Chapter 8. Separation and Classification of Nanoparticles

8.1 Introduction

- Separation = recovery = collection

- Classification

Separation Mechanisms

- Sedimentation: Settling chamber, centrifuge*

- Inertial deposition: Cyclone, scrubber, inertial impactor*

- Brownian diffusion: Diffusion batteries

- Migration of charged particle in an electric field :

Electrostatic precipitator, dynamic mobility analyzer

- Thermophoresis: Thermal precipitator (thermopositor)

- Filters: particle collection by the combined mechanism.

** Generally not suitable for nanoparticle collection but used for precollector*

Collection efficiency

- Fraction of particles fed in collected (deposited) on the interior wall of the collector…

** Fractional (grade) efficiency*

- based on number of particles

$$G_N\left(d_p\right) \equiv \frac{n_{feed}(d_p)dd_p - n_{product}(d_p)dd_p}{n_{feed}(d_p)dd_p} = \frac{n_{feed}(d_p) - n_{product}(d_p)}{n_{feed}(d_p)}$$

- based on mass of particles

$$G_M\left(d_p\right) \equiv \frac{n_{m,feed}(d_p) - n_{m,product}(d_p)}{n_{m,feed}(d_p)}$$

cf. $f(d_p)$ *vs.* $n(d_p)$

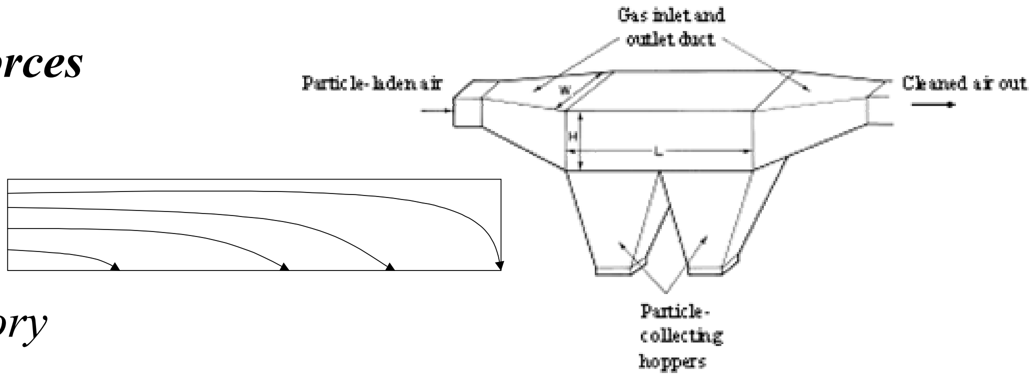
** Total efficiency*

$$E_T = \int_0^\infty G(d_p)n(d_p)dd_p$$

8.2 Separation by Mechanical Forces

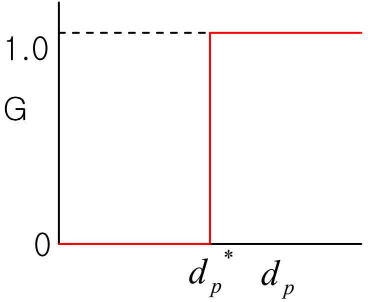
(1) Gravitational settler

- For laminar or plug flow

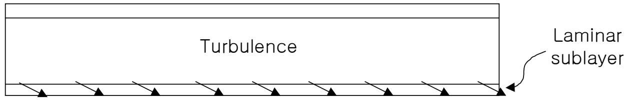


By analysis of particle trajectory

$$G(d_p) \equiv \frac{y^*}{H} = \frac{U_t(d_P)L}{\bar{U}H}$$



- For turbulent Flow

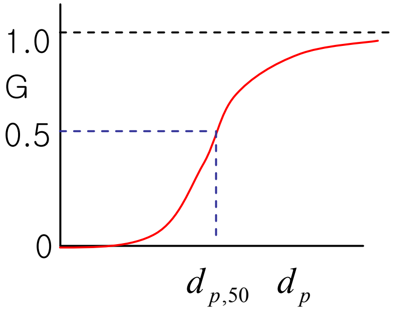


Considering the particle trajectory in differential length analysis

$$\therefore G(d_p) = 1 - \exp\left(-\frac{U_T(d_p)L}{UH}\right) = 1 - \exp\left[-\frac{A_C U_T(d_p)}{Q}\right]$$

** Cut size (diameter):* $d_{p,50}$

: particle diameter at $G(d_p)=0.5$



(2) Inertial Separator

** Particle trajectory from similitude analysis and thus for* $G(d_p)$

$$G(d_p) = f(St, \mathrm{Re}, d_p / L)$$

where L: characteristic length of the separator

U: characteristic velocity of the particle in the separator

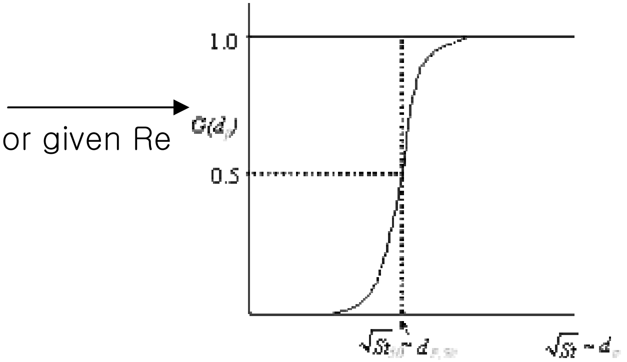
where $St \equiv \dfrac{\rho_P d_p^2 U}{18 \mu L}$ *and* $\mathrm{Re} \equiv \dfrac{\rho_f U L}{\mu}$

** For given inertial separator*

Efficiency $G(d_p) = f(St, \mathrm{Re})$

Cut diameter $0.5 = f(St_{50}, \mathrm{Re}) \rightarrow St_{50} = f_1(\mathrm{Re})$

For given Re



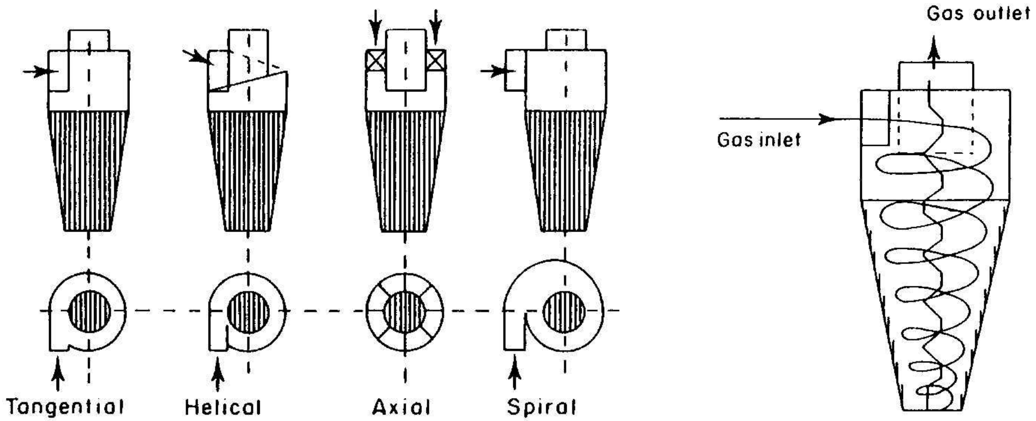
** Power requirement* $\equiv Q \Delta p$

where $\Delta p = f(L, \upsilon, \rho_f, \mu)$

- Similar similitude analysis gives

$Eu = f(\mathrm{Re})$ *where* $Eu \equiv \dfrac{\Delta p}{\rho_f \, \upsilon^2 / 2}$

Cyclone (hydrocyclone)



Flow patterns in cyclones

- *Grade efficiency of practical cyclone*

Based on fluid tangential velocity profile $U_f r^m = const$

$$G(d_p) = 1 - \exp(-\Psi d_p{}^M)$$

where $M = \dfrac{1}{m+1}$, $m = 1 - (1 - 0.67 D_c{}^{0.14})\left(\dfrac{T}{283}\right)^{0.3}$

$$\Psi = 2\left[\frac{KQ\rho_p C_c (m+1)}{18\mu D_c{}^3}\right]^{M/2}$$

K: dimensionless geometric parameter

where D_c *(m);* d_p *(cm);* ρ *(g/cm*^{3}*) ; T(K);* μ *(g/c m s); Q(m*^{3}*/s)*

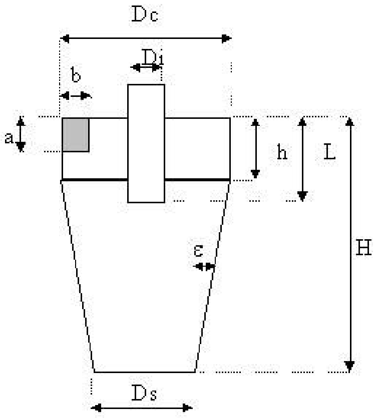
- From both theoretical and actual analysis for given cyclone and

For wide range of Re,

$$St_{50}\left(\equiv \frac{\rho_P d_p^2 U}{18\mu D}\right) \sim constant \rightarrow \quad d_{p,50} \propto \sqrt{\mu D^3 / \rho_p Q}$$

$$Eu\left(\equiv \frac{\Delta P}{\rho_f \,U^2\!/_2}\right) \sim constant \rightarrow \quad \Delta p \propto Q^2\!/_{D^4}$$

** Standard Cyclone Design – determination of dimension " Stairmand design rule"*

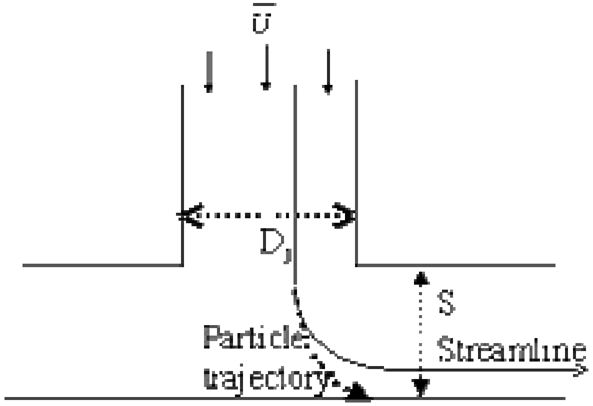


Cyclone type	*H*	*h*	D_s	*L*	*b*	*a*	D_j
Stairmand, High efficiency	4.0	1.5	0.375	0.5	0.2	0.5	0.5
Stairmand, High flowrate	4.0	1.5	0.575	0.875	0.375	0.75	0.75

- High efficiency Stairmand cyclone: $St_{50}=1.4x10^{-4}$ *and* $Eu=320$

High flowrate Stairmand cyclone: $St_{50}=6x10^{-3}$ *and* $Eu=46$

Impactor



- Separation by impact on the surface perpendicular to the flow

- From numerical and/or experimental analysis

  - St_{50}: *also almost independent of Re and further independent of geometry…*

  **For* $500 < Re < 3000$ *and* $S/D_j > 1.5$

    For circular nozzle, $St_{50} = 0.22$

    For rectangular nozzle, $St_{50} = 0.53$

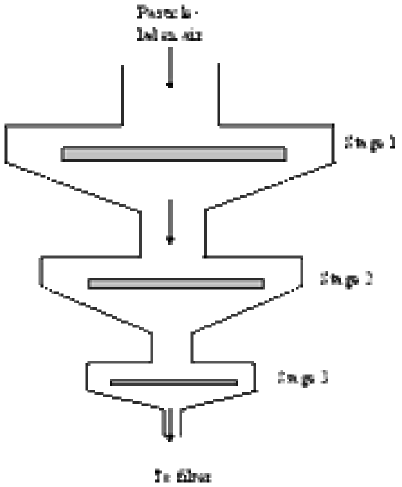
$$\therefore d_{p50} = \left(\frac{18 \mu D St_{50}}{\rho_p U} \right)^{1/2}$$

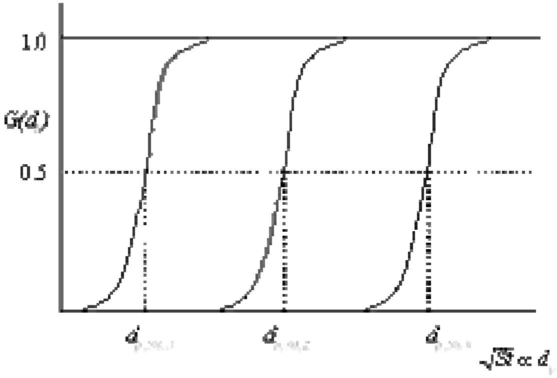
- *To collect nanoparticles,* $D\downarrow\downarrow$, $U\downarrow\downarrow$ *and* $C_c\uparrow\uparrow$

  Vacuum operation with supersonic velocity is required…

  "hypersonic impactor"

** Cascade impactor*



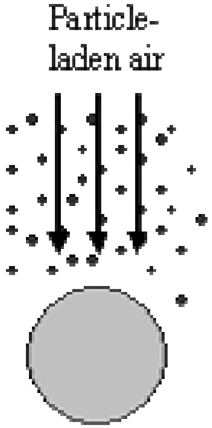


- *Overlapping of efficiency curve of one stage with neighboring plate: avoided*

- *Measurement of particle size distribution*

- *Used for classification of particles*

** Andersen impactor*



Venturi Scrubbers

- *Collection of particles by use of water spray*
  - *Scavenging of particles by water droplets* ☞
  - *Formation of slurry droplets by condensational growth of particles in humid air*

* *Grade efficiency*

Calvert(1984)

$$G(d_p) = 1 - \exp\left[\frac{1}{55}\frac{W}{G}\frac{U_g \rho_l d_d}{\mu_g} F(2St \cdot f)\right]$$

where W *: water feed rate (m³/s)*

G, U_g *: gas flow rate (m³/s) and gas velocity*

d_d *:droplet diameter (m)*

f*: empirical parameter encountering mode other than impaction, usually =0.5*

* *Characteristics of venturi scrubber*

- *High efficient for particles smaller than 2 um*
- *The only choice for sticky, flammable or highly corrosive particles*
- *High gas velocity(~120 m/s) → smaller-size equipment made of less corrosion-resistant materials*
- *Liquid-to-gas volumetric flow rate ratio = 0.001~0.003*

8.3 Separation by Filters

(1) Introduction

Filter and membrane materials

Inorganic	*Inorganic - Organic*	*Organic*
◦ *glasses* ◦ *ceramics* ◦ *metals* ◦ *polymers*	◦ *ion-containing polymers* ◦ *polysiloxanes* ◦ *polyphosphazenes*	◦ *natural polymers* ◦ *polysaccharides* ◦ *polypeptides* ◦ *rubbers* ◦ *synthetic polymers* ◦ *thermoplastics* ◦ *rubbery polymers* ◦ *soluble linear* ◦ *insoluble crosslinked*

Formation Techniques

Fibers	*Particles*	*Films*
◦ *wet-lay (many paper filters)* ◦ *dry-lay (spunbonded olefins)* ◦ *wound (glass filament cartridges)* ◦ *woven (polymeric and/or metal filter meshes)*	◦ *sol-gel (ceramic ultrafilters)* ◦ *compression or sintering (metal and glass filters and frits)* ◦ *extruded (alumina microfilter monoliths)*	◦ *extruded dense films (silicone films)* ◦ *extruded and stretched dense film (teflon and olefin microfilters)* ◦ *cast or extruded films with phase inversion step (cellulose acetate ultrafilters)* ◦ *nuclear-particle track etched (polycarbonate microfilters)* ◦ *electrochemical deposition (homoporous alumina microfilters)*

Characteristics of filter and membranes

Transport properties	*Pore size characteristics*	*Surface properties*
◦ *solvent flow (hydraulic permeability)* ◦ *solute or particle rejection (sieving coefficient)* ◦ *solute diffusion*	◦ *pore size distribution* ◦ *pore shape* ◦ *pore morphology gradient through membrane thickness*	◦ *chemical composition* ◦ *hydrophobicity -hydrophilicity* ◦ *surface charges* ◦ *solute-membrane affinity* ◦ *surface texture*

** Filter rating*

- Speed: how fast you can process a specified volume of fluid.

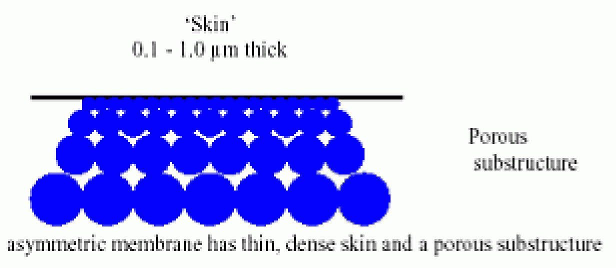
-Q/A ratio

- Collection efficiency

- Pressure drop: power requirement

- Stability: life, depending on chemical and mechanical strength

** Asymmetric membrane*



asymmetric membrane has thin, dense skin and a porous substructure

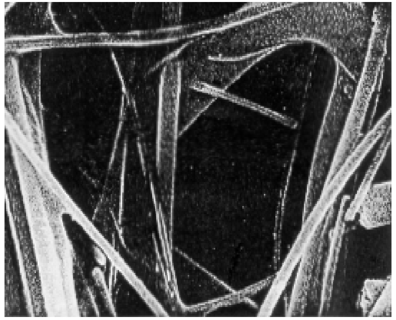
(2) Gas filtration

Filter materials – cellulose (wood), glass, plastic fibers

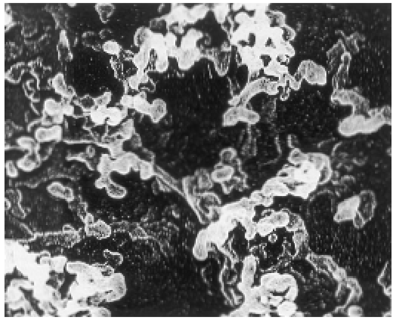
* High-temperature filters - metal. graphite, quartz, ceramic

<u>Air filters</u> - depth filters

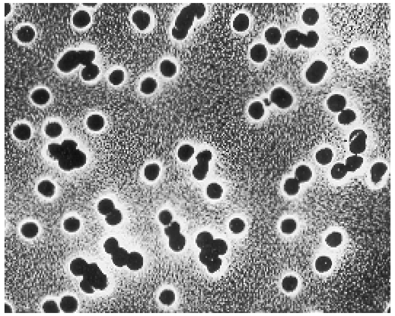
- Filter Types



Fibrous filters



Membrane(porous) filters



Capillary filters

- Low solid loading ~mg/m^3

  e.g. air-conditioning filters

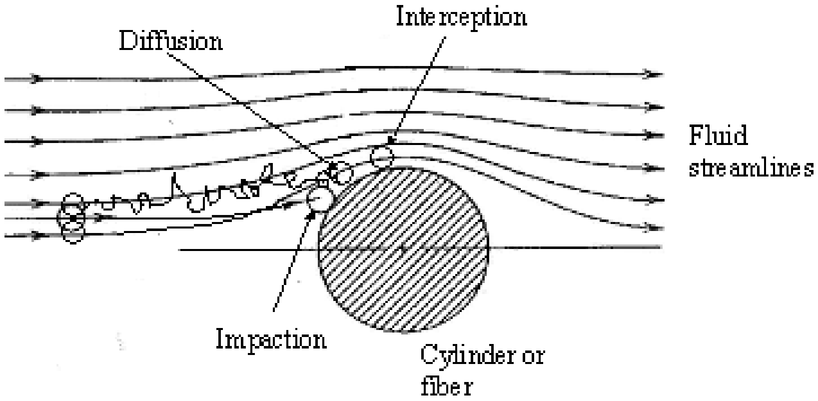
- $U \sim 0.25-1.5m/s, \Delta p \sim 10-1000Pa$

* HEPA (high efficiency particulate air) filter

- used in glove box, clean rooms, nuclear fuel industry
- $U \sim 0.1m/s, \Delta p \sim 200Pa$

* *Collection mechanisms of the fibrous filters*

- *Diffusion* : $< 0.3\mu m$
- *Inertial impaction* : $0.3 - 1\mu m$
- *Interception* : $1 - 10\mu m$
- *Gravity*: $> 10\mu m$
- *Electrostatic attraction* : $0.01\mu m - 5\mu m$



* *Grade efficiency of air filters*

$$G(d_p) = 1 - \exp\left(\frac{-4\alpha E_f t}{\pi d_f}\right)$$

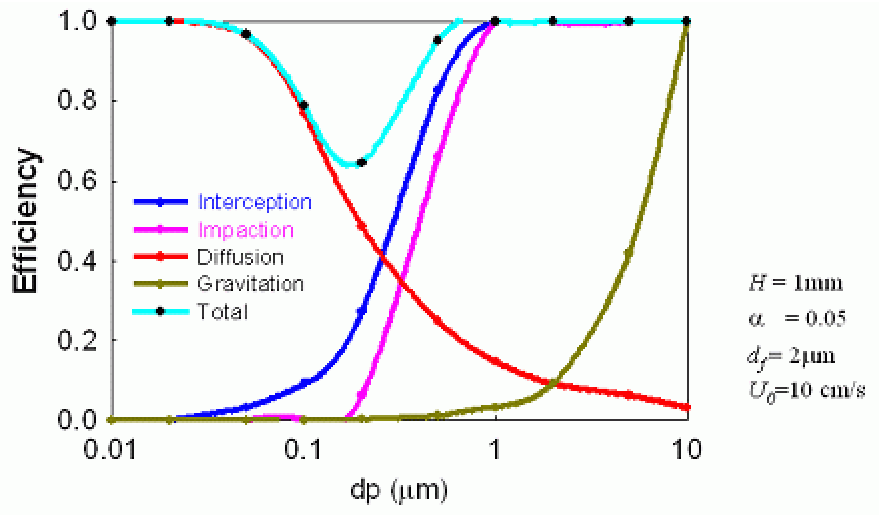
where $E_f = 1.44\left[\left(\frac{1-\alpha}{Ku}\right)^5\left(\frac{\sqrt{\lambda}kT}{\mu}\right)^4\left(\frac{1}{U_0{}^4 d_f{}^{10}}\right)\right]^{1/9}$ *Single fiber efficiency*

d_f: *fiber diameter*

$Ku = -\frac{\ln\alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$ *Kuwabara number*

α : *solid fraction(1-ε),* ε : *void fraction*

λ, μ, *T*, U_0: *mean free path, viscosity, temperature, and approaching velocity of the gas*



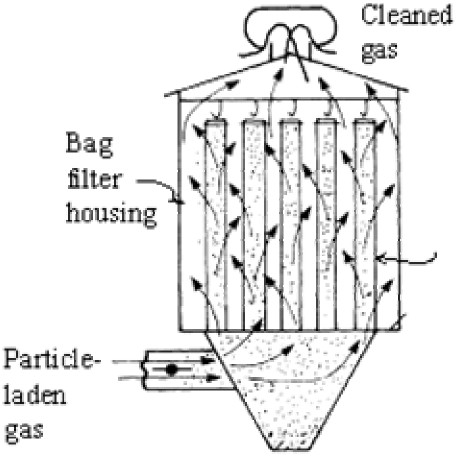
Filter efficiency for individual mechanism and combined mechanisms.

Particle diameter of minimum efficiency

$$d_{p,\min} = 0.885\left[\left(\frac{Ku}{1-\alpha}\right)\left(\frac{\sqrt{\lambda}kT}{\mu}\right)\left(\frac{d_f{}^2}{U_0}\right)\right]^{2/9}$$

Bag (fabric) filters - surface filters

- Filter media : cylindrical bag type
- L/D ratio ~ 20, D~ 120-150mm
- High solid loading ~ g/m^3



* Particle collection mechanisms

- Firstly, collection on individual fibers
- Secondly, filtration by particle cake

* Collection Efficiency

$$G(d_p) = 1 - \exp(-\alpha W)$$

where W : Dust mass per unit bag surface area, Areal density, kg/m^2, $W = cVt$

c : Inlet dust loading, kg/m^3

t : Operation time since last cleaning

V : Gas-to-cloth ratio, $V \equiv \dfrac{Q}{A}$

α : Cake penetration decay rate

* *Permeation rate and pressure drop*

$$V = \frac{\Delta p(t)}{R_m + R_C(t)}$$

where R_m*: resistance of filter media, reciprocal of permeance*

R_c*: resistance of filter cake,* $R_c(t) = KcVt$

K: function of the properties of dust

- Constant-pressure operation: permeation rate decrease

* *Regeneration (cleaning) of filters*

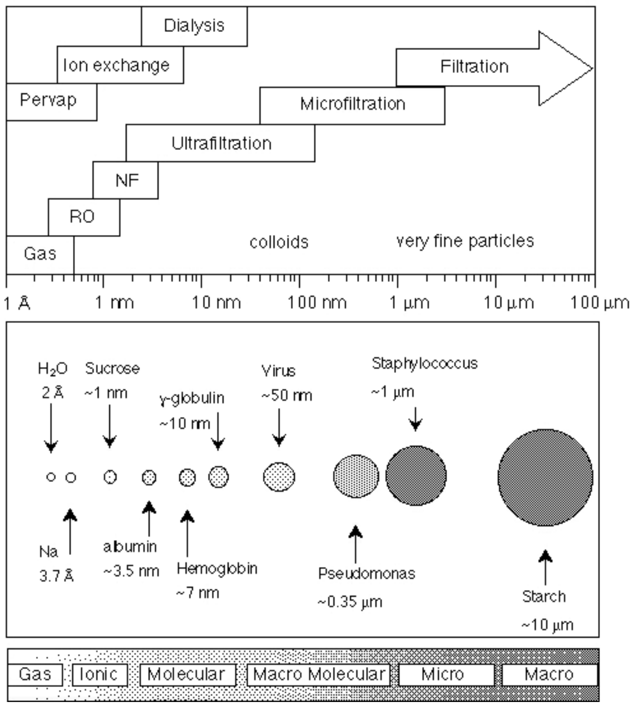
- shaker (vibrator), reverse flow, pulse jet

- use of cleaning ring

(3) Liquid filtration *See http://www.membranes.nist.gov/ACSchapter/pellePAGE.html*

** Classification of liquid filtration*

The Membrane Spectrum

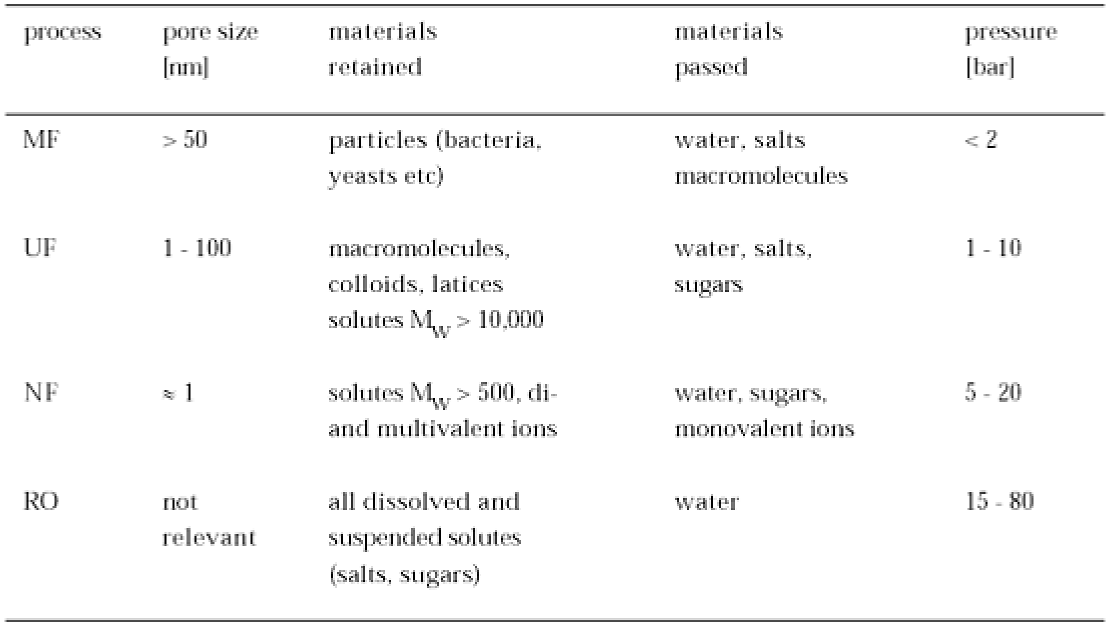


(UF – ultrafiltration, MF – microfiltration, NF – nanofiltration, RO – reverse osmosis. GS – gas and vapor separation)

Pore Characteristics

Macropore	*width > 50 nm*	*UF, MF, and filtration*
Mesopore	*2 nm < width < 50 nm*	*UF, NF*
Micropore	*width < 2 nm*	*NF*
Supermicropore	*0.7 nm < width < 2 nm*	*RO, NF*
Ultramicropore	*width < 0.7 nm*	*RO, GS, dialysis*
Ultrapore	*width < 0.35 nm*	*RO, GS, dialysis*

Table . Comparison of pressure-driven liquid (aqueous) phase membrane processes



process	pore size [nm]	materials retained	materials passed	pressure [bar]
MF	> 50	particles (bacteria, yeasts etc)	water, salts macromolecules	< 2
UF	1 - 100	macromolecules, colloids, latices solutes $M_W > 10{,}000$	water, salts, sugars	1 - 10
NF	≈ 1	solutes $M_W > 500$, di- and multivalent ions	water, sugars, monovalent ions	5 - 20
RO	not relevant	all dissolved and suspended solutes (salts, sugars)	water	15 - 80

* *Permeation rate and pressure drop across filter membrane*

$$V = \frac{\left(\Delta p - \Delta \Pi\right)}{R_m + R_c(t)}$$

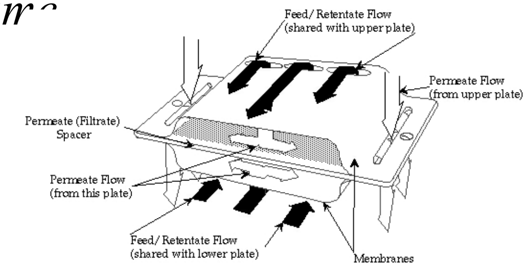
where $\prod$*: osmotic pressure*

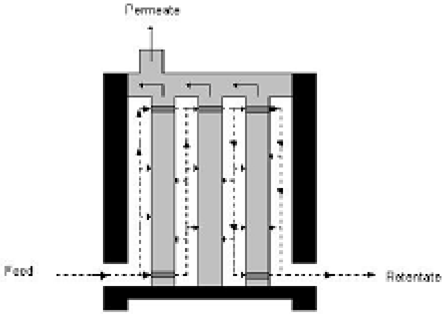
- *Constant- pressure operation*
- *Constant-flow rate operation*

* *Clean-up by back-flushing*

* Equipments

- Plate-and-frame





- Spiral wounded

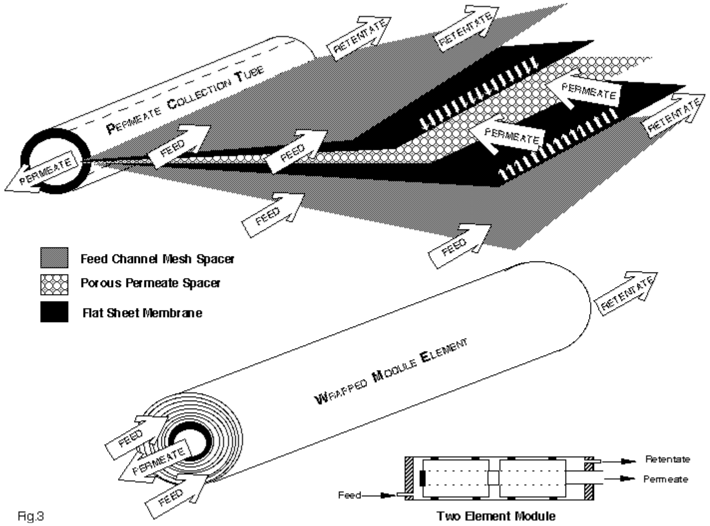
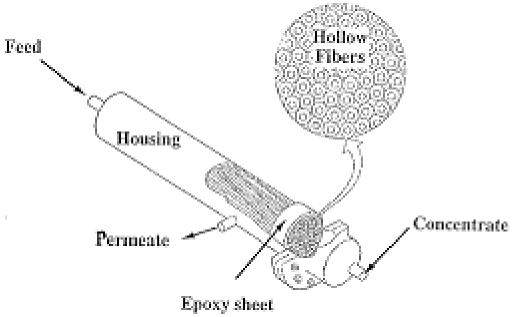


Fig.3

- Hollow fiber



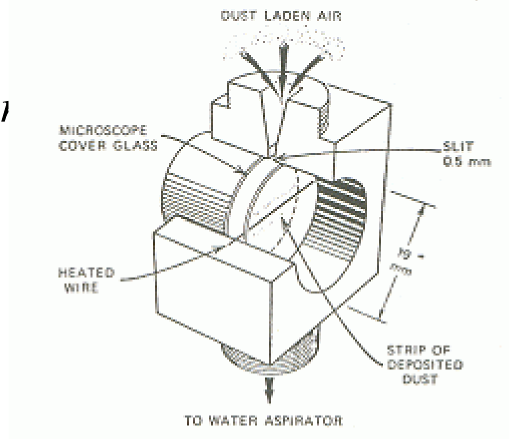
8.4 Separation by Nonequilibrium Gas

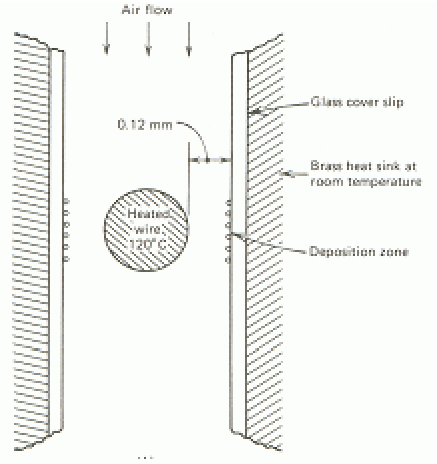
(1) Thermal precipitators

- *Collection efficiency for particles having* $d_p \langle 5-10\mu m = 1$
- *Used in lab-scale particle collection for electron microscopes*
- *Volumetric flow rate ~ 4-5*cm^3*/min*
- ΔT*=50-200K with 1000-10000K/cm*

** Wire-and-plate form*

- *Used for dust collection for British mi*
- *0.25mm Nichrome wire*
- *Temperature gradient: 8000K/cm*
- *Gas flow rate: 7.2*cm^3*/min*





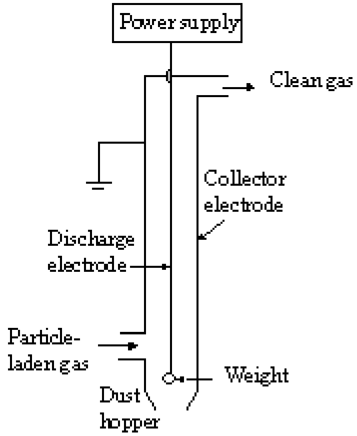
(2) Electrostatic precipitator

Particle Charging - Corona Discharge

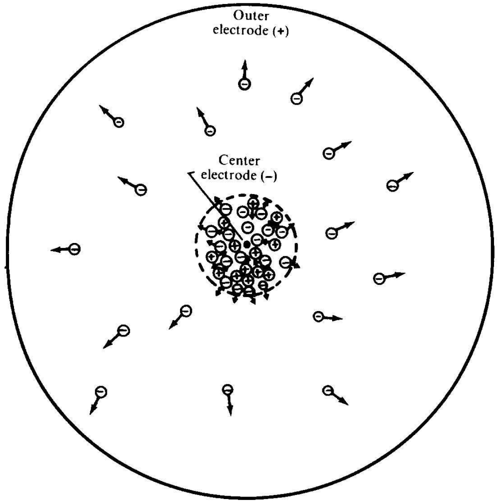
For a cylindrical (wire-in-tube) ESP

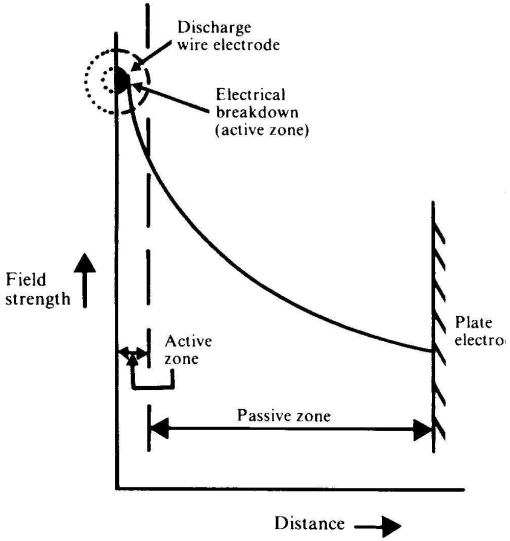
As V↑, air → electrical breakdown near the wire

Two zones in corona discharge



Single-zone ESP

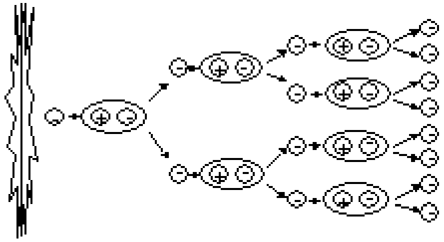




- *Active zone → active electrical breakdown*

  "Electron avalanche" - blue glow

- *Passive zone → particle charging*



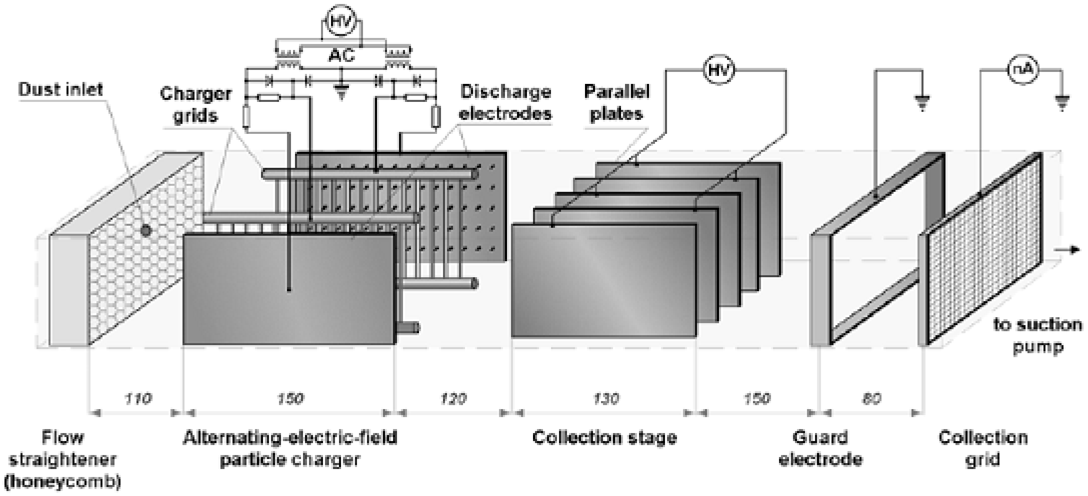
Electron avalanche

* Positive corona vs. negative corona

Positive corona	*Negative corona*
Suitable for domestic application	*-More stable than positive corona* *-Needs electron absorbing gas*(SO_2, O_2, H_2O) *-Produces* O_3 *as byproduct* *-Suitable for industrial applications*

*Diffusion charging vs. field charging

Two-zone ESP



Collection Efficiency

$$G(d_p) = 1 - \frac{n_{out}}{n_{in}} = 1 - \exp\left(\frac{PLU_e(d_p)}{Q}\right) = 1 - \exp\left(\frac{AU_e(d_p)}{Q}\right)$$

where $U_e = \frac{qEC_c}{3\pi\mu d_p}$ *: electrical migration velocity*

A_c*: cross sectional area of the ESP*

P: Perimeter of the ESP wall (P=A/L)

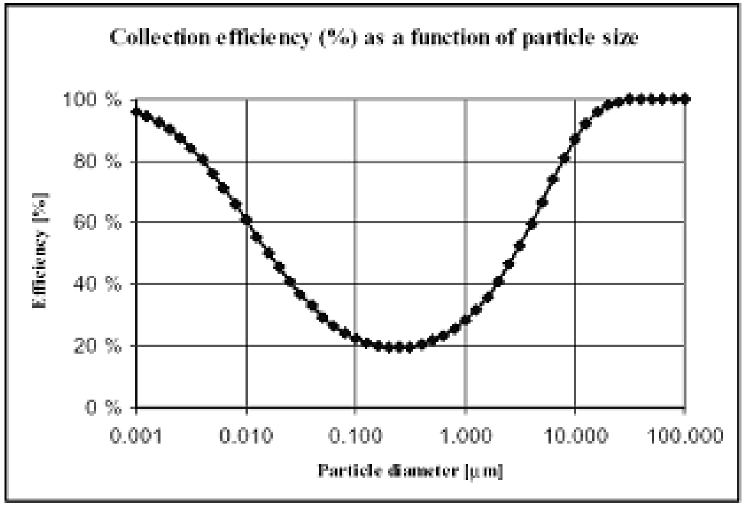


Figure 2: Collection efficiency for an electrostatic precipitator as a function of particle size. The calculations have been made for a system with the following dimensions:

- **Flow rate $\dot{V}$ =3.0 m³/s**
- **Length of collection section L=2.6 m**
- **Diameter of the collector tube d=1.6 m**
- **Corona current I=3.2 mA**

Particles suitable for ESP collection

Electrical resistivity of particles ← $V = iR = i\dfrac{\rho l}{A}$

e.g. Fly ash : $10^6 \sim 10^{11}\,\Omega\cdot m$

Carbon black : $10^{-5}\,\Omega\cdot m$

- *If* $\rho \langle 10^2\,\Omega\cdot m$ *: fast charge transfer to electrode* → *reentrainment of particles* $\rightarrow G\downarrow$

- *If* $\rho \rangle 2\times10^8\,\Omega\cdot m$*: slow charge transfer (charge: longer stay)* → *reverse corona* $\rightarrow G\downarrow$

$\therefore$ *Optimum* ρ *for ESP:*

$$10^6\,\Omega\cdot m \langle \rho \langle 10^8\,\Omega\cdot m$$

* *ESP vs. fabric filter system*