Electrostatics of Granular Flow in Pneumatic Systems

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STEP 1 (Static-Tribo-Electricity of Powder) 2014/12/19-12/21
Soka University, Hachioji, Tokyo, Japan
In a polishing workshop powder induced an extremely large accident (96 person die).

Possible reason: particle-particle/particle-wall interaction causes electrostatic charge and charges accumulate, which grows more and more to become explosion source.
Experiment setup

<table>
<thead>
<tr>
<th>Particles conveying style</th>
<th>Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle material:</td>
<td>Polypropylene(PP)</td>
</tr>
<tr>
<td>Pipe material:</td>
<td>Polyvinyl Chloride (PVC)</td>
</tr>
<tr>
<td>Pipe thickness:</td>
<td>5.0 mm</td>
</tr>
<tr>
<td>Air flow rate:</td>
<td>860~1600 liters/min</td>
</tr>
<tr>
<td>Temperature:</td>
<td>28~30 °C</td>
</tr>
</tbody>
</table>

| Particle diameter:       | 2.8 mm |
| Particle density:        | 1123 kg/m³ |
| Pipe diameter(inner):    | 40.0 mm |
| Relative humidity:       | 5% |
| Air superficial velocity:| 11.4~21.2 m/s |

The clusters were located fairly high up in the pipe and traveled along a curved path by the pipe wall. These clusters appeared and disappeared intermittently in an unpredictable manner.

Yao et al. 2004. Ind. Eng. Chem. Res. 43, 7181-
Particles were observed to cluster on the side of the vertical pipe wall distant from the position of the lower horizontal pipe to form a half-annular ring structure.

Initial condition

Half hour later

Particles were observed to travel in a spiral fashion up the vertical pipe along the pipe wall. This resulted in a ring or annulus structure with high particle concentrations adjacent to the wall and a relatively empty core region.

Flow rate = 960 liters/min
Air velocity = 11.406 m/s

Initial condition

Fifteen minutes later

Induced current acquired at the vertical pipe:

(left) disperse flow (air flow rate 1600 L/min, solids feed rate 35.3 (3.2 kg/m² s);
(middle) half-ring flow (air flow rate 1000 L/min, solids feed rate 13.8 (2.4 kg/m² s);
(right) ring flow (air flow rate 80 L/min, solids feed rate 8.1(1.6 kg/m² s).
Left: Comparison of the current value (negative) for the three flows.
Right: Comparison of the charge accumulation for the three flows.
Electrostatic field simulation
- point-point charge sources

\[ e = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r_x^2} \]  
(Halliday et al. 1997)

\( \varepsilon_0 \): permittivity constant (in vacuum \( 8.85 \times 10^{-12} \text{ C}^2/\text{N} \cdot \text{m}^2 \))

\( r_x \): the distance from the point charge

\( q \): the point charge

\[ e_x = e \cdot \cos \theta_x = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r_x^2} \cdot \cos \theta_x \]

\[ e_y = e \cdot \sin \theta_x = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r_x^2} \cdot \sin \theta_x \]

\[ r_x^2 = r_1^2 + r_0^2 - 2 \cdot r_1 \cdot r_0 \cdot \cos(\theta_0 - \theta_1) \]

*Fundamentals of Physics Extended. 5th ed.*, P558.

Yao et al. 2006 *AIChE J.* 52, 3775-.
In a two-dimension field, the electrostatic field generated by a point charge $q$ at the point $(i, j)$ can be calculated:

$$
e_{x(i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2_{x(i,j)}} \cdot \cos \theta_{x(i,j)}$$

$$
e_{y(i,j)} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2_{x(i,j)}} \cdot \sin \theta_{x(i,j)}$$

Yao et al. 2006 AIChE J. 52, 3775-.
Electrostatic field simulation
- points-points charge sources

\[ e_{x(l,k,i,j)} = \frac{1}{4\pi \varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2_x(l,k,i,j)} \cdot \cos \theta_{x(l,k,i,j)} \]

\[ e_{y(l,k,i,j)} = \frac{1}{4\pi \varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2_x(l,k,i,j)} \cdot \sin \theta_{x(l,k,i,j)} \]

\[ E_{x(i,j)} = \sum_{l=1}^{m} \sum_{k=1}^{n} \sum_{i=1}^{m} \sum_{j=1}^{n} e_{x(l,k,i,j)} = \sum_{l=1}^{m} \sum_{k=1}^{n} \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{1}{4\pi \varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2_x(l,k,i,j)} \cdot \cos \theta_{x(l,k,i,j)} \]

\[ E_{y(i,j)} = \sum_{l=1}^{m} \sum_{k=1}^{n} \sum_{i=1}^{m} \sum_{j=1}^{n} e_{y(l,k,i,j)} = \sum_{l=1}^{m} \sum_{k=1}^{n} \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{1}{4\pi \varepsilon_0} \cdot \frac{q_{(l,k)}}{r^2_x(l,k,i,j)} \cdot \sin \theta_{x(l,k,i,j)} \]

\[ E_{(i,j)} = \sqrt{E_{x(i,j)}^2 + E_{y(i,j)}^2} \]

Yao et al. 2006 AIChE J. 52, 3775-.
Electrostatic field
- pipe wall

Yao et al. 2006 AIChE J. 52, 3775-.
ECT & Electrostatic field
- particles at vertical pipe

ECT solid fraction (Rao et al. 2001; Zhu et al. 2003)

Electrostatic field

<table>
<thead>
<tr>
<th>L/min</th>
<th>Image 1</th>
<th>Image 2</th>
<th>Image 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>1100</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>960</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Yao et al. 2006 AIChE J. 52, 3775-.
PIV measurements
– particles at vertical pipe

<table>
<thead>
<tr>
<th>Air flow rate (L/min)</th>
<th>1600 (left)</th>
<th>1100(middle)</th>
<th>950(right)</th>
</tr>
</thead>
</table>

(m/s): | 5.10 | - | - |

Core region (r/R<0.7): | 5.10 | - | - |

Boundary region (0.8<r/R<1.0): | 3.60 | 0.23 | 0.04 |

$F_D(N)$: | 1.62E-02 | 9.89E-04 | 1.65E-04 |

Boundary region (0.8<r/R<1.0): | 1.62E-02 | 9.89E-04 | 1.65E-04 |

Yao et al. 2006 AIChE J. 52, 3775-.
The highest electrostatic force appears near the pipe wall and degrades from the pipe wall to the pipe center.

Electrostatic force increases with decreasing air flow rate.

Yao et al. 2006 AIChE J. 52, 3775-.
Dynamics analysis - particles at vertical pipe

<table>
<thead>
<tr>
<th></th>
<th>Air flow rate (L/min)</th>
<th>Gravity (N)</th>
<th>$F_D$ (N)</th>
<th>$F_f$ (N)</th>
<th>$F_E$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core region:</td>
<td>1600</td>
<td>1.27E-04</td>
<td>7.56E-02</td>
<td>2.62E-12~1.19E-09</td>
<td>4.68E-12~2.13E-09</td>
</tr>
<tr>
<td>Boundary region:</td>
<td>1600</td>
<td>1.27E-04</td>
<td>1.62E-02</td>
<td>1.00E-09~1.25E-08</td>
<td>1.79E-09~2.23E-08</td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>1.27E-04</td>
<td>9.89E-04</td>
<td>5.26E-09~2.35E-06</td>
<td>9.39E-09~4.19E-06</td>
</tr>
<tr>
<td></td>
<td>950</td>
<td>1.27E-04</td>
<td>1.65E-04</td>
<td>3.60E-07~1.89E-05</td>
<td>6.42E-07~3.37E-05</td>
</tr>
</tbody>
</table>

Core region: $r/R < 0.7$; boundary region: $0.8 < r/R < 1$.

Lower air flow rates give rise to half-ring and ring flows. Fluid drag forces within the wall boundary layer are reduced to the same order of magnitude as that of gravitational forces. A dynamic equilibrium may be established between the two types of forces.

Electrostatic force may then emerge as the dominant factor affecting granule behavior.
Granular attrition effect

Yao et al. 2006. *Chem. Eng. Sci.* 61, 3858-
Granular electrostatics – attrition

Yao et al. 2006. *Chem. Eng. Sci.* 61, 3435-
Charge generation mechanism - triboelectrification

Single-granule test

Setup: **Faraday cage** (TR8031, Advantest Corporation, Japan)
Electrometer (Advantest R8252 Digital Electrometer, Advantest Corporation, Japan)
High-speed camera (Japan: OLYMPUS, i-speed LT)
Stainless steel: 15cm*5cm
Sliding velocity effect

$T = 0.2s$

Time cost:
0.238s  0.236s  0.230s
0.226s  0.222s  0.220s

Electrostatics at corresponding point
Granular shape effect

Front-facing angle

Area

Length ratio

Length ratio
Conclusions

• In the granular conveying system, air flow rate is a key factor determining the electrostatic behavior of granular flow. The lower the air flow rate, the higher the induced current and particle charge density. These in turn lead to particle clustering and the formation of such structures as half-ring and ring in the vertical conveying pipe.

• The electrostatics of granular flow in a pneumatic conveying system was quantitatively characterised by induced current, particle charge density and equivalent current of the charged granular flow and found to increase with granular attrition occurring in the rotary valve. A new method using granule size and shape is proposed as a useful tool for characterisation of electrostatics in general systems where granules are made up of complex combinations of different sizes and geometries.

• Granular size/shape due to attrition is found to affect electrostatic charge generation characteristics. It was found that some factors, such as granular front-facing angle, length-ratio, sliding direction, sliding times and environmental relative humidity, had significant effects on granular electrostatics generation.

• The mechanism of electrostatic charge generation for the granular flow in the pneumatic conveying system mainly depends on triboelectrification due to strong force effect on the surface when the particles slide on the pipe wall.
Acknowledgements

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