Chapter 7 Mixing and Granulation

7.1 Mixing and Segregation (Chapter 9)

Mixing vs. segregation

(1) Types of Mixture

* Perfect mixing
  Random mixing
  Segregating mixing

Figure 9.1

(2) Segregation

1) Causes and Consequences of Segregation

- Particles with the same physical property (size, density and shape) collect together in one part of the mixture.
- Usually it occurs during moving, pouring, conveying, processing
- Its degree depends on particle-particle interaction*

* Free-flowing powder or coarse particles → segregating rather than mixing
  Cohesive powder or fine particles → mixing rather than segregating but easily aggregating

2) Mechanisms of Separation Figure 9-2

- Trajectory segregation
  From Chapter 3 in lecture note,
  \[ s = \frac{\rho x^2 U}{18} \]
- Percolation of fine particles - Figure 9.3
  Rise of coarse particles on vibration - Figure 9.4
- Elutriation segregation
3) Reduction of Segregation
- Make the sizes of the components as close as possible
- Reduce the absolute size of the particles
  \[ < 30 \text{ m} \text{ with density about } p = 2000-3000 \text{kg/m}^3 \]
  Critical diameter lowered as the density increases.
- Use of interparticulate forces
  Add a small amount of liquid (Use of liquid-bridge force)
- Make one of the components very fine (less than 5 m)
  Ordered mixing*
  Figure 9.3
- Avoid to promote the segregation
- Use continuous mixing for very segregating materials

4) Equipment for Particulate Mixing
- Mechanisms of Mixing and Types of Mixer (9.5.1 and 9.5.2)

<table>
<thead>
<tr>
<th>Diffusive mixing</th>
<th>- Random walk phenomenon</th>
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<tbody>
<tr>
<td></td>
<td>- Essential for microscopic homogenization</td>
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<tr>
<td></td>
<td>- Not suitable for segregating particles</td>
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<td>Shear mixing</td>
<td>- Induced by the momentum exchange of powders having different velocities</td>
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<td>- Semi-microscopic mixing</td>
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<td>Convective mixing</td>
<td>- Circulation of powders by rotating blades</td>
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<td></td>
<td>- Beneficial for batch mode, not for continuous mixing</td>
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<tr>
<td></td>
<td>- Suitable for segregating particles</td>
</tr>
<tr>
<td>Tumbling mixers, Figure 9.6</td>
<td>High-velocity rotating blade</td>
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<td>Low velocity-high compression rollers,</td>
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<td></td>
<td>Ribbon blender, Figures 9.7, 9.8</td>
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<td></td>
<td>Fluidized-bed mixer</td>
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</tbody>
</table>

* Ordered mixture by dry impact blending method
5) **Assessing the Mixture**

For Binary mixture(2 components)

If \( y_i (i=1,2,\ldots,N) \): composition of the key component in the i-th sample,

**Sample mean**

\[
\bar{y} = \frac{1}{N} \sum_{i=1}^{N} y_i
\]

* True mean?

**Standard deviation** (standard variance, \( \sigma^2 \))

- Estimated standard variance( \( S^2 \))

\[
S^2 = \frac{1}{N} \sum_{i=1}^{N} (y_i - \bar{y})^2
\]

- **Theoretical Limits of variance**

  Upper limit: true standard deviation for a completely unmixed system, \( \sigma^0 \)

  \[
  \sigma^0 = p(1-p)
  \]

  Lower limit: true standard deviation of random binary mixture, \( \sigma^r \)

  \[
  \sigma^r = \frac{p(1-p)}{n}
  \]

  where \( p, 1-p \): fractions of two components in the whole mixture

**Degree of Mixing (Mixing indices)**

The ratio of mixing achieved to mixing possible

Lacey : \[
\frac{\sigma^2}{\sigma^0} - \frac{\sigma^2}{\sigma^r}
\]

Poole : \[
\frac{\sigma^2}{\sigma^r}
\]

**Worked Example 9.1, 9.2, 9.3**

7.2 **Size Enlargement - Granulation (Chapter 11)**

* Size enlargement - agglomeration of particles
* Why enlarge the particles?
  - To reduce dust hazard
  - To reduce cake and lump formation
  - To increase flow properties
  - To increase bulk density for storage
  - To increase nonsegregating mixtures
  - To provide defined metered quantity of active ingredients
  - To control surface-to-volume ratio

* How enlarge the particles?
  - Granulation: agglomeration by agitation (relative motion of particles)
  - Machine granulation: compaction (tabletting), extrusion
  - Sintering: thermal, final densification
  - Spray drying: starting from droplets followed by its drying
  - Prilling (freeze drying)

(1) **Interparticle Forces (11.2)**

1) **Van der Waals Forces**
   - Between two spheres
   \[ W = \frac{A}{12z} \frac{x_1x_2}{x_1 + x_2} \]
   where \( A \) : Hamaker constant
   \( z \) : separation

2) **Forces due to Adsorbed Liquid Layers**
   - Overlapping of adsorbed layers
   - Dependent on area of contact and tensile strength of the adsorbed layers

3) **Forces due to Liquid Bridges**
For **pendular state** Figure 11.1

\[ F = 2 \gamma r_2 + \gamma r_1 \left[ \frac{1}{r_1} - \frac{1}{r_2} \right] \]

* Strong granules in which the quantity of liquid is not critical...

* Granule strength continuously decreases in funicular, capillary and droplet states.

4) **Electrostatic Forces**

* Contact electrification:
  - Friction caused by interparticle collision \(\rightarrow\) Transfer of electrons between bodies

5) **Solid bridges**

- Crystalline bridges
- Liquid binder bridges
- Solid binder bridges

6) **Comparison and Interaction between Forces**

- Humidity vs. van der Waals forces, interparticle friction, liquid bridges and electrostatic forces

Figure 11.2 Tensile strength for various bonding mechanisms

(2) **Granulation** (11.3)

- Agitation: distribute liquid binder and impart energy to particles and granules for relative motion to meet together...

1) **Granulation Rate Process** (11.3.2)

i) Wetting

- Rate of penetration of liquid
\[ \frac{dz}{dt} = \frac{R_p \cos \frac{\theta}{4}}{z} \]

Washburn equation

where \( R_p \): average pore radius, depending on particle size and packing density or packing..

\( \theta \): dynamic contact angle

\( \mu \): viscosity of liquid, depending on the binder concentration

ii) Growth

- Nucleation - shatter
- Coalescence - breakage
- Layering - attrition
- Abrasive transfer

Define \( Stk = \frac{\varphi \cdot V_{app} \cdot \gamma}{16} \) \( \approx \) Box on p274 Ennis and Litster (1997)

\[ Stk^* = \left( 1 + \frac{1}{\varepsilon} \right) \ln \left( \frac{h}{h_s} \right) \]

where \( \varepsilon \): coefficient of restitution

\( h_s \): surface roughness of granules

- Noninertial regime: \( Stk \ll Stk^* \)
  \* all collisions effective for coalescence
  \* rate of wetting controls
  \* independent of liquid viscosity, granule size and kinetic energy of collision

- Inertial regime: some \( Stk \) exceeds \( Stk^* \)
  \* the proportion of successful collision decreases
  \* dependent on viscosity, granule size and kinetic energy

- Coating regime: average \( Stk \) exceeds \( Stk^* \)
  \* granule growth is balanced by breakage
  \* growth continues by coating of primary particles onto existing granules
iii) Granule consolidation
- increase in granule density by closer packing density
- squeeze out liquid

2) Simulation of Granule Growth (11.3.3)

\[
\frac{\partial n(v,t)}{\partial t} = \frac{Q_{in}}{V} n_{in}(v) - \frac{Q_{out}}{V} n_{out}(v) + \frac{\partial G(v)n(v,t)}{\partial v} + B_{vac}(v) + \frac{1}{2} \int_{0}^{v} \beta(u,v-u,t)n(u,t)n(v-u,t)du - \int_{0}^{\infty} \beta(u,v,t)n(u,t)n(v,t)du - \frac{\partial A(v)n(v,t)}{\partial v}
\]

(11.7) (11.8) (11.9) + (11.10) + (11.11)

3) Granulation Equipments (11.3.4) Table 11.1
- Tumbling granulator  Figure 11.4
  - Tumbling inclined drum and pan
  - Operate in continuous mode

- Mixer granulator
  - Rotating agitator
  - From 50 rpm(horizontal pug mixer-fertilizer) to 3000 rpm(vertical Schugi high shear continuous granulator-detergent, agricultural chemicals)

- Fluidized bed granulators
- Bubbling or spouted bed  Figure 11.5
- Operate in batch or continuous mode
- Good heat and mass transfer
- Mechanical simplicity
- Combine drying stage with granulation
- Produce small granules
- Running cost and attrition rates: higher