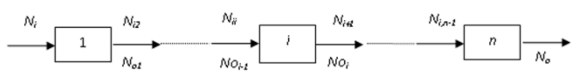
Particle Separation Efficiency of Multiple Devices



$$P = \prod P_i$$

$$\eta(d_p) = 1 - P = 1 - \prod P_i = 1 - \prod \left[1 - \eta_i(d_p)\right]$$

- **Critical assumption:** particle separation efficiencies of the identical units are the same.
- This is actually not justified in many engineering applications because the particle separation of a unit depends on the incoming particle concentration

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Example

- Two identical filters, filtration efficiency is each 85%, what is the total efficiency if two of them working in serial
- Solution

  P1=P2=0.15

  P=0.0225

  $\eta = 0.9775 = 97.75\%$

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Major Particulate Separation Technologies

- Gravitational settling
- Electrostatic precipitation
- Cyclone
- Filtration

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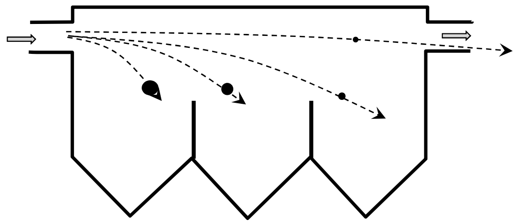
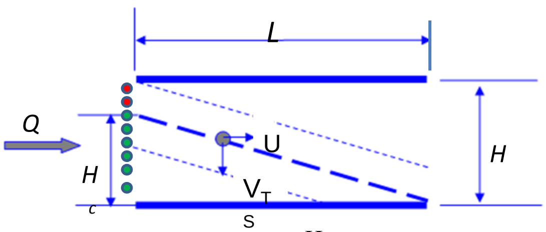
Gravity Settling Chamber

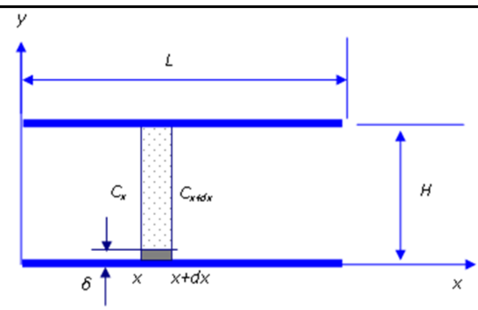


- **Laminar Flow Model**
- Monodisperse, uniform inlet concentration



$$\eta(d_p) = \frac{H_c}{H}$$

$\eta(d_p) = \frac{H_c}{H}$
$t = \frac{L}{U} = \frac{H_c}{V_{TS}}$
$H_c = \frac{V_{TS}L}{U}$
$\eta(d_p) = \frac{V_{TS}L}{UH}$
$U = \frac{Q}{WH}$
$V_{TS} = \frac{\rho_p d_p^2 g C_c}{18\mu}$
$\eta(d_p) = \frac{\rho_p g d_p^2 C_c}{18\mu}\frac{LW}{Q}$



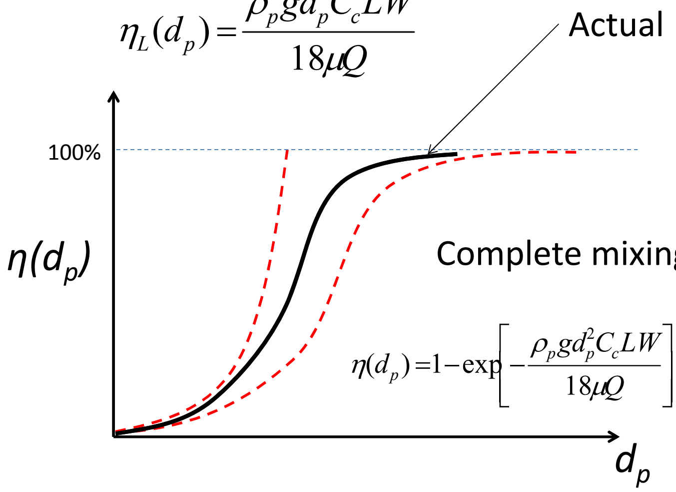
Complete Mixing Model

$C_x UWH = CV_{TS}W(dx) + C_{x+dx}UWH$
$\frac{dC}{C} = -\frac{V_{TS}}{H}dt$
$\frac{dC}{C} = -\frac{V_{TS}}{HU}dx$
$\int_{C_i}^{C_o}\frac{dC}{C} = -\int_0^L \frac{V_{TS}}{HU}dx$
$P = \exp\left(-\frac{V_{TS}L}{HU}\right)$ $=\exp\left(-\frac{V_{TS}LHW}{HQ}\right)$
$\eta = 1 - \exp\left(-\frac{V_{TS}LW}{Q}\right)$

- Particles and air are completely mixed at any cross section perpendicular to the direction of airflow.
- In dx, the concentration of particles within it is assumed to be uniform and the particles settle down at V_{TS}.
- During dt the particles at the bottom of the chamber within a distance $\delta = V_{TS}\,dt$ above the lower collecting plate are considered collected

Laminar

$$\eta_L(d_p) = \frac{\rho_p g d_p^2 C_c L W}{18 \mu Q}$$



$$\eta(d_p) = 1 - \exp\left[-\frac{\rho_p g d_p^2 C_c L W}{18 \mu Q}\right] = 1 - \exp(-\eta_L)$$

Example

- Consider a gravity settling chamber that is 1-m wide (W=1 m) and 1-m high (H=1 m).
- Air flow rate is 1 m^3/s (=3600 m^3/hr)
- Under standard ambient condition and laminar flow assumption,
- Estimate its separation efficiency vs. aerodynamic diameter

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$$\eta_L(d_p) = \frac{\rho_p g d_p^2 C_c L W}{18\mu Q}$$

$$C_c \approx 1$$

$$\eta_L(d_p) = \frac{\rho_p g d_p^2 L W}{18\mu Q}$$

$$= \frac{(1000)(9.81)(1)(1)}{(18)(1.81\times10^{-5})(1)} d_p^2$$

$$= 3.01\times10^7 d_p^2$$

d_p(μm)	η(d_p)
10	0.03%
100	3%
150	7%
200	12%
250	19%
350	37%
500	75%
575	100%

- The stringent control requirements adopted in the late 1960s through early 1970s have resulted in a sharp decline in the use of Gravity settling chamber.
- There are very few gravity settling chambers still in commercial use.

❑But it happens everywhere in air duct

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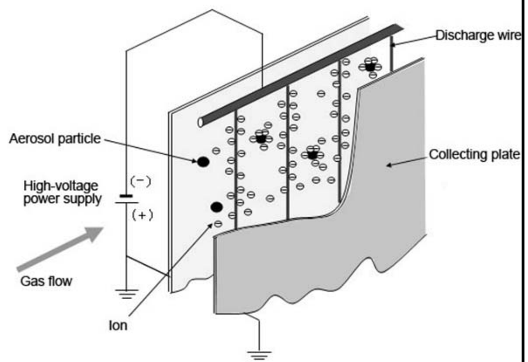
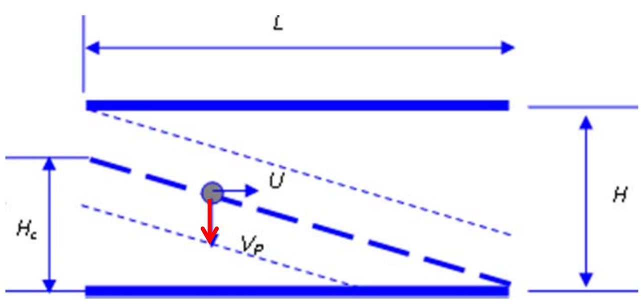
Electrostatic Precipitation



Model analysis by similar approach to gravitational settling



"Settling" in electrostatic force field

$\eta(d_p) = \frac{V_P L}{UH} = \frac{V_P L b}{UHb} = \frac{V_P A}{Q}$	(Laminar)
$\eta(d_p) = 1 - \exp\left(-\frac{V_P A}{Q}\right)$	(Turbulent)

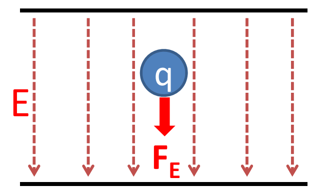
Terminal precipitation velocity

Electrical force = Drag force

$F_E = F_D$

$$qE = \frac{3\pi V_p d_p \mu}{C_c}$$

$$V_p = \frac{qEC_c}{3\pi d_p \mu}$$



- *q* is the charge carried by the particles
- *E* is the electric field strength

If you know q and E!

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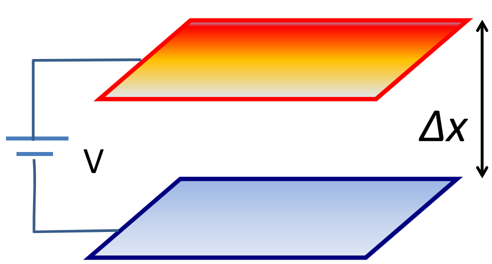
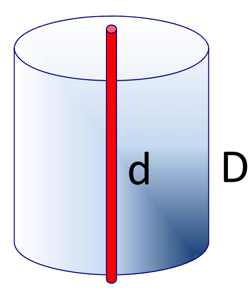
Electrical Field Intensity, E



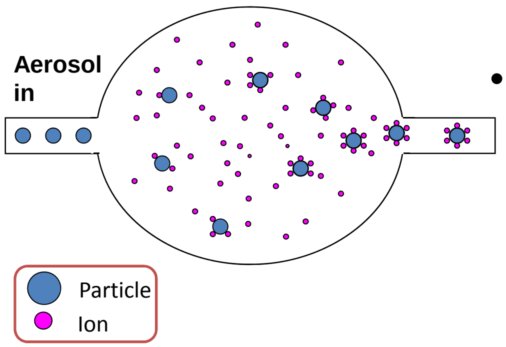
$$E = \frac{V}{\Delta x}$$



$$E(r) = \frac{V}{r \ln\left(D/d\right)}$$

Particle Charging

- Particles passing through a space filled with ions with be charged



- **Field charging** – ion attached to particles in an electrical field driven by the electrical force
- **Diffusion charging** – ions attached to particles due to Brownian motion of ions (not the electrical field).

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1. Diffusion Charging

$$n = \frac{d_p kT}{2K_E e^2} \ln\left[1 + \left(\frac{N_0 c_i \pi d_p K_E e^2}{2kT}\right) t\right]$$

Under standard conditions,

- $K_E = 9x10^9$ Nm^2/C,
- c_i=240 m/s,
- k =1.38x10^{-23} J/K,
- e =1.6x10^{-19} C.
- A typical concentration of ions is N_0=5x10^{14} ion/m^3,
- The diameters of most airborne particles are smaller than 10 µm and time t is in the order of unit or less

2. Field charging

$$n = \frac{E d_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)\left(\frac{t}{t + \tau}\right)$$

- E = intensity of the electric field with a typical value of 10^6 V/m,
- $\varepsilon_r = \varepsilon/\varepsilon_0$= relative permittivity or dielectric constant of the particle with respect to a vacuum,
  - ❑ ε_0 =8.854x10^{-12} C/V.m, is the permittivity of a vacuum.
  - ❑ The permittivity of typical particles can be found in handbooks.

Field Charging

$$n = \frac{Ed_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)\left(\frac{t}{t+\tau}\right)$$

The number of ions that is eventually charged to a particle depends on three factors:

- time t,
- the concentration of ions in the charging zone N_0, and
- the electric mobility of these ions B_e, which determines the moving speed of the ions in response to the electric field E.

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Saturation Field Charge

$$n = \frac{Ed_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)\left(\frac{t}{t+\tau}\right)$$

- $t \sim \infty, \quad \frac{t}{t+\tau} \sim 1$

- τ is the charging constant and it varies with the field condition. Typically = 0.003 s

$$n_s = \frac{Ed_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)$$

$$\tau = \frac{1}{\pi N_0 K_E e B_e}$$

- K_E = 9x10^9 Nm^2/C^2, is a force constant.
- the concentration of ions in the charging zone N_0, and
- the electric mobility of these ions B_e, which determines the moving speed of the ions in response to the electric field E.

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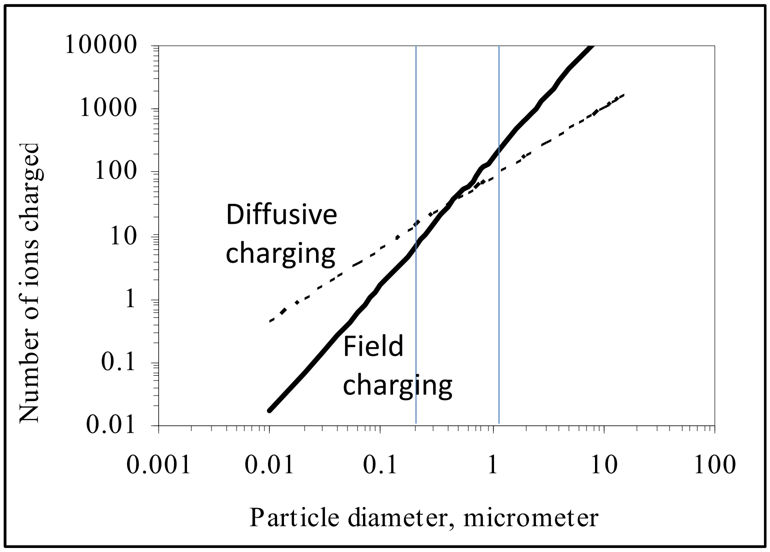
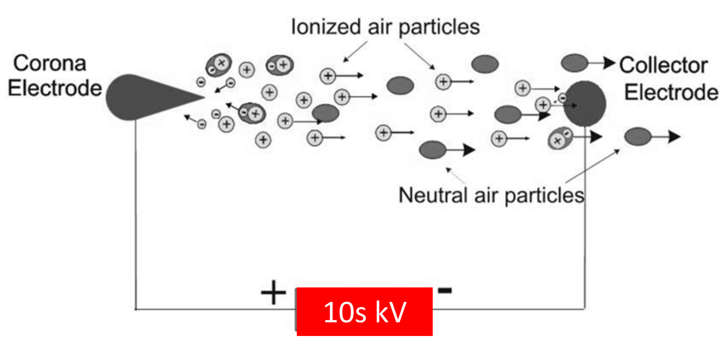
Combined charging

$$n = \frac{d_p kT}{2K_E e^2}\ln\left[1+\left(\frac{N_0 c_i \pi d_p K_E e^2}{2kT}\right)t\right] + \frac{Ed_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r+2}\right)\left(\frac{t}{t+\tau}\right)$$



How to produce sufficient ions?

- **Corona discharge** is an electrical discharge brought on by the ionization of a fluid surrounding a conductor that is electrically energized



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Summary of Equations for Parallel Plate ESP

$$\eta(d_p) = \frac{V_P A}{Q} \qquad \text{Laminar}$$

$$\eta(d_p) = 1 - \exp\left[-\frac{V_P A}{Q}\right] \qquad \text{Complete mixing}$$

$$V_P = \frac{qEC_c}{3\pi d_p \mu} = \frac{neEC_c}{3\pi d_p \mu}$$

$$n = \frac{d_p kT}{2K_E e^2} \ln\left[1 + \left(\frac{N_0 c_i \pi d_p K_E e^2}{2kT}\right)t\right] + \frac{Ed_p^2}{4K_E e}\left(\frac{3\varepsilon_r}{\varepsilon_r + 2}\right)\left(\frac{t}{t+\tau}\right)$$

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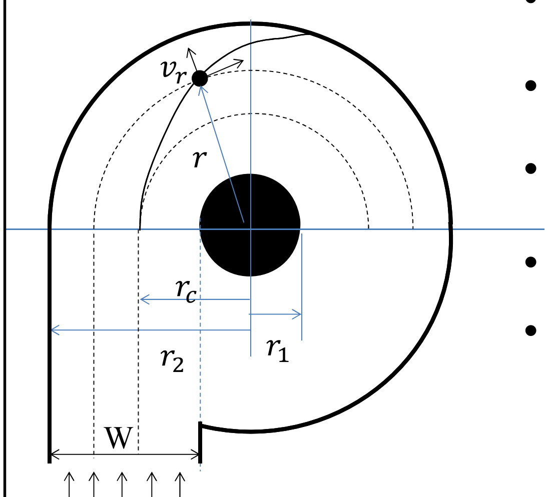
"Centrifugal force"



- $\eta(d_p) = \frac{r_2 - r_c}{r_2 - r_1} = \frac{r_2 - r_c}{W}$
- $\bar{u}_g = \frac{Q}{WH}$
- $m_p \frac{dv_r}{dt} = F_C - F_D = 0$
- $F_C = m_p \frac{v_\theta^2}{r}$
- $F_D = 8\pi\mu d_p v_r$

$$v_r = \frac{\rho_g d_p^2 v_\theta^2}{18\mu r}$$

Crawford model (1976)*

$$v_r = \frac{\rho_g d_p^2 v_\theta^2}{18 \mu r}$$

$$v_\theta = u_\theta = \frac{Q}{H \ln(r_2/r_1)} \frac{1}{r}$$

$$v_r = \frac{\rho_p d_p^2}{18\mu} \left[\frac{Q}{H\ln(r_2/r_1)}\right]^2 \frac{1}{r^3}$$

$$r d\theta = v_\theta dt$$

$$dr = v_r dt \qquad \frac{dr}{r d\theta} = \frac{v_r}{v_\theta}$$

$$r^2 - r_c^2 = \left[\frac{\rho_p d_p^2}{9\mu} \frac{Q}{H\ln(r_2/r_1)}\right]\theta$$

$$\eta(d_p) = \frac{r_2 - \left[r_2^2 - \frac{\rho_p d_p^2 Q \theta_2}{9\mu H \ln(r_2/r_1)}\right]^{1/2}}{r_2 - r_1}$$

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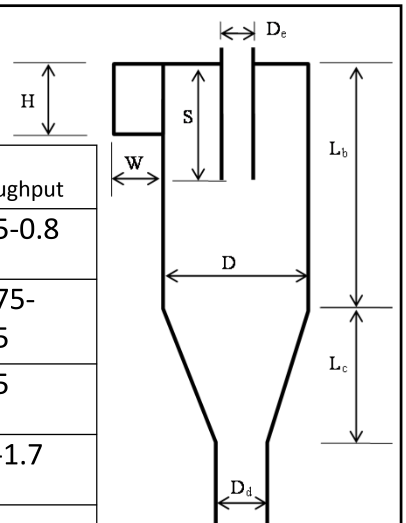
Lapple (1951) model



	High efficiency	Conventional	High throughput
Height of inlet H/D	0.5-0.44	0.5	0.75-0.8
Width of inlet W/D	0.2-.021	0.25	0.375-0.35
Diameter of gas exit De/D	0.4-0.5	0.5	0.75
Length of vortex finder S/D	0.5	0.625-0.6	1.5-1.7
Length of body, L_B/D	1.4	1.75	1.7
Cone length, L_C/D	2.5	2	2.5-2
Diameter of dust outlet	0.375-0.4	0.25-0.4	0.375-0.4

$$\eta(d_p) = \frac{r_2 - r_c}{W} = \frac{\rho_g d_p^2 v_\theta^2}{18\mu r W} t$$

Lapple model

$$v_r = \frac{r_2 - r_c}{t} \qquad t = \frac{2\pi r N_e}{\bar{u}_g}$$

$$v_\theta \approx u_\theta \approx \bar{u}_g$$

$$N_e = \frac{L_B + 0.5L_C}{H}$$

$$\eta(d_p) = \frac{\rho_g d_p^2 v_\theta^2}{18\mu r W}\frac{2\pi r N_e}{\bar{u}_g} \Rightarrow \eta(d_p) = \left(\frac{\pi \bar{u}_g N_e \rho_p}{9\mu W}\right) d_p^2$$

- Lapple gave an efficiency formula for traditional reverse flow cyclones in terms of cut size,

$$d_{50} = \left[\frac{4.5\mu W}{\pi N_e \bar{u}_g \rho_p}\right]^{1/2} \qquad \eta(d_p) = \frac{1}{1 + (d_{50}/d_p)^2}$$

Example 5.3: Cyclone efficiency

- A conventional cyclone has a body diameter of 20 cm and other geometries are listed in the table as follows. It operates at an inlet volumetric flow rate of 360 m^3/hr. Assume standard condition, plot its fractional efficiency curve vs. particle aerodynamic diameter.

Height of inlet H/D	0.5
Width of inlet W/D	0.25
Length of body, L_B/D	1.75
Cone length, L_C/D	2

Solution

	Dimension
Body diameter D (m)	0.2
Height of inlet H	0.1
Width of inlet W	0.05
Diameter of gas exit D_e	0.1
Length of body, L_B	0.35
Cone length, L_C	0.4

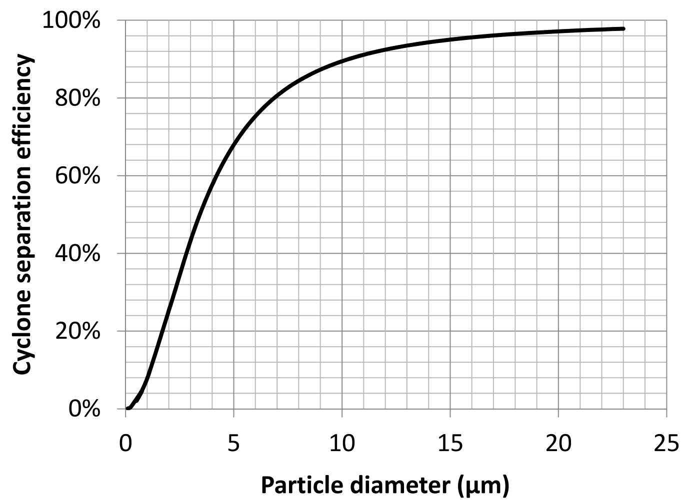
$$N_e = \frac{L_B + 0.5L_C}{H} = \frac{0.35 + 0.5 \times 0.4}{0.1} = 5.5$$

$$A = HW = 0.005\ (m^2)$$

$$\bar{u}_g = \frac{Q}{A} = \frac{360\frac{m^3}{hr} \times \frac{1\ hr}{3600s}}{0.005\ m^2} = 20\ m/s$$

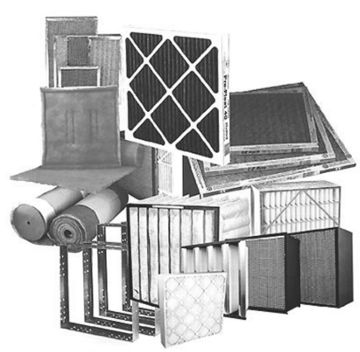
$$d_{50} = \left[\frac{9\mu W}{2\pi N_e \bar{u}_g (\rho_p - \rho_g)}\right]^{1/2} = \left[\frac{9 \times 1.81 \times 10^{-5} \times 0.05}{2\pi \times 5.5 \times 20(1000 - 1.21)}\right]^{1/2} = 3.43 \times 10^{-6}\ m$$

$$\eta(d_p) = \frac{1}{1 + \left(d_{50}/d_p\right)^2}$$



Filtration

- Granular filter
- Fibrous filter
- Filter Porosity
- Filter Solidity
- Pressure drop
- Collection efficiencies



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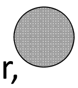
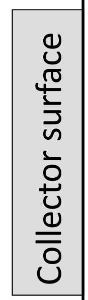
Filtration fundamentals

- Two steps:
  1. Particle transport to a collector, quantified by collision efficiency
  2. Attach to a collector, quantified by adhesion efficiency
- In the past, research has been focused on transport efficiency by assuming "always adhere"





$$\eta = \eta_{ts} \cdot \eta_{ad} \qquad \eta_{ad} \equiv 1$$

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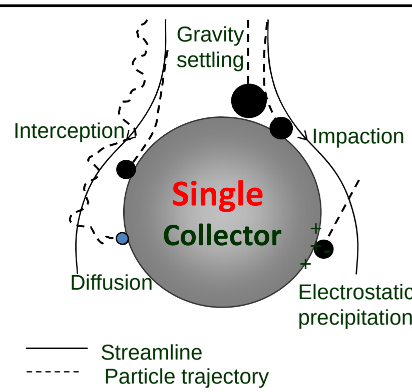
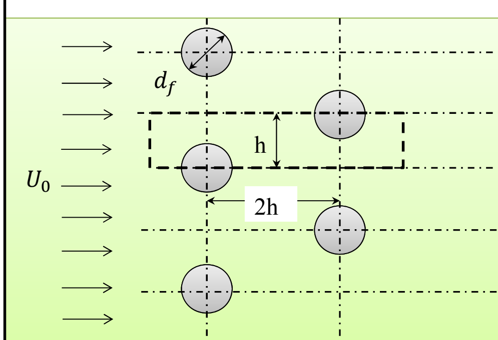
Five Transport Mechanisms of A Single Collector

- Adhesion efficiency = 1
- Ignored gravitational Settling
- Electrostatic precipitation not considered





Staggered-array models

- For efficiency per unit length for each mechanism

Single Fiber Efficiency per unit length of fiber by Interception

$$\eta_{it} = \frac{1+R}{2Y}\left[2\,ln(1+R) - (1-\alpha) + \left(1-\frac{\alpha}{2}\right)(1+R)^{-2} - \frac{\alpha}{2}(1+R)^{2}\right]$$

- $\alpha = (1 - porosity)$, is the solidity of filter;
- $R = d_p/d_f$, is the ratio of particle diameter to fiber diameter, and
- Y is the Kuwabara hydrodynamic factor defined below, with slip effect taken into consideration

$$Y = -\frac{ln\alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$$

Single Fiber Efficiency Per Unit Length of Fiber by Inertial Impaction

$$\eta_{ip} = \frac{J}{4Y^2} Stk \quad \leftarrow \quad Stk = \frac{\rho_p d_p^2 U_0 C_c}{18\mu d_f}$$

$$Y = -\frac{ln\alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$$

$$J = \left(29.6 - 28\alpha^{0.62}\right)R^2 - 27.5R^{2.8} \quad \text{for } R<0.4$$

$$J = 2, \;\; for\ R \geq 0.4$$

$$R = d_p/d_f$$

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Single Fiber Efficiency Per Unit Length of Fiber
by Diffusion

$$\eta_D = \frac{3.65(Pe_m)^{-\frac{2}{3}} + 0.624(Pe_m)^{-1}}{2Y}$$

$$D_p = \frac{kTC_c}{3\pi\mu d_p}$$

D_p: Particle diffusion coefficient

$$Pe = \frac{U_0 d_f}{D_p}$$

Pe: Peclet number

$$Pe_m = \frac{Pe}{2Y}$$

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Example Filtration efficiency

A furnace filter is made of fiberglass with a solidity of 3%, it is 2-cm thick. The average diameter of the fiber is 5 μm. Face velocity is 5 cm /s. Estimate the following efficiencies as a function of particle aerodynamic diameter under standard conditions

a) Single fiber efficiency by interception only
b) Single fiber efficiency by impaction only
c) Single fiber efficiency by diffusion only

Solution:

In this equation, the following parameters are considered as constant

$$d_f = 5\ \mu m, \alpha = 0.03, Kn_f = \frac{2\lambda}{d_f} = 0.0264$$

$$Y = \frac{ln\alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4} = 1.033054, \mu = 1.81 \times 10^{-5}\ Pa.s, U_0 = 0.05\ m/s$$

The following variables can be calculated in an Excel sheet for different particle diametersR $= \frac{d_p}{d_f}, Stk_f = \frac{\rho_p d_p^2 C_c U_0}{18\mu d_f}, Stk_m = \frac{Stk}{2Y}$

$$I = \begin{cases} (29.6 - 28\alpha^{0.62})R^2 - 27.5R^{2.8} & for\ R < 0.4 \\ 2 & for\ R \geq 0.4 \end{cases}$$

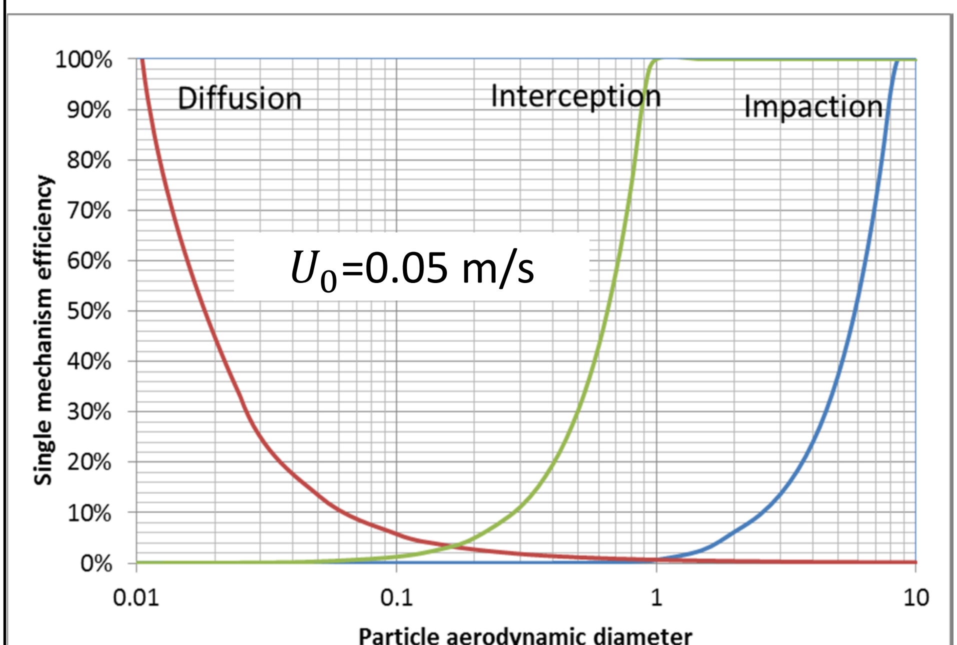
$$D_p = \frac{kTC_c}{3\pi\mu d_p}, Pe = \frac{U_0 d_f}{D_p}, Pe_m = \frac{Pe}{2Y}$$

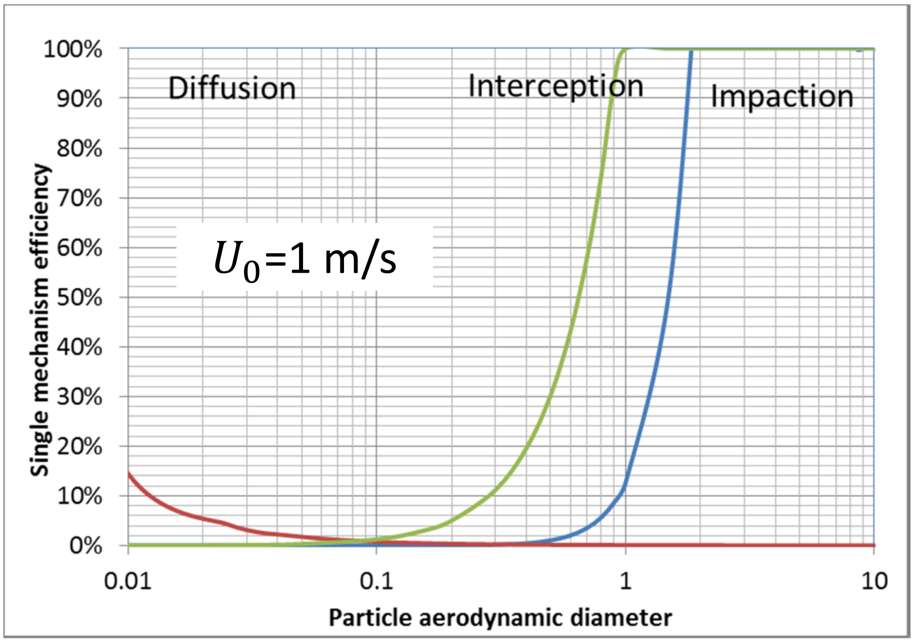
The the single fiber filtration efficiency by inertial interception, impaction and diffusion, per unit length of fiber is calculated using

$$\eta_{it} = \frac{1+R}{2Y}\left[2\ln(1+R) - (1-\alpha) + \left(1 - \frac{\alpha}{2}\right)(1+R)^{-2} - \frac{\alpha}{2}(1+R)^2\right]$$

$$\eta_{ip} = \frac{I}{2Y} Stk_m$$

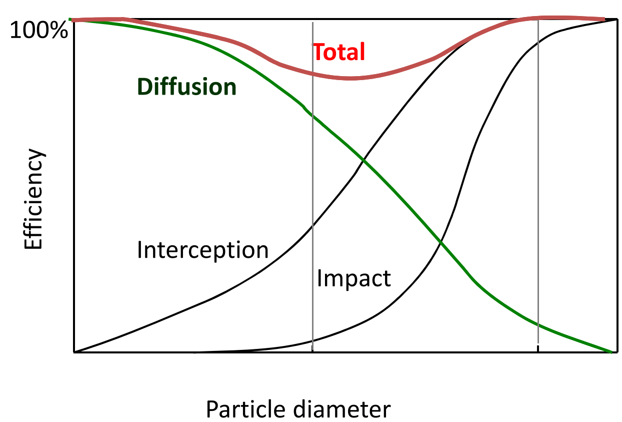
$$\eta_D = \frac{3.65(Pe_m)^{-\frac{2}{3}} + 0.624(Pe_m)^{-1}}{2Y}$$





Total Single Fiber Efficiency Per Unit Length of Fiber

$$\eta_{sf} = 1-(1-\eta_{it})(1-\eta_{ip})(1-\eta_D)$$



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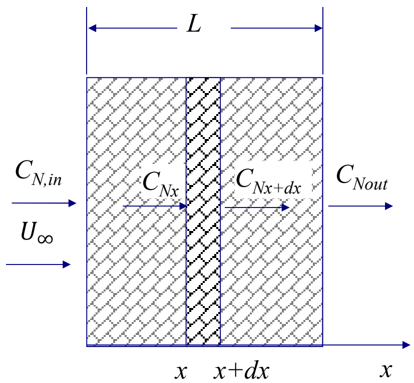
Correlation between total single fiber efficiency and overall filtration efficiency



- Within an elemental thickness of *dx*, the solidity, α, from its definition is

$$\alpha = \frac{\left(\pi d_f^2/4\right)\cdot ds_f}{A_c \cdot dx}$$

- A_c is the bulk cross section area of the filter that is normal to the face velocity. It can be determined by the air flow rate

$$A_c = \frac{Q}{U_\infty}$$

- U_∞ is the bulk face speed, or the air speed approaching the filter. It is less than that approaching the fiber within the filter, U_0, because of the existence of solid fibers

$$U_0 = \frac{U_\infty}{1-\alpha} = \frac{Q}{(1-\alpha)A_c}$$

- The number concentration of particles lost per unit volume from the bulk air over the distance *dx* equals to that captured by the fiber with a single fiber efficiency η_{sf} corresponding to an approaching flow rate of $U_0\, d_f \cdot ds_f$, where $d_f \cdot ds_f$ defines the cross section area of the fiber with the length of ds_f and the diameter of d_f

$$Q \cdot dC_N(x) = -\eta_{sf} C_N(x) U_0 d_f \cdot ds_f$$

- all these particles passed through a single fiber with a cross section area of $\left(d_f \cdot ds_f\right)$ with an approaching speed of U_0 and a single fiber efficiency of η_{sf}

$$A_c U_\infty \cdot dC_N(x) = -C_N(x)\eta_{sf} U_0 d_f \cdot \frac{4\alpha A_c \cdot dx}{\pi d_f^2}$$

$$\frac{dC_N(x)}{C_N(x)} = -\left(\frac{U_0}{U_\infty}\frac{\eta_{sf} 4\alpha}{\pi d_f}\right) dx$$

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Overall Filtration Efficiency of a Filter

$$\frac{dC_N(x)}{C_N(x)} = -\left[\frac{\eta_{sf}4\alpha}{(1-\alpha)\pi d_f}\right]dx$$

$$\int_{C_{N_i}}^{C_{N_o}}\frac{dC_N(x)}{C_N(x)} = \int_0^L -\left[\frac{\eta_{sf}4\alpha}{(1-\alpha)\pi d_f}\right]dx$$

$$P(d_p) = \frac{C_{N_o}}{C_{N_i}} = exp\left[\frac{-\eta_{sf}4\alpha L}{(1-\alpha)\pi d_f}\right]$$

$$\eta(d_p) = 1 - \exp\left[\frac{-\eta_{sf}4\alpha L}{(1-\alpha)\pi d_f}\right]$$

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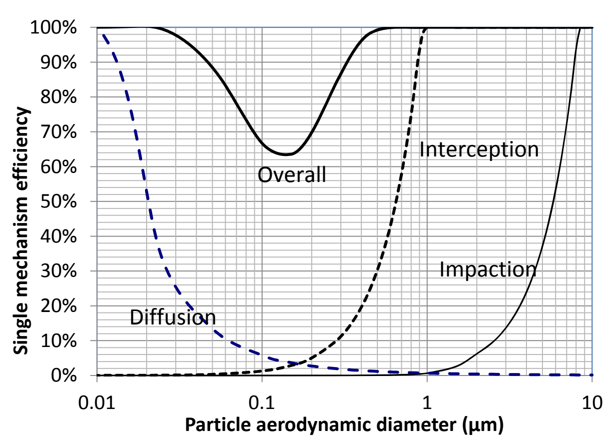
Example 5.5: Filtration total efficiency

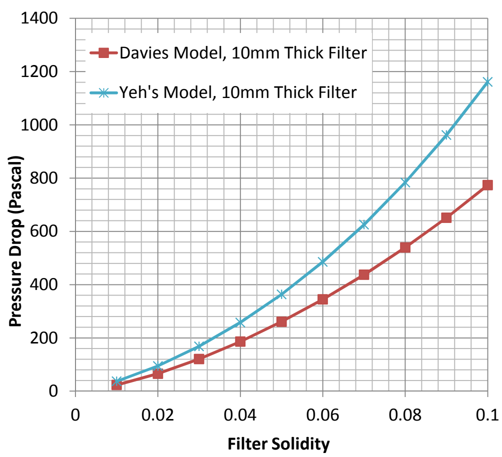
A filter is made of fiberglass with a solidity of 3%, and it is 2-mm thick. The average diameter of the fiber is 5 µm. When the face velocity is 0.05 m/s, estimate its overall fractional filtration efficiency as a function of particle aerodynamic diameter under standard conditions (consider only interception, impaction, and diffusion).



Fiber Filter Pressure Drop

$$\Delta P = C_{\Delta P}\left(4\mu U_0 L/d_f^2\right)$$
$$C_{\Delta P} = 16\alpha^{1.5}(1 + 56\alpha^3)$$

$$\eta\left(d_p\right) = 1 - \exp\left[\frac{-\eta_{sf} 4\alpha L}{(1-\alpha)\pi d_f}\right]$$



- Both efficiency and pressure drop increase with solidity
- Particle accumulation increase the filter solidity
  - o it increases efficiency slightly, but increases pressure drop greatly

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