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

![Diagram of a gas cyclone]

Figure 7.2

7.2 Flow Characteristics
Rotational flow in the forced vortex in the cyclone body
→ radial pressure gradient

Resistance coefficient: Euler number

\[ Eu = \frac{\Delta p}{\varrho \omega^2/2} \]

where \[ v = \frac{A q}{\pi D^2} \sim \frac{\text{pressure force}}{\text{inert force}} \]

* Economy of the collectors

Based on $/(1000 \, \text{m}^3 \, \text{cleaned gas} / \text{h})

\text{annualized capital cost} + \text{operating cost}^* :

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

where \[ \Delta p = f(L, v, \varrho, \nu) \rightarrow Eu = f(Re) \sim \text{constant} \]

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

\[ M \frac{dF}{dx} = M_f \frac{dF_f}{dx} + M_c \frac{dF_c}{dx} \quad (*) \]

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, \( G(x) \)

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

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

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, \( r \)

\[
3\pi x^2 U_r = \frac{\pi x^3}{6} (\varrho_p - \varrho_f) \frac{U_0^2}{r}
\]

\[
F_D = F_C - F_B
\]

where \( U_0 r^{1/2} = \text{constant for confined vortex} \)

\[= U_0 r^{1/2} \]

\( U, r = \text{constant for radially inward flow} \)

\[= U_r R \]

\[
\therefore \quad x^2 = \frac{18 \varrho_0}{\varrho - \varrho_f} \frac{U_r}{U_0 R} r
\]
where \( r \): the radius of the equilibrium orbit (displacement) for a particle of diameter \( x \)

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

\[
x_{\text{crit}}^2 = \frac{18\mu}{\rho_p - \rho_f} \frac{U_R}{U_{bR}} R
\]

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

\[
\downarrow
\]

or

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

(3) Cyclone Grade Efficiency in Practice

Ideal grade efficiency curve \hspace{1cm} \text{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 \( x_{\text{crit}} \) and \( St_{\text{crit}} \)

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

7.4 Scale-up of Cyclone

\textbf{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

\[
St = \frac{\rho x^2 U}{18\mu L} \quad \text{and} \quad Re = \frac{\rho U L}{\mu}
\]

From both theoretical and actual analysis for given cyclone,
\[ St_{50} \left( \equiv \frac{\rho \cdot x_{50}^2 U}{18 \nu D} \right) \sim \text{constant} \rightarrow x_{50} \propto \sqrt[3]{\rho D^3/\rho Q} \]

\[ Eu \left( \equiv \frac{\Delta \rho}{\rho U^2/2} \right) \sim \text{constant} \rightarrow \Delta \rho \propto Q^3/D^4 \]

\[ \uparrow \quad \uparrow \quad \text{independent of } Re \]

\[ U = Q/\frac{\pi}{4} D^2 \]

**Standard Cyclone Designs - dimension**

Figure 7.5

- **High efficiency Stairmand cyclone:**
  \[ St_{50} = 1.4 \times 10^{-4} \text{ and } Eu = 320 \]

- **High flow rate Stairmand cyclone**
  \[ St_{50} = 6 \times 10^{-3} \text{ and } Eu = 46 \]

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 \((> 5 g/m^3) \rightarrow \text{high separation efficiency due to agglomeration}\)

For well-designed cyclone

\[ Eu = \sqrt{\frac{12}{5} \cdot \frac{1}{S_i k_{50}}} \]
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

\[ N \text{ cyclones in parallel} \]

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,

\[ G(x) = f \left( Stk(x), Re, \frac{S}{D_i} \right) \]

where \( Stk(x) = \frac{\tau(x) \bar{U}}{D} \)

For given geometry \( (S/D_i) \)

\[ 0.5 = f(Stk_{50}, Re) \rightarrow Stk_{50} = f_1(Re) \]
From numerical and/or experimental analysis

\[ Stk(x) : \text{almost independent of } Re \]

Or for \( 500 < Re < 3000 \) and \( S/D > 1.5 \)

For circular nozzle, \( Stk_{50} = 0.22 \)
For rectangular nozzle, \( Stk_{50} = 0.53 \)

\[ \therefore x_{50} = \left[ \frac{9 \nu D Stk_{50}}{\rho U c_c} \right]^{1/2} \]

작은 입자를 잡으려면 노즐 입구를 줄이고, 유속을 높이는 방법과 \( C_c \)를 올리는 방법이 있다.

\( C_c \)를 올리려면 어떻게 해야 하나?

* Cascade impactor

- Measurement of particle size distribution
- Classification of particles
### Summary of Particulate Collection

<table>
<thead>
<tr>
<th>Device</th>
<th>Minimum particle size (μm)</th>
<th>Efficiency (% mass basis)</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational settler</td>
<td>&gt;50</td>
<td>&lt;50</td>
<td>Low-pressure loss</td>
<td>Much space required</td>
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<td></td>
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<td>Simplicity of design and maintenance</td>
<td>Low collection efficiency</td>
</tr>
<tr>
<td>Cyclone</td>
<td>5-25</td>
<td>50-90</td>
<td>Simplicity of design and maintenance</td>
<td>Much head room required</td>
</tr>
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<td></td>
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<td></td>
<td>Little floor space required</td>
<td>Low collection efficiency of small particles</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Dry continuous disposal of collected dusts</td>
<td>Sensitive to variable dust loadings and flow rates</td>
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<td></td>
<td>Low-to-moderate pressure loss</td>
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<td>Handles large particles</td>
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<td>Handles high dust loadings</td>
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<td>Temperature independent</td>
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<tr>
<td>Wet collectors</td>
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<td>Simultaneous gas absorption and particle removal</td>
<td>Corrosion, erosion problems</td>
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<tr>
<td>Spray towers</td>
<td>&gt;10</td>
<td>&lt;80</td>
<td>Ability to cool and clean high-temperature, moisture-laden gases</td>
<td>Added cost of wastewater treatment and reclamation</td>
</tr>
<tr>
<td>Cyclonic</td>
<td>&gt;2.5</td>
<td>&lt;80</td>
<td>Low efficiency on submicron particles</td>
<td></td>
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<tr>
<td>Impingement</td>
<td>&gt;2.5</td>
<td>&lt;80</td>
<td>Corrosive gases and mists can be recovered and neutralized</td>
<td>Contamination of effluent stream</td>
</tr>
<tr>
<td>Venturi</td>
<td>&gt;0.3</td>
<td>&lt;99</td>
<td>Reduced dust explosion risk</td>
<td>by liquid entrainment</td>
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<td>Efficiency can be varied</td>
<td>Freezing problems in cold weather</td>
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<td>Reduction in buoyancy and plume rise</td>
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<td>Water vapor contributes to visible plume under some atmospheric</td>
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<td></td>
<td></td>
<td>conditions</td>
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<tr>
<td>Electrostatic precipitator</td>
<td>&lt;1</td>
<td>95-99</td>
<td>Very small particles can be collected</td>
<td>Relatively high initial cost</td>
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<td>Particles may be collected wet or dry</td>
<td>Precipitators are sensitive to variable dust loadings or flow</td>
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<td>Pressure drops and power requirements are small compared with other high-</td>
<td>rates</td>
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<td>efficiency collectors</td>
<td>Resistivity causes some material to be economically uncollectable</td>
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<td>Maintenance is nominal unless corrosive or adhesive materials are handled</td>
<td>Precautions are required to safeguard personnel from high</td>
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<td>Few moving parts</td>
<td>voltage</td>
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<td>Can be operated at high temperatures(573 to 723 K)</td>
<td>Collection efficiencies can deteriorate gradually and</td>
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<td>imperceptibly</td>
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<tr>
<td>Fabric filtration</td>
<td>&lt;1</td>
<td>&gt;99</td>
<td>Dry collection possible</td>
<td>Sensitivity to filtering velocity</td>
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<td></td>
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<td></td>
<td>Decrease of performance is noticeable</td>
<td>High-temperature gases must be cooled</td>
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<td>Collection of small particles possible</td>
<td>Affected by relative humidity (condensation)</td>
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<td></td>
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<td></td>
<td>High efficiencies possible</td>
<td>Susceptibility of fabric to chemical attack</td>
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