Chapter 5 Separation of Particles from a Gas

5.1 Gas Cyclones (Chapter 7)

For either gas cleaning (removal of dusts) or recovery of particulate products

Separation Mechanisms

- *Sedimentation :*
  - *Settling chamber, centrifuge*
- *Migration of charged particle in an electric field :*
  - *Electrostatic precipitator*
- *Inertial deposition :*
  - *Cyclone, scrubber, filters, inertial impactor*
- *Brownian diffusion :*
  - *Diffusion batteries*

* *Filters*

Figure 7.1

(1) Gas Cyclones

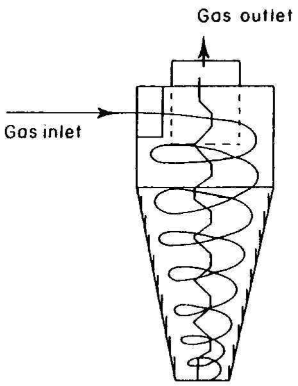


Figure 7.2

(2) Flow Characteristics

- Rotational flow in the forced vortex in the cyclone body
  → radial pressure gradient

- Resistance coefficient: Euler number

$$Eu \equiv \frac{\Delta p}{\rho_f v^2/2}$$

$$\text{where} \quad v = \frac{4q}{\pi D^2} \sim \frac{\text{pressure force}}{\text{inert force}}$$

D: cyclone inside diameter

* Economy of the collectors

Based on \$/(1000 m^3 cleaned gas /h)

annualized capital cost + operating cost* :

- Power requirement ≡ $Q \Delta p$, [W]

$$\text{where} \quad \Delta p = f(L, v, \rho_f, \ ) \quad \rightarrow \quad Eu = f(Re_p) \sim \text{constant}$$

By dimensional analysis   for a given cyclone,
independent of D

(3) Efficiency of Separation

1) Total Efficiency and Grade Efficiency

Total mass balance

$$M = M_f + M_c$$

where M : total mass flow rate

M_c : mass flow rate discharged from the solid exit orifice (coarse product)

M_f : solid mass flow rate leaving with the gas (fine product)

Component mass balance

$$M\frac{dF}{dx} = M_f\frac{dF_f}{dx} + M_c\frac{dF_c}{dx} \qquad (*)$$

where $\frac{dF}{dx}$, $\frac{dF_c}{dx}$, $\frac{dF_f}{dx}$ *: differential frequency size distributions*

by mass for the feed, coarse product and fine product

Total efficiency, E_T

$$E_T = \frac{M_c}{M}$$

Grade efficiency, $G(x)$

$$G(x) = \frac{mass\ of\ solids\ of\ size\ x\ in\ coarse\ product}{mass\ of\ solids\ of\ size\ x\ in\ feed}$$

$$G(x) = \frac{M_c \frac{dF_c}{dx}}{M \frac{dF}{dx}} = E_T \frac{\frac{dF_c}{dx}}{\frac{dF}{dx}}$$

From (*)/M

$$\frac{dF}{dx} = E_T \frac{dF_c}{dx} + (1 - E_T)\frac{dF_f}{dx}$$

In cumulative form

$$F = E_T F_c + (1 - E_T) F_f$$

2) Simple Theoretical Analysis for Gas Cyclone Separator

Figure 7.3

At equilibrium orbit, r

$\pi\mu$

$$3\ \ x\ U_r = \frac{x^3}{6}(\ _p - \ _f)\frac{U^2}{r}$$

$$F_D \qquad\qquad F_C - F_B$$

θ

$$\text{where}\ \ U\ r^{1/2} = constant\ for\ confined\ vortex$$

θ

$$= U\ \ _R R^{1/2}$$

$$U_r r = constant\ for\ radially\ inward\ flow$$

$$= U_R R$$

μ

$\rho\theta$

$$\therefore x^2 = \frac{18}{_p - \ _f}\frac{U_R}{U^2\ _R}\,r$$

where r *: the radius of the equilibrium orbit (displacement) for a particle of diameter* x

For all the particles to be collected, $r \geq R$

$$x_{crit}^2 = \frac{18\mu}{\rho_p - \rho_f} \frac{U_R}{U_\theta^2 R} R$$

where x_{crit} *: critical(minimum) diameter of the particles to be collected*

↓

or

If $x > x_{crit}$, $G(x) = 1$ *and otherwise,* $G(x) = 0$

3) Cyclone Grade Efficiency in Practice

- *Ideal grade efficiency curve Figure 7.4*

  Actual grade efficiency curve, "S"-shaped

  : distorted due to velocity fluctuation and particle-particle interaction

* x_{50} *and* St_{50} *in stead of* x_{crit} *and* St_{crit}

where cut size, $x_{50} \equiv x$ *at* $G(x) = 0.5$

(4) Scale-up of Cyclone

Cut diameter and pressure drop

- *Dimensional analysis for* $G(x)$

$$G(d_p) = f(x, \rho_p, \rho_f, L, v) \rightarrow G(x) = f(St, Re, x/L)$$

where L *: characteristic length of the separator*

U *: characteristic velocity of the particle in the separator*

$$St \equiv \frac{\rho_p x^2 U}{18\mu L} \quad \text{and} \quad Re \equiv \frac{\rho_f U L}{\mu}$$

From $G(x) = f(St, Re, x/L)$,

$$0.5 = f(St_{50}, Re, x/L)$$

or

$$St_{50} = f_1(Re,\ x/L)$$

From both theoretical and actual analysis for given cyclone,

St_{50} is independent of Re for a given cyclone geometry

ρ
ρ
μ

$$St_{50}\left(\equiv\frac{{}_p x_{50}^2\, U}{18\quad D}\right)\sim\ constant\ \rightarrow\ x_{50}\propto\sqrt{D^3/\ {}_p Q}$$

π

$$\uparrow\ U = Q/\frac{\ }{4}D^2$$

Similarly, from $Eu = f_2(Re_p)$

Eu is independent of Re_p for a given cyclone geometry

Δ
Δ
ρ

$$Eu\left(\equiv\frac{p}{{}_f U^2/2}\right)\ \sim\ constant\ \rightarrow\quad p\propto Q^2/D^4$$

π

$$\uparrow\ U = Q/\frac{\ }{4}D^2$$

Standard Cyclone Designs - dimension

Figure 7.5

- *High efficiency Stairmand cyclone:*

$$St_{50} = 1.4\times10^{-4}\ \ and\ \ Eu = 320$$

- *High flow rate Stairmand cyclone*

$$St_{50} = 6\times10^{-3}\ \ and\ \ Eu = 46$$

Grade efficiency

$$G(x) = \frac{\left(\frac{x}{x_{50}}\right)^2}{\left[1+\left(\frac{x}{x_{50}}\right)^2\right]}$$

for the geometry shown in p182

Figure 7.6

(5) Range of operation

Figure 7.7 : optimum operation somewhere between A and B

cf. Reentrainment

(6) Some Practical Design and Operation Details

- *High dust loading* ($> \sim 5g/m^3$) → *high separation efficiency due to agglomeration*
- *For well-designed cyclone*

$$Eu = \sqrt{\frac{12}{Stk_{50}}}$$

- *Abrasion: gas inlet and particle outlet*

  lined with rubber, refractory lining or the materials
- *Attrition: large particles with recirculation system*
- *Blockages: overloading, mechanical defects and water condensation*
- *Discharge hoppers(vortex breaker and stepped cone) and diplegs (internal cyclone in fluidized bed)*
- *Cyclones in series: increasing recovery*

<u>*N cyclones in parallel*</u>

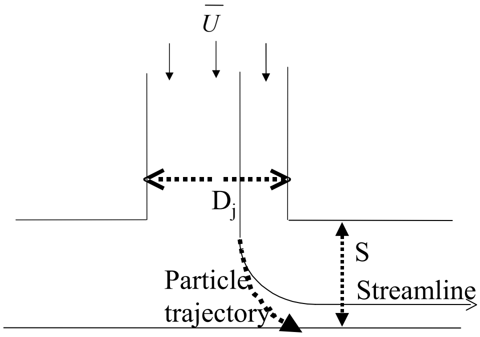
For large gas flow rate

$$Q \rightarrow Q/N$$

Worked Example 7.1

Worked Example 7.2

5.2 Aerosol Impactor (Classifier)(Supplement)



In general, for inertial motion of particles,

$$G(x) = f\left(Stk(x), Re, \frac{S}{D_j}\right)$$

τ

$$where \quad Stk(x) = \frac{(x)\overline{U}}{D}$$

For given geometry (S/D_j)

$$0.5 = f(Stk_{50}, Re) \ \rightarrow \ Stk_{50} = f_1(Re)$$

From numerical and/or experimental analysis

$$Stk(x): \ almost \ independent \ of \ Re$$

Or for $500 < Re < 3000$ *and* $S/D > 1.5$

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

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

μ

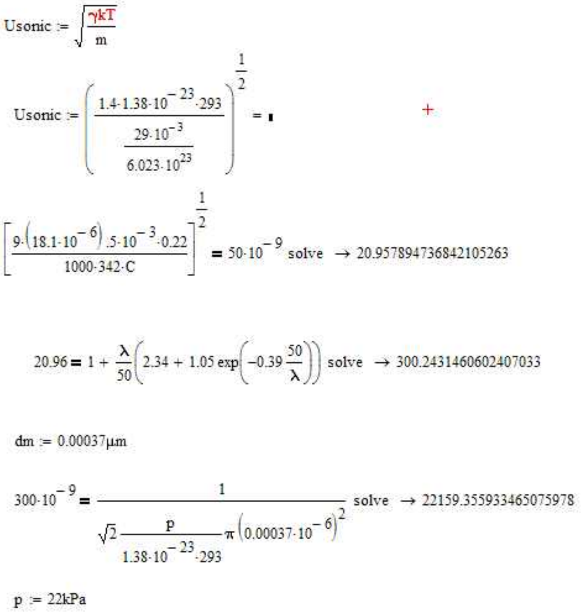
ρ

$$\therefore x_{50} = \left[\frac{9 \ DStk_{50}}{{}_pUC_c}\right]^{1/2}$$

* *How to collect nanoparticles?*

Example.

직경이 0.5mm인 노즐로 에어로졸제트를 만든다고 하면 50nm의 나노에어로졸 입자를 포집시키기 위해서 취할 수 있는 방법은 무엇이 있을까? 노즐에서 나오는 기류의 속도는 음속이다.



$$\text{Usonic} := \sqrt{\frac{\gamma kT}{m}}$$

$$\text{Usonic} := \left(\frac{1.4\cdot1.38\cdot10^{-23}\cdot293}{\frac{29\cdot10^{-3}}{6.023\cdot10^{23}}}\right)^{\frac{1}{2}} = \blacksquare$$

$$\left[\frac{9\cdot\left(18.1\cdot10^{-6}\right).5\cdot10^{-3}\cdot0.22}{1000\cdot342\cdot C}\right]^{\frac{1}{2}} = 50\cdot10^{-9} \text{ solve } \rightarrow 20.957894736842105263$$

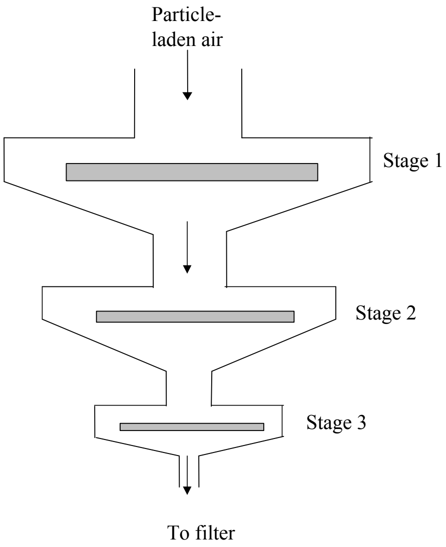
$$20.96 = 1 + \frac{\lambda}{50}\left(2.34 + 1.05\exp\left(-0.39\frac{50}{\lambda}\right)\right) \text{ solve } \rightarrow 300.2431460602407033$$

$$dm := 0.00037\mu m$$

$$300\cdot10^{-9} = \frac{1}{\sqrt{2}\frac{p}{1.38\cdot10^{-23}\cdot293}\pi\left(0.00037\cdot10^{-6}\right)^2} \text{ solve } \rightarrow 22159.355933465075978$$

$$p := 22kPa$$

* *Cascade impactor*



- *Measurement of particle size distribution*
- *Classification of particles*

5.3 (Gas) Filtration

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

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

(1) *Air filters - depth filters*

Filter Types

- *Fibrous filters*
- *Membrane(porous) filters*
- *Capillary filters*

Low solid loading $\sim mg/m^3$

e.g. Air-conditioning filters

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

HEPA(high efficiency particulate air) filter

- *used in glove box, clean rooms, nuclear fuel industry*

Δ - $U \sim 0.1 m/s, \quad p \sim 200 Pa$

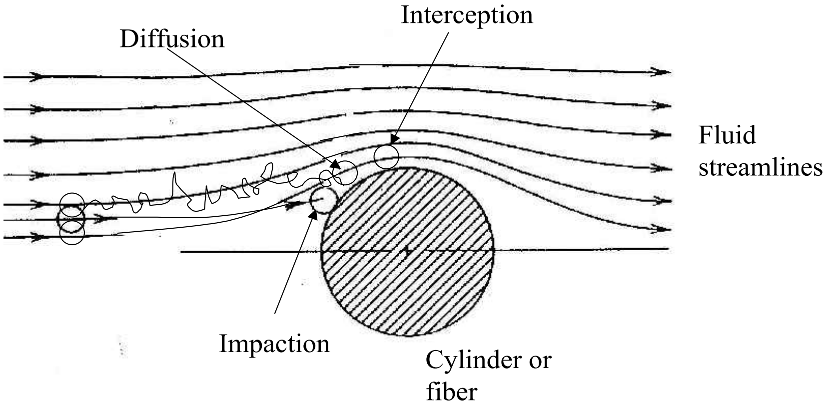
Collection mechanisms of the fibrous filters

μ - *Diffusion* : < 0.5 *m*

μ - *Inertial impaction* : > 1 *m*

μ - *Interception* : > 1 *m*

μ - *Electrostatic attraction* : 0.01 *m* to 5 *m*



Three major mechanisms of particle collection on *fibrous filter*

Integration of the material balance for particles in the filter thickness dx

ηα
αε

$$G(x) = 1 - \frac{n(L)}{n_0} = 1 - \exp\left[- \frac{4 \quad L}{(1- \quad)D_f} \right]$$

αε where : *solid fraction of the bed* $= 1 -$

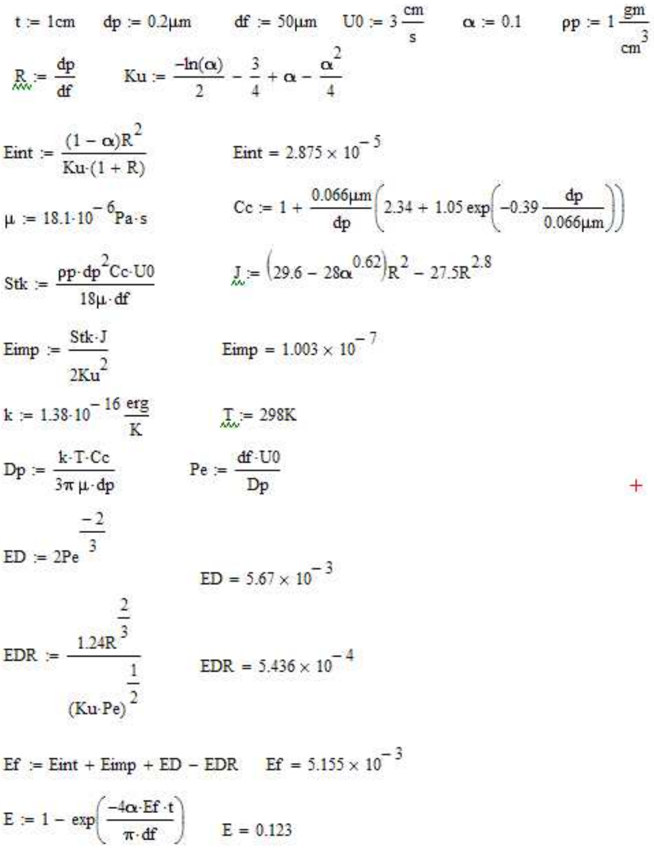
D_f : *fiber diameter*

η : *single fiber collection efficiency*

η $\approx \ _{diffusion} + \ _{impaction} + \ _{interception} + \ _{elctrostatic} + \cdots$

Example.

Compute the collection efficiency of a cigarette filter which is a fiber layer of thickness 1 cm and void fraction 0.9. Assume that the smoke particles are a monodisperse aerosol of diameter $0.2\mu m$ *and density* $1g \cdot cm^{-3}$ *and that the fiber filaments have a diameter of* $50\mu m$. *Smoke is inhaled at a velocity of* $3cm \cdot s^{-1}$ *and at 298L and 1atm.*



$t := 1\text{cm}\quad dp := 0.2\mu\text{m}\quad df := 50\mu\text{m}\quad U0 := 3\frac{\text{cm}}{\text{s}}\quad \alpha := 0.1\quad \rho p := 1\frac{\text{gm}}{\text{cm}^3}$

$R := \frac{dp}{df}\qquad Ku := \frac{-\ln(\alpha)}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$

$Eint := \frac{(1-\alpha)R^2}{Ku\cdot(1+R)}\qquad Eint = 2.875\times 10^{-5}$

$\mu := 18.1\cdot 10^{-6}\text{Pa}\cdot\text{s}\qquad Cc := 1 + \frac{0.066\mu\text{m}}{dp}\left(2.34 + 1.05\exp\left(-0.39\frac{dp}{0.066\mu\text{m}}\right)\right)$

$Stk := \frac{\rho p\cdot dp^2 Cc\cdot U0}{18\mu\cdot df}\qquad J := \left(29.6 - 28\alpha^{0.62}\right)R^2 - 27.5R^{2.8}$

$Eimp := \frac{Stk\cdot J}{2Ku^2}\qquad Eimp = 1.003\times 10^{-7}$

$k := 1.38\cdot 10^{-16}\frac{\text{erg}}{\text{K}}\qquad T := 298\text{K}$

$Dp := \frac{k\cdot T\cdot Cc}{3\pi\,\mu\cdot dp}\qquad Pe := \frac{df\cdot U0}{Dp}$

$ED := 2Pe^{\frac{-2}{3}}\qquad ED = 5.67\times 10^{-3}$

$EDR := \frac{1.24R^{\frac{2}{3}}}{(Ku\cdot Pe)^{\frac{1}{2}}}\qquad EDR = 5.436\times 10^{-4}$

$Ef := Eint + Eimp + ED - EDR\qquad Ef = 5.155\times 10^{-3}$

$E := 1 - \exp\left(\frac{-4\alpha\cdot Ef\cdot t}{\pi\cdot df}\right)\qquad E = 0.123$

(2) *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

Pressure drop

For shaking and reverse-flow filters

$\Delta\mu\varepsilon$

ε

$$\frac{(-\quad p)}{H} = \frac{30\quad U(1-\quad)^2}{x^2\quad{}^3}$$

$$\mathit{Since}\quad H = \frac{C_i V}{(1-\epsilon)\rho_p A} = \frac{C_i U t}{(1-\epsilon)\rho_p}$$

$$(-\Delta p) = \frac{30\mu U(1-\varepsilon)^2}{x^2\varepsilon^3}\frac{C_iUt}{(1-\varepsilon)\rho_p} = \frac{30\mu(1-\varepsilon)}{x^2\varepsilon^3\rho_p}C_iU^2t$$

where C_i: *Inlet dust loading,* kg/m^3

t : *Operation time since last cleaning*

$$U \equiv \frac{1}{A}\frac{dV}{dt}$$

superficial velocity or gas-to-cloth ratio

More generally, including media resistance

$$\Delta p(t) = S(t)U$$

where $S(t)$: *Drag through the fabric and cake*

$$S(t) = S_m + KC_iUt$$

Collection Efficiency

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

where W : *Dust mass per unit bag surface area,*

Areal density, Kg/m^2

$$W = C_iUt$$

a : *Cake penetration decay rate, determined empirically*

Cleaning methods

Fabric filter는 정해진 압력강하 이상이 얻어지면 퇴적 먼지를 털어내어 제거하고 다시 재사용된다. Cleaning횟수는 1000회 정도 반복.

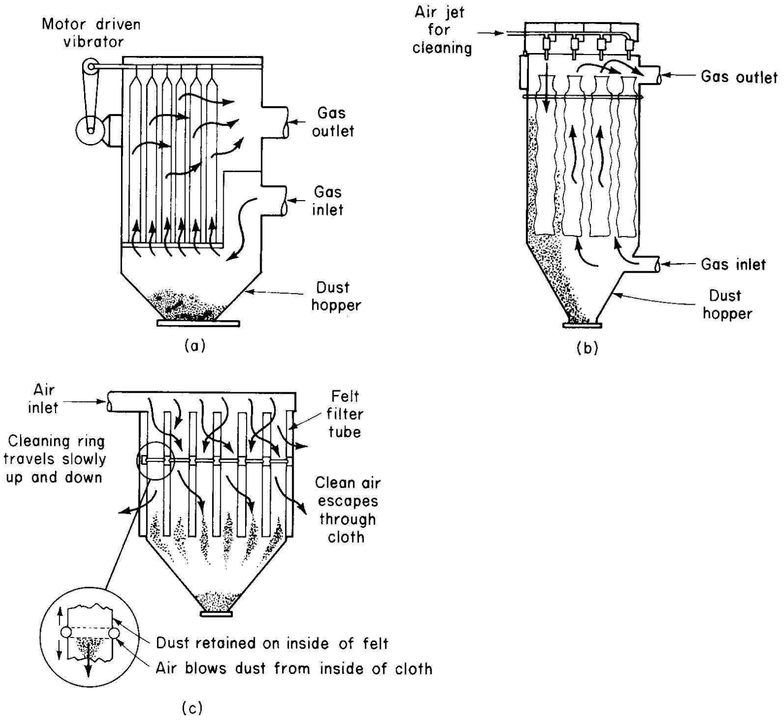
- *shaker (vibrator), reverse flow, pulse jet*
- *use of cleaning ring*

Optimal gas-to-cloth Ratio

$$U \text{ or } \frac{1}{A}\frac{dV}{dt}$$

If high, operating cost gets high

If low, capital cost gets high...



$$*U_{opt} \approx \frac{1m^2}{1m^3/\min} = 1.7\frac{cm}{s},\ \ usually\ \ up\ \ to\ \ 10\frac{cm}{s}$$

- *Used to determine total area and number of filters*

Example.

매시 3500m^3의 먼지를 가진 기체가 bag filter를 투과한다. filter의 여과면적 및 filter 재생에 필요한 시간을 구하여라. 여기서 입구분진농도는 4g/m^3, 분진입자의 비표면적대표지름은 1.5um, 진비중은 3.0, 공극률은 0.9, 최고허용압력손실 60mmH_2O(6g force/cm^2)이며 여과포통과속도 (gas-to-cloth ratio)를 3.2cm/s라 한다.

5.4 Electrostatic Precipitators (ESP)

Collection of charged particles on opposite electrode

$$Q := 3500\,\frac{m^3}{hr}$$

$$U := 3.2\,\frac{cm}{s} \qquad \mu := 18.1\cdot 10^{-6}\,Pa\cdot s \qquad \rho\_p := 3.0\,\frac{gm}{cm^3}$$

$$x := 1.5\cdot 10^{-6}\,m \qquad DelP := 60mm\cdot\frac{1}{13.6}\cdot\frac{1}{76cm}\,atm$$

$$C\_i := 4\,\frac{gm}{m^3} \qquad \varepsilon := 0.9 \qquad DelP = 588.187\,Pa$$

$$Area := \frac{Q}{U} \qquad Area = 30.382\,m^2$$

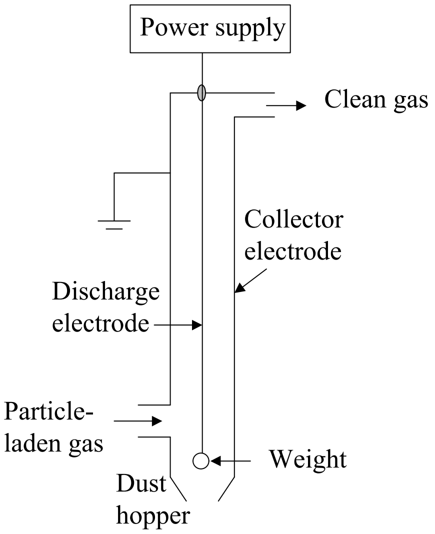
$$t := \frac{DelP}{\left[\frac{30\mu\cdot(1-\varepsilon)}{x^2\varepsilon^3\rho\_p}C\_i U^2\right]}$$

$$t = 216.888\,min$$

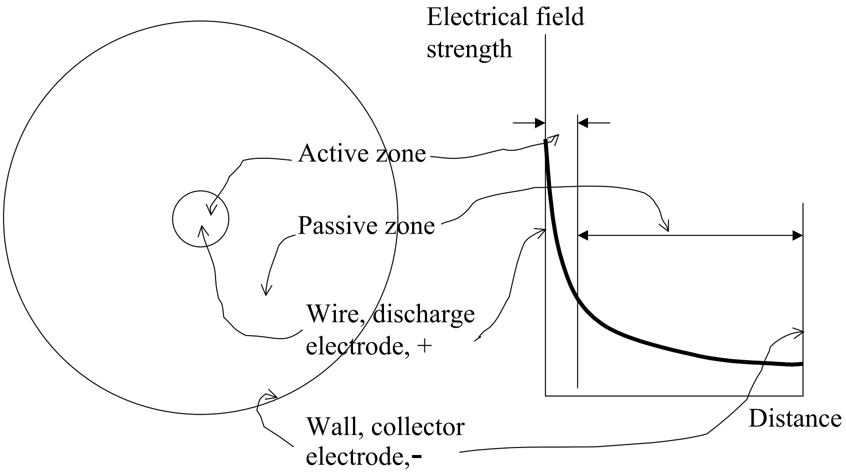
(particle charging / collection)

(1) Particle Charging - Corona Discharge

Consider a cylindrical(wire-in-tube) ESP



As $V\uparrow$, *air → electrical breakdown near the wire*



- *Active zone → Active electrical breakdown*

  "Electron avalanche" - Blue glow

- *Passive zone → Particle charging*

* *Charging mechanisms*

- *Field charging*
- *Diffusion charging*

* *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*

(2) Collection Efficiency

Assuming turbulent flow,

U and n *:uniform across cross sectional area*

Choose Δy*: laminar sublayer wall thickness and* Δx *such that*

Δ Δ

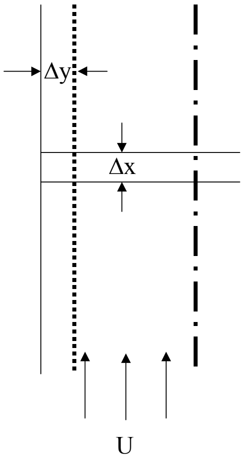
$$y = U_e \ \ t = U_e \frac{x}{U}$$

μ

$$\text{where} \quad U_e = \frac{qEC_c}{3 \quad d_p}$$

Electrical migration velocity from

$F_e = F_D$



☞ *Coordinate system : regarded as rectangular, even though cylindrical coordinate system prevails, since the layer is so thick.*

Material balance for particles in Δx

Δ Δ

$$UA_c(n|_x - n|_{x+ \ \ x}) = \left[\left(\frac{P \ \ y}{A_c} \right) n|_x \right] UA_c$$

where A_c*: cross sectional area of the ESP*

P *: perimeter of the ESP wall*

Δ *Substituting for* y*, and* $x \to 0$

$$-\frac{dn}{n} = -\frac{PU_e dx}{A_c U} = -\frac{PU_e dx}{Q}$$

Integration yields

$$G(x) = 1 - \frac{n_{out}}{n_{\in}} = 1 - \exp\left(\frac{PLU_e(x)}{Q} \right) = 1 - \exp\left(\frac{A_c U_e(x)}{Q} \right)$$

$$\uparrow$$

$$P = A_c/L$$

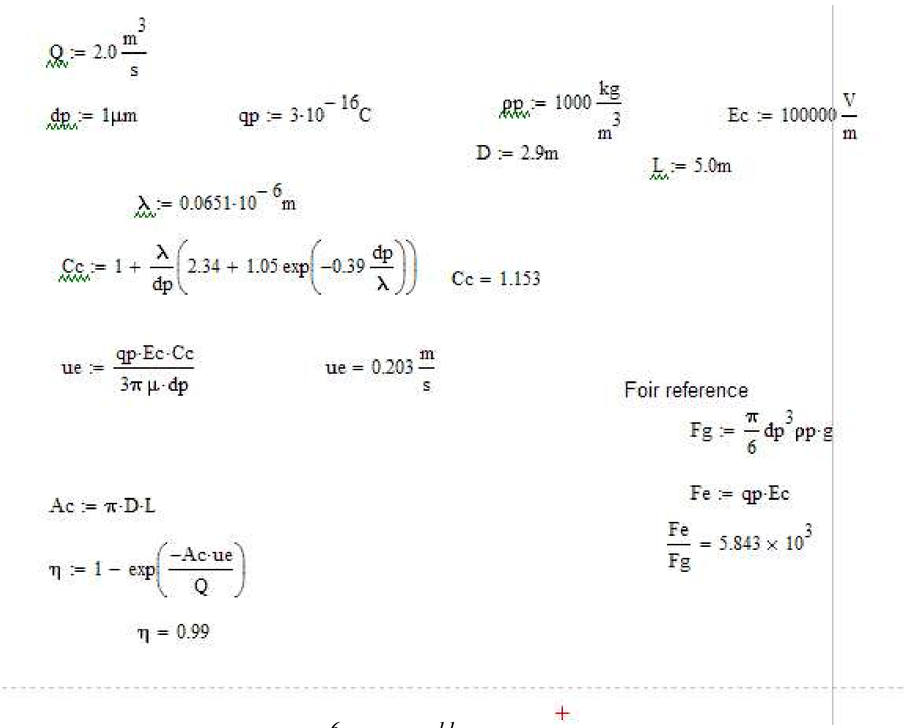
Example.

Dust particles of 1.0-μm *diameter with an electrical charge of* $3 \times 10^{-16}\,C$ *and a density of 1000*kg/m^3 *come under the influence of an electric field with a strength of 100,000V/m. The particles are suspended in air at 298K and 1atm. Consider a tubular ESP with a diameter of the collecting electrode of 2.9m and a length of 5.0m. If the gas flow rate is 2.0*m^3/s*, estimate the collection efficiency for 1.0-*μm *diameter particles. Corroborate the assumptions of turbulent flow and Stokes's law applicability.*

(3) Particles suitable for ESP collection

β

* *(electrical resistivity) of particles* $\leftarrow V = iR = i\frac{l}{A}$



$Q := 2.0\,\frac{m^3}{s}$

$dp := 1\mu m$ $qp := 3\cdot 10^{-16}C$ $\rho p := 1000\,\frac{kg}{m^3}$ $Ec := 100000\,\frac{V}{m}$

$D := 2.9m$ $L := 5.0m$

$\lambda := 0.0651\cdot 10^{-6}m$

$Cc := 1 + \frac{\lambda}{dp}\left(2.34 + 1.05\exp\left(-0.39\,\frac{dp}{\lambda}\right)\right)$ $Cc = 1.153$

$ue := \frac{qp\cdot Ec\cdot Cc}{3\pi\,\mu\cdot dp}$ $ue = 0.203\,\frac{m}{s}$

Foir reference

$Fg := \frac{\pi}{6}dp^3\,\rho p\cdot g$

$Fe := qp\cdot Ec$

$\frac{Fe}{Fg} = 5.843\times 10^3$

$Ac := \pi\cdot D\cdot L$

$\eta := 1 - \exp\left(\frac{-Ac\cdot ue}{Q}\right)$

$\eta = 0.99$

Ω *e.g. Fly ash : 10^6 ~ 10^{11} · m*

Ω *Carbon black : 10^{-5} · m*

ρΩ *If* 〈 10^2 · *m : fast transfer of charge from particle to electrode*

→ *reentrainment of particles* → *G* ↓

ρΩ *If* 〉 2×10^8 · *m: slow transfer of charge from particle to electrode*

→ *charge : stay longer* → *reverse corona* → *G* ↓

ρΩ ∴ *Optimum* : 10^6 · *m*〈 〈 10^8 · *m*

* *Artificial modification of resistivity* ☞

ρ *Addition of SO_3, water, NH_3 to high- particles* → ↓