Chapter 7 Separation of Particles from a Gas

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

7.1 Gas Cyclones

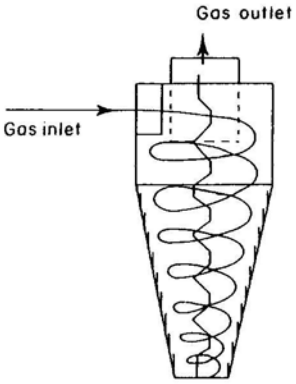


Figure 7.2

7.2 Flow Characteristics

Rotational flow in the forced vortex in the cyclone body

→ radial pressure gradient

Resistance coefficient: Euler number

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

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

* *Economy* of the collectors

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

annualized capital cost + *operating cost** :

* Power requirement $\equiv Q\,\Delta p$, [W]

where $\Delta p = f(L, v, \rho_f, \mu)$ $\rightarrow$ $Eu = f(Re_p)$ ~ constant

By dimensional analysis

for a given cyclone, independent of D

7.3 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 distribution s 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 (*)

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

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

$$3\pi x \mu U_r = \frac{\pi x^3}{6} (\rho_p - \rho_f) \frac{U_\theta^2}{r}$$

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

where $U_\theta r^{1/2} = constant$ for confined vortex

$$= U_{\theta R} R^{1/2}$$

$U_r r = constant$ for radially inward flow

$$= U_R R$$

$$\therefore\ x^2 = \frac{18\mu}{\rho_p - \rho_f} \frac{U_R}{U_{\theta R}^2} r$$

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

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

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

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 $G(x) = 0.5$

7.4 Scale-up of Cyclone

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

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

From both *theoretical and actual* analysis for given cyclone,

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

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

$$\uparrow \qquad\qquad \uparrow$$

independent $\quad U=Q/\frac{\pi}{4}D^2$

of Re

Standard Cyclone Designs - dimension

Figure 7.5

- *High efficiency* Stairmand cyclone:

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

- *High flow rate* Stairmand cyclone

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

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

7.5 Range of operation

Figure 7.7 : optimum operation somewhere between A and B

cf. Reentrainment

7.6 Some Practical Design and Operation Details

High dust loading ($>\sim5g/m^3$) → 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

N cyclones in parallel

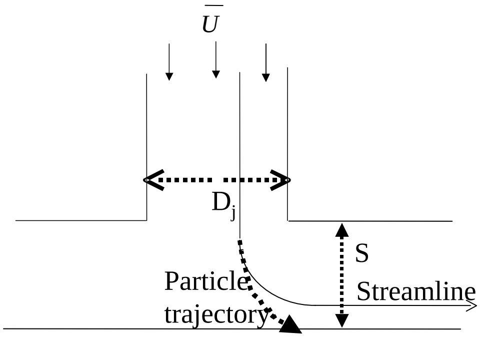
For large gas flow rate

$$Q \rightarrow Q/N$$

Worked Example 7.1

Worked Example 7.2

7.7S Aerosol Impactor



In general, for inertial motion of particles,

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

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

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

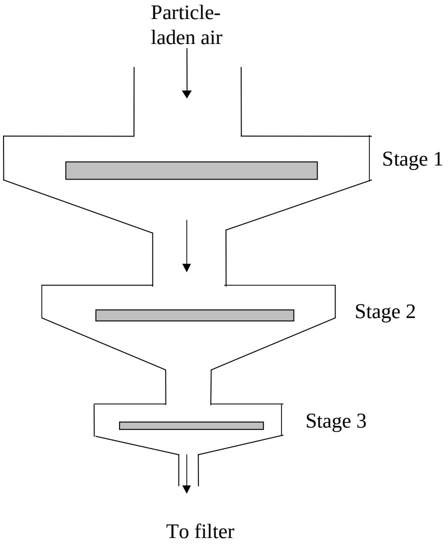
For *rectangular* nozzle, Stk_{50} = 0.53

$$\therefore x_{50} = \left[\frac{9\mu D Stk_{50}}{\rho_p U C_c} \right]^{1/2}$$

작은 입자를 잡으려면 노즐 입경을 줄이고, 유속을 올리는 방법과 C_c를 올리는 방법이 있다.

C_c를 올리려면 어떻게 해야 하나?

* Cascade impactor



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

Summary of Particulate Collection

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