**Terminal settling and thermophoretic velocities in a temperature gradient of 1°C/cm at 293K** [a] $k_p = 10k_a$

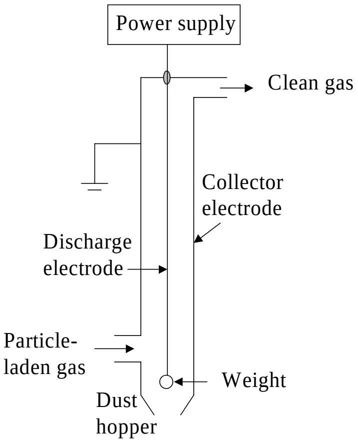
| Particle diameter( $\mu m$) | Terminal settling velocity(m/s) | Thermophoretic velocities in a temperature gradient of 1°C/cm at 293K[a] |
|---|---|---|
| 0.01 | $6.7\times10^{-8}$ | $2.8\times10^{-6}$ |
| 0.1 | $8.6\times10^{-7}$ | $2.0\times10^{-6}$ |
| 1.0 | $3.5\times10^{-5}$ | $1.3\times10^{-6}$ |
| 10.0 | $3.1\times10^{-3}$ | $7.8\times10^{-7}$ |

# Chapter 7S. Separation of Particles from a Gas: ESP and Filters

## 7S.1 Electrostatic Precipitators (ESP)

Collection of *charged* particles on *opposite* electrode

(particle charging / collection)



### 1) Particle Charging - *Corona Discharge*

Consider a *cylindrical(wire-in-tube)* ESP

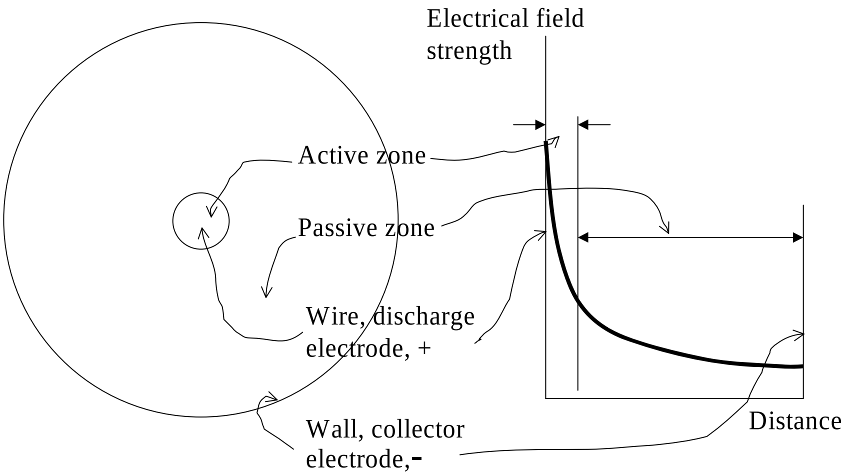
As $V\uparrow$, air → *electrical breakdown* near the wire

그리고 다음 그림에서 보듯 두 *개의 zone*이 생긴다.

- *Active* zone → Active electrical breakdown

  *"Electron avalanche"* - Blue glow

- *Passive* zone → Particle charging



* *Positive* corona vs. *negative* corona

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

## 2) ***Collection Efficiency***

Particle balance:

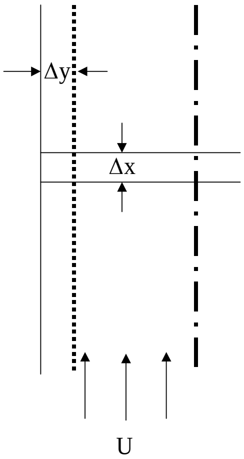
Assuming *turbulent flow*,

$U$ and $n$ :uniform across cross sectional area

Choose wall layer thickness, $\Delta y = U_e \Delta t = U_e \frac{\Delta x}{U}$

where $U_e = \frac{qEC_c}{3\pi\mu d_p}$

*electrical migration velocity*



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

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

where $A_c$: cross sectional area of the ESP

$P$ : Perimeter of the ESP wall

Substituting for $\Delta y$, and $\Delta x \rightarrow 0$

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

Integration yields

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

$$\uparrow$$

$$P = A/L$$

### 3) *Particles suitable for ESP collection*

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

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

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

If $\rho < 10^2 \Omega\cdot m$ : *fast transfer of charge* from particle to electrode

→ *reentrainment* of particles → $G\downarrow$

If $\rho > 2\times10^8 \Omega\cdot m$: *slow transfer of charge* from particle to electrode

→ charge : stay longer → *reverse corona* → $G\downarrow$

∴ *Optimum* : $10^6 \Omega\cdot m < \rho < 10^8 \Omega\cdot m$

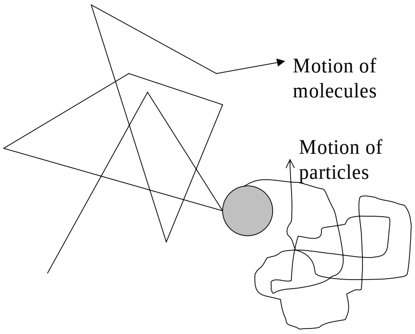
※ *Artificial modification of resistivity* ☞

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

## 7S.2 Particle (Brownian) Diffusion

### 1) Introduction

Brownian motion



: Random wiggling motion of particles by collision of fluid molecules on them

*Brownian Diffusion* :

Particle migration due to concentration gradient by Brownian motion

$$\vec{J} = -D_p \overrightarrow{\nabla} n$$

***Fick's law***

where $D_p$ : diffusion coefficient of particles cm$^2$/s

$C$ : particle concentration by number or mass

확산의 표시방법은 일반적인 migration 표시방법과 다르다.

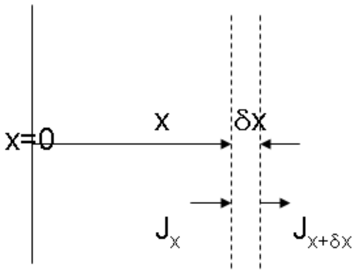
## 2) Coefficient of Diffusion $D_p$

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

액체분자의 확산계수 가 10$^{-5}$cm$^2$/s 정도임에 유의

## 3) Root-mean square displacement

Particle conservation equation



$$\frac{\partial n}{\partial t} \Delta x \cdot S = -\Delta J_x \cdot S$$

where S: crossectional area

$/\Delta x$ and $\Delta x \rightarrow 0$

*Diffusion Coefficient of Unit-density sphere at 20°C in air*

| Particle diameter, $\mu m$ | Diffusion coefficient, $D_p$(cm$^2$/s) |
|---|---|
| 0.00037(air molecule) | 0.19 |
| 0.01 | $5.2\times10^{-4}$ |
| 0.1 | $6.7\times10^{-6}$ |
| 1.0 | $2.7\times10^{-7}$ |
| 10 | $2.4\times10^{-8}$ |

$$\therefore \frac{\partial n}{\partial t} = -\frac{\partial J_x}{\partial x}$$

Introducing Fick's law

$$\frac{\partial n}{\partial t} = D_p \frac{\partial^2 n}{\partial x^2}$$

for constant $D_p$

B.C. $n = 0$ for $x \neq 0$ and $t=0$

$n = n_0$ for $x=0$ and $t=0$

$\frac{\partial n}{\partial x} = 0$ for $x=0$ and all $t$

$n = 0$ for $x=\pm\infty$ and all $t$

The solution is:

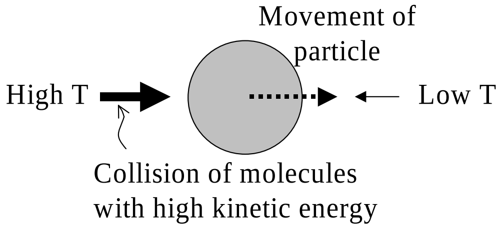
$$n(x, t) = \frac{n_0}{(4\pi D_p t)^{1/2}} \exp\left(\frac{-x^2}{4D_p t}\right)$$

Root-mean square displacement, $x_{rms}$

$$x_{rms} = \left[\frac{\int_{-\infty}^{+\infty} x^2 n(x, t) dt}{n_0}\right]^{1/2} = \sqrt{2D_p t}$$

## 7S.3 Thermophoresis

- Discovered by Tyndall in 1870



실제 예 : radiator의 벽이나 인근 벽에 먼지가 쓸지 않는 현상
담배연기가 차가운 벽 또는 창문 쪽으로 이동해 가는 현상
차가운 쪽에 면한 벽이 먼저 더러워지는 현상

In free molecular regime

$$\overrightarrow{F_{th}} = -p\lambda d_p^2 \frac{\overrightarrow{\nabla T}}{T}$$

Waldmann and Schmidt(1966)

$$\therefore \quad \overrightarrow{U_{th}} = -\frac{3\nu \overrightarrow{\nabla T}}{4\left(1+\frac{\pi\alpha}{8}\right)T} = \sim 0.55\,\nu \frac{\overrightarrow{\nabla T}}{T}$$

- independent of $d_p$

Correction for continuum fluid-particle interaction

$$\overrightarrow{F_{th}} = \frac{-9\pi\mu^2 d_p H \overrightarrow{\nabla T}}{2\rho_G T}$$

Brock(1962)

$$H \sim \frac{1}{1+6Kn}\left(\frac{\frac{k_G}{k_p}+4.4Kn}{1+2\frac{k_G}{k_p}+8.8Kn}\right)$$

$$\therefore \quad \overrightarrow{U_{th}} = \frac{-3\mu C_c H \overrightarrow{\nabla T}}{2\rho_G T}$$

## 7S.4 *Filters*

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

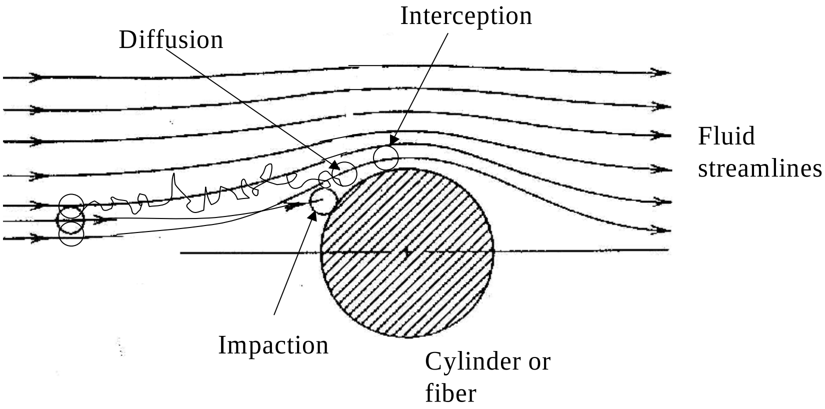
*Low solid loading* $\sim$mg/m$^3$

e.g. air-conditioning filters

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

*HEPA(high efficiency particulate air) filter*

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



*Three major mechanisms* of particle collection on *fibrous filter*

*Collection mechanisms* of the fibrous filters

- *Diffusion* : < $0.5 \mu m$
- *Inertial impaction* : < $1 \mu m$
- *Interception* : $1 \mu m$
- *Electrostatic attraction* : $0.01 \mu m$ to $5 \mu m$

From the particle balance around differential section $dx$ in the fibrous bed,

$$\frac{dn}{dx} = -\frac{4\alpha\eta(d_p)}{\pi(1-\alpha)D_f}n$$

where $\alpha$ : solid fraction of the bed $=1-\varepsilon$

$D_f$ : fiber diameter

$\eta(d_p)$ : single fiber collection efficiency

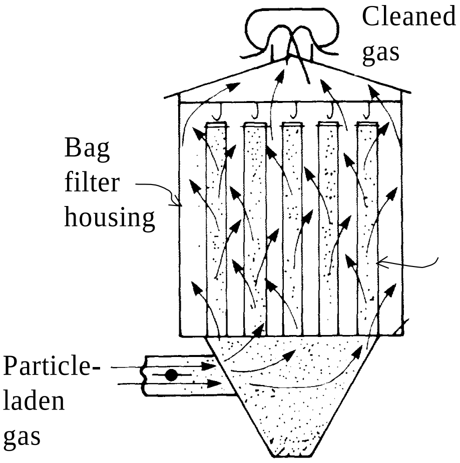
$$\eta(d_p) = \eta_{diffusion} + \eta_{impaction} + \eta_{interception} + \eta_{elctrostatic} + \ldots.$$

Given by semiempirical equation

Integration

$$G(d_p) = 1 - \frac{n(L)}{n_0} = 1 - \exp\left[-\frac{4\alpha\eta(d_p)L}{\pi(1-\alpha)D_f}\right]$$

## 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*

### *Collection Efficiency*

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

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

Areal density, Kg/m$^2$

$$W = C_i V t$$

$C_i$: Inlet dust loading, kg/m$^3$

$t$ : Operation time since last cleaning

$V$ : Gas-to-cloth ratio

$$V \equiv \frac{Q}{A}$$

$a$ : *Cake penetration decay rate*

### *Pressure drop*

For *shaking and reverse-flow* filters

$$\Delta p(t) = S(t)\, V$$

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

$$S(t) = S_e + K_2 W(t) = S_e + K_2 C_i V t$$

$S_e$ , $K_2$: $fn$(*properties of fabric and dust, respectively*)

### *Cleaning* methods

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

제거방법

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

# Summary of Particulate Collection

| Device | Minimum particle size (μm) | Efficiency (%) (mass basis) | Advantages | Disadvantages |
|---|---|---|---|---|
| Gravitational settler | >50 | <50 | Low-pressure loss<br>Simplicity of design and maintenance | Much space required<br>Low collection efficiency |
| Cyclone | 5-25 | 50-90 | Simplicity of design and maintenance<br>Little floor space required<br>Dry continuous disposal of collected dusts<br>Low-to-moderate pressure loss<br>Handles large particles<br>Handles high dust loadings<br>Temperature independent | Much head room required<br>Low collection efficiency of small particles<br>Sensitive to variable dust loadings and flow rates |
| Wet collectors | | | Simultaneous gas absorption and particle removal<br>Ability to cool and clean high-temperature, moisture-laden gases<br>Corrosive gases and mists can be recovered and neutralized<br>Reduced dust explosion risk<br>Efficiency can be varied | Corrosion, erosion problems<br>Added cost of wastewater treatment and reclamation<br>Low efficiency on submicron particles<br>Contamination of effluent stream by liquid entrainment<br>Freezing problems in cold weather<br>Reduction in buoyancy and plume rise<br>Water vapor contributes to visible plume under some atmospheric conditions |
| Spray towers | >10 | <80 | | |
| Cyclonic | >2.5 | <80 | | |
| Impingement | >2.5 | <80 | | |
| Venturi | >0.5 | <99 | | |
| Electrostatic precipitator | <1 | 95-99 | 99+% efficiency obtainable<br>Very small particles can be collected<br>Particles may be collected wet or dry<br>Pressure drops and power requirements are small compared with other high-efficiency collectors<br>Maintenance is nominal unless corrosive or adhesive materials are handled<br>Few moving parts<br>Can be operated at high temperatures(573 to 723 K) | Relatively high initial cost<br>Precipitators are sensitive to variable dust loadings or flow rates<br>Resistivity causes some material to be economically uncollectable<br>Precautions are required to safeguard personnel from high voltage<br>Collection efficiencies can deteriorate gradually and imperceptibly |
| Fabric filtration | <1 | >99 | Dry collection possible<br>Decrease of performance is noticeable<br>Collection of small particles possible<br>High efficiencies possible | Sensitivity to filtering velocity<br>High-temperature gases must be cooled<br>Affected by relative humidity (condensation)<br>Susceptibility of fabric to chemical attack |