Week #7
Dynamics of Particulate systems (Part 2)

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On the Electrostatics of Pneumatic Conveying of Granular Solids Using Electrical Capacitance Tomography (ECT)

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Experimental

Recycle Feed Hopper

Solid Feed Hopper

Air from compressor mains

Rotameter

Rotary air lock feeder

Weight Indicator

PC

ECT

0.71 m

0.85 m
Physical properties of particles used in this work

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean particle diameter $10^3$ (m)</th>
<th>Particle density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass powder</td>
<td>0.5</td>
<td>2980</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>2.8</td>
<td>1123</td>
</tr>
<tr>
<td>Larostat-519</td>
<td>0.02</td>
<td>520 kg/m$^3$</td>
</tr>
</tbody>
</table>

Present study considered coarse PP particles compared to 500 $\mu$m glass powder, and anti-static powders.
Pneumatic Conveying Electrostatic Analysis

- Characterize wall charge accumulation.
- Investigate concentration measurement under static charge effect.
- Examine the effects of operation conditions on the wall charge accumulation.
- Study the mechanism for special pattern formation.
Schematic diagram of voltmeter measurement

\[ h = 43 \text{ mm} \]
\[ h_1 = 4 \text{ mm} \]
\[ \theta = 45^0 \]

1 – sensor
2 – pipe segment
3 – copper plane
4 – voltmeter
5 – support
6 – clamp
Contact potential measurement

\[ V'_{0, \text{Sample/Au}} = \frac{\rho A d^2}{2\varepsilon_a} \]
Contact potential measurement for particles and inner wall of PVC pipe
Variation of time averaged solids concentration distribution – influence of electrostatic charges

horizontal pipe 1.2 m from downstream bend

\[ G_s = 0.08 \text{ kg/s} \]
Charge accumulation at the wall during pneumatic conveying system – effect of conveying velocity

Vertical pipe
Z = 2.05 m

G_s = 0.08 kg/s
Pneumatic conveying of polypropylene granules. Solids mass flow rate $G_s = 0.08 \text{ kg/s}$. A: surface potential, $U = 18.9 \text{ m/s}$, horizontal conveying; B: surface potential, $U = 17.3 \text{ m/s}$, vertical conveying; C: solid concentration, $U = 18.9 \text{ m/s}$, horizontal conveying; D: solid concentration, $U = 17.3 \text{ m/s}$, vertical conveying.
Distribution of polypropylene particles in a vertical riser flow – annular capsule flow

Slugging flow

\[ U_g = 13.0 \text{ m/s} \]
\[ G_s = 7.0 \text{ kg/(m}^2\text{s)} \]
\[ Z = 2.05 \text{ m} \]

Induced current measurement

- Polymer film
- Sections A & C
- Test station B
- Aluminum foil
- Pipe wall
- Electrometer
U = 14.3 m/s, $G_s = 0.08$ kg/s

Moving capsule flow
Influence of Larostat-519 antistatic powder

$U = 23.4 \text{ m/s}, \quad G_s = 0.08 \text{ kg/s}$

(a) w/o larostat  
(b) with larostat

Scanning electron micrographs of polypropylene particles – after conveying

(a) – with addition of larostat 519 powder
(b) – without larostat 519 powder
Glass Powder Tests

- Experiments are repeated for glass powder (mean diameter = 500 mm, density = 2980 kg/m$^3$). Similar trends in the induced current are found with complicated polarity changes.

- It is noted that the induced currents detected for a fresh pipe segment (as high as several nA) are significantly larger than that for a used pipe (less than 0.1nA).

- The surface potential measured using the electrostatic voltmeter increases slowly from -0.2kV only to around ~3 kV for a used pipe, while the surface potential increases drastically to a value higher than 20 kV for a fresh pipe.

- This observation confirms the induced current measurement results and suggests that attrition of conveying pipe may considerably alter the pipe properties for static electricity.
ECT measurement drifting is due to electrostatic charge

Reliable solid volume fraction can be obtained if the electrostatic charge influence is considered

Wall charge accumulation are characterized by ECT measurement and this is consistent with electrostatic voltmeter observation

Wall electrostatic charges are enhanced with lower conveying velocities at the same solids flow rate

Current due to charged particles detected by MPCT were in good agreement with ECT measurement

Addition of antistatic powder (larostat 519) can reduce the charge generation
Discrete Element Method Simulation for Pneumatic Conveying Systems

\[ m_i \frac{dv_i}{dt} = m_i g + \sum_{j=1}^{k_i} \left( f_{c,ij} + f_{d,ij} \right) + f_{f,i} \]

\[ I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{k_i} T_{ij} \]

- Discrete Element Method (DEM)
- Originally developed for describing the mechanical behavior of assemblies of discs and spheres

\[ f_{cn,ij} = -\left(\kappa_{n,i} \delta_{n,ij}\right)n_i \]
\[ f_{ct,ij} = -\left(\kappa_{t,i} \delta_{t,ij}\right)t_i \]
\[ f_{dn,ij} = -\eta_{n,i} (v_r \cdot n_i) n_i \]
\[ f_{dt,ij} = -\eta_{t,i} \left[ (v_r \cdot t_i) t_i + \left(\omega_i \times R_i - \omega_j \times R_j\right)\right] \]
\[ f_{s,\text{max}} = f_n \tan \phi + c \]
COMPUTATIONAL FLUID DYNAMICS

\[ \frac{\partial \varepsilon}{\partial \tau} + \nabla \cdot (\varepsilon u) = 0 \]

\[ \frac{\partial (\rho_f \varepsilon u)}{\partial \tau} + \nabla \cdot (\rho_f \varepsilon uu) = -\varepsilon \nabla p + \nabla \cdot (\varepsilon \Gamma) + \rho_f \varepsilon g - F \]

• Coupling between CFD and DEM via fluid-particle drag force model

• Additional source term in momentum equation to represent reaction force on fluid
FLUID DRAG FORCE

\[ f_{f,i} = f_{f0,i} e^{-\chi} \]

\[ f_{f0,i} = 0.5c_{d0,i} \rho_f \pi R_i^2 |u_i - v_i| (u_i - v_i) \]

\[ \chi = 3.7 - 0.65 \exp \left[ - \frac{(1.5 - \log_{10} Re_{p,i})^2}{2} \right] \]

### GRANULAR FLOW SIMULATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape of particles</td>
<td>Spherical</td>
</tr>
<tr>
<td>Number of particles</td>
<td>5310</td>
</tr>
<tr>
<td>Particle diameter, $d$</td>
<td>$1.8 \times 10^{-3} \text{ m}$</td>
</tr>
<tr>
<td>Particle density, $\rho_p$</td>
<td>2980 kg m$^{-3}$</td>
</tr>
<tr>
<td>Particle-particle coefficient of restitution, $e_p$</td>
<td>0.95</td>
</tr>
<tr>
<td>Particle-wall coefficient of restitution, $e_w$</td>
<td>0.97</td>
</tr>
<tr>
<td>Spring constant in discrete model, $\kappa$</td>
<td>5000 N m$^{-1}$</td>
</tr>
<tr>
<td>Solids volume fraction, $\nu$</td>
<td>0.15</td>
</tr>
<tr>
<td>Aspect ratio, $\Delta/d$</td>
<td>33.3</td>
</tr>
<tr>
<td>Simulation time step, $\Delta t$</td>
<td>$10^{-7} \text{ s}$</td>
</tr>
</tbody>
</table>

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GRANULAR FLOW SIMULATION

- $f = 0.0$
- $f = 0.1$
- $K_x = 0.1$
- $f = 10.0$
- $K_x = 3.5$
GAS FLUIDIZATION
GAS FLUIDIZATION
# Material properties and system parameters

<table>
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<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>Shape of particles</td>
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</tr>
<tr>
<td>Type of particles</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>Number of particles</td>
<td>500, 1000, 1500, 2000</td>
</tr>
<tr>
<td>Particle diameter, $d$</td>
<td>$2.8 \times 10^{-3} \text{ m}$</td>
</tr>
<tr>
<td>Particle density, $\rho_p$</td>
<td>1123 kg m$^{-3}$</td>
</tr>
<tr>
<td>Spring constant in force model, $\kappa$</td>
<td>$5.0 \times 10^3 \text{ N m}^{-1}$</td>
</tr>
<tr>
<td>Viscous contact damping coefficient, $\eta$</td>
<td>0.35</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.3</td>
</tr>
<tr>
<td>Gas density, $\rho_f$</td>
<td>1.205 kg m$^{-3}$</td>
</tr>
<tr>
<td>Gas viscosity, $\mu_f$</td>
<td>$1.8 \times 10^{-5} \text{ N s m}^{-2}$</td>
</tr>
<tr>
<td>Pipe diameter</td>
<td>0.04 m</td>
</tr>
<tr>
<td>Pipe length</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Computational cell size</td>
<td>4 mm $\times$ 4 mm</td>
</tr>
<tr>
<td>Simulation time step, $\Delta t$</td>
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</table>
HORIZONTAL PNEUMATIC CONVEYING
HORIZONTAL PNEUMATIC CONVEYING
PHASE DIAGRAMS

- **Plug Flow**
- **Dispersed Flow**
- **Slug Flow**
- **Homogeneous Flow**
- **Moving dunes**

**Vertical pneumatic conveying**

**Horizontal pneumatic conveying**
Transient development of solid flow rates

vertical pneumatic conveying

horizontal pneumatic conveying
PRESSURE DROPS

vertical pneumatic conveying  
horizontal pneumatic conveying
The Discrete Element Method utilizing a linear spring-dashpot-friction slider force-displacement model was coupled with Computational Fluid Dynamics and used for the simulation of pneumatic conveying of granular material in both vertical and horizontal pipes in this study.

The simulation results obtained were in good agreement with previously reported experimental observations in terms of the types of flow patterns arising at different operating conditions used.

These various flow regimes and their corresponding operating conditions have been represented in the form of phase diagrams. Quantitative data such as solid flow rates and pressure drops of the gas also show good agreement with well established trends for such pneumatic conveying operations.
Electrostatic Characterization

Disperse flow — pattern observed in the vertical pipe

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.

Ring flow - vertical granular pattern

Initial condition

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.

Induced current measurement

U = 14.3 m/s, G_s = 0.08 kg/s

Moving capsule flow

(a) Comparison of the current value (negative) for the three flows.
(b) Comparison of the charge accumulation for the three flows.

Summary: Electrostatics in Pneumatic Conveying

- 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.

- Electrostatic effects increase with time. The charge accumulated at the pipe wall increases with time and the rate of increase seems constant for each of the three types of flow. Particle charge density also increases with time and this may account for clustering behavior occurring at the vertical pipe wall even when a high air flow rate is used and the dominant flow regime is that of disperse flow. Pipe wall material has an obvious effect on the electrostatics of the granular flow.

- Electrostatic effects depend on composition for particle mixture. The commercially available anti-static agent, Larostat-519 powder, was found to reduce electrostatic effects within the system effectively.

- 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.
DEM Simulation

• **Newton’s Laws of Motion**

\[
m_i \frac{dv_i}{dt} = \sum_{j=1}^{N} (f_{c,ij} + f_{d,ij}) + m_i g + f_{f,i}
\]

\[
I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{N} T_{ij}
\]

• **Force-displacement Model**

\[
f_{cn,ij} = -\kappa_{n,i} \delta_{n,ij}
\]

\[
f_{ct,ij} = -\kappa_{t,i} \delta_{t,ij}
\]

\[
f_{dn,ij} = -\eta_{n,i} (v_r \cdot n_i) n_i
\]

\[
f_{dt,ij} = -\eta_{t,i} \left[ (v_r \cdot t_i) t_i + (\omega_i \times R_i - \omega_j \times R_j) \right]
\]

Reversed flow in pneumatic conveying in an inclined pipe
DEM Simulation

- Computational Fluid Dynamics

\[ \frac{\partial \epsilon}{\partial t} + \nabla \cdot (\epsilon u) = 0 \]

\[ \frac{\partial (\rho_f \epsilon u)}{\partial t} + \nabla \cdot (\rho_f \epsilon uu) = -\nabla P + \nabla \cdot (\mu_f \epsilon \nabla u) + \rho_f \epsilon g - F \]

Pneumatic Conveying simulations using DEM
## Simulation Conditions

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<td>( 10^{-7} ) s</td>
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Simulation Conditions

• Particles first allowed to settle under gravity for 0.5 s before gas flow was initiated
• Periodic boundary conditions applied to the solid phase to simulate an open flow system
• Solid concentration, $\alpha$, defined as overall volume fraction of particles divided by volume fraction of particles at maximum packing (0.64)
Results and Discussion

Dispersed Flow
\[ \alpha = 0.08 \]
Gas velocity 14 m s\(^{-1}\)

Plug Flow
\[ \alpha = 0.32 \]
Gas velocity 14 m s\(^{-1}\)

Results and Discussion

Stratified Flow
\[ \alpha = 0.08, \text{Gas velocity 10 m s}^{-1} \]

Moving dunes
\[ \alpha = 0.16, \text{Gas velocity 10 m s}^{-1} \]

Slug Flow
\[ \alpha = 0.32, \text{Gas velocity 10 m s}^{-1} \]

Homogeneous Flow
\[ \alpha = 0.16, \text{Gas velocity 30 m s}^{-1} \]

Results and Discussion

• The different flow regimes in vertical pneumatic conveying are represented in the form of phase diagrams.

• Dashed lines separate regions representing different flow regimes while dashed circles enclose regions where transition between two adjacent flow regimes might be taking place.

• In vertical pneumatic conveying, the dispersed flow regime is dominant at high gas velocities and low solid concentrations while the plug flow regime is dominant otherwise.

Results and Discussion

- Similarly, the homogeneous flow regime is dominant at high gas velocities and low solid concentrations while the slug flow regime is dominant otherwise in horizontal conveying.

- At low gas velocities and solid concentrations, effects of gravitational settling result in the formation of the moving dunes and stratified flow regimes.

- Intermediate values of gas velocities involve transitions between moving dunes and homogeneous flow and between stratified and homogeneous flow.

Results and Discussion

- The solid concentration profile for dispersed flow in vertical pneumatic conveying shows that solid concentrations are higher near the walls than in the center of the pipe.
- This trend is similar for all gas velocities simulated.

Results and Discussion

• The solid concentration profiles in horizontal pneumatic conveying show quantitatively the effects of gravitational settling which results in higher solid concentrations along the bottom wall of the pipe.

• As before, the solid concentration profiles are quantitatively similar for different gas velocities used.