INVESTIGATION OF GAS-SOLID FLUIDIZED BED DYNAMICS WITH NON-SPHERICAL PARTICLES

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Presented by: Norman Love
Project Participants

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Graduates
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MD Mahamudur Rahman (Now at Drexel Univ)
Publications and Presentations

JOURNAL PAPER

CONFERENCE PAPERS


Gasification

- **Gasifier:**
  - Types of gasifiers used commercially:
    - Counter-current fixed bed
    - Co-current fixed bed
    - Fluidized bed
    - Entrained flow

Fluidized Bed Reactor:
- Solid particles
- Become suspended
- Behave as though they were a fluid

Fluidized Bed

http://en.wikipedia.org/wiki/Fluidized_bed
Background

- **2006 Multiphase Workshop** - postulated a set of near-midterm, mid-term, and long-term research needs to attain a significant development in the design, operation, and troubleshooting of multiphase flow devices in fossil fuel processing plants by the year 2015.

- Despite previous efforts on gas-solid flows in a fluidized bed, bed dynamics and particle scale motions are still poorly understood.

- A majority of past experimental and computational efforts have been focused on the behavior fluidized bed with spherical particles whereas in most fossil-fuel processes the particles are often non-spherical.
**Objective 1:** To Evaluate Drag Force on Non-Spherical Particles

**Objective 2:** To Incorporate Experimental Data for Non-Spherical Particles in MFIX and FLUENT

**Objective 3:** To Obtain Full-Field Visualization of Motions of Non-Spherical Particles
Tasks- Overview

**Year 1:**
- Task 1: Design of the Experimental Setup: Production and Categorization of Non-Spherical Particles
- Task 2: Map fluidization velocities in bed
- Task 3: Terminal Velocity Determination of Free Falling Non-Spherical Particles

**Year 2:**
- Task 4: Obtain Drag relations for Non-Spherical Particles
- Task 5: Modeling of Pressure Drop and Terminal Velocities in Fluidized Bed for Non-Spherical Particles
- Task 6: Implement Experimental Drag Relations Using Numerical Model

**Year 3:**
- Task 6 Continued: Implement Experimental Drag Relations Using Numerical Model
- Task 7: Integration of the Imaging Instrumentation and Diagnostics with the Experimental Setup
- Task 8: Development of Algorithm for Detection of Non-Spherical Geometries, Particle Pair Identification, Trajectory, and Velocity Components
• Experimental Benchmarking – Spherical Particles
  – 1st Generation Bed
  – 2nd Generation Bed

• Measure the effect of:
  – Bed Height
  – Particle Shape

• Development of numerical models
  – Benchmarking with experimental data
  – Drag model development
  – Implementation into FLUENT

• Qualitative comparisons with Computational Data
  – High-speed camera Images
Experimental Setup 1st Gen

1. Pressure Transducer
2. High-Speed Camera
3. LDV
Experimental Setup 2\textsuperscript{nd} Gen

- Hopper
- Vibrator
- High Speed Camera
- Fluidized Bed
- Thermal Mass Flow meter
- Butterfly valve
- Sheet Metal Pipe

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POWERING INNOVATION THROUGH DIVERSITY
Experimental Setup
Test Particles

Spherical
Mean Diameter = 1 mm

Non-spherical
Mean Diameter = 0.9-1 mm
Particle Production

Sieve Shaker and Sieves

Hydraulic Compressor
**Particle Size**

- **Spherical Particles**
  - 1 mm borosilicate glass beads with a density of 2230 kg/m³

- **Non-Spherical Particles:**
  - Sieve was used to get the particle size distribution
  - Mean particle size is 0.9 – 1 mm

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Coefficient of expansion (20°C–300°C) 3.3 x 10⁻⁶ K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ = 80.6%</td>
<td>Density 2.23g/cm³</td>
</tr>
<tr>
<td>B₂O₃ = 13.0%</td>
<td>Refractive index (Sodium D line) 1.474</td>
</tr>
<tr>
<td>Na₂O = 4.0%</td>
<td>Dielectric constant (1MHz, 20°C) 4.6</td>
</tr>
<tr>
<td>Al₂O₃ = 2.3%</td>
<td>Specific heat (20°C) 750J/kg°C</td>
</tr>
<tr>
<td>Optical Information</td>
<td></td>
</tr>
<tr>
<td>Refractive index (Sodium D line) = 1.474</td>
<td>Thermal conductivity (20°C) 1.14W/m°C</td>
</tr>
<tr>
<td>Visible light transmission, 2mm thick glass = 92%</td>
<td>Poisson’s Ratio (25°C – 400°C) 0.2</td>
</tr>
<tr>
<td>Visible light transmission, 5mm thick glass = 91%</td>
<td>Young’s Modulus (25°C) 6400 kg/mm²</td>
</tr>
</tbody>
</table>
Experimental Benchmarking

\[
\frac{\Delta P_b}{L} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu f U}{(\varphi d_m)^2} + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho f U^2}{\varphi d_m}
\]

Graph showing pressure drop vs. superficial gas velocity with Ergun Equation and experimental data points.
Spherical Particles

- Fluidized beds are made densely packed by shaking.

- Voidage ranged from 0.37 to 0.39 for dense packed bed of monosized spherical particles.

Non-Spherical Particles

- Packing void fraction depends on particles sphericity.

<table>
<thead>
<tr>
<th>Sphericity</th>
<th>Loose Packing</th>
<th>Dense Packing</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.85</td>
<td>0.8</td>
</tr>
<tr>
<td>0.3</td>
<td>0.8</td>
<td>0.75</td>
</tr>
<tr>
<td>0.35</td>
<td>0.75</td>
<td>0.7</td>
</tr>
<tr>
<td>0.4</td>
<td>0.72</td>
<td>0.67</td>
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<tr>
<td>0.45</td>
<td>0.68</td>
<td>0.63</td>
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<tr>
<td>0.5</td>
<td>0.64</td>
<td>0.59</td>
</tr>
<tr>
<td>0.55</td>
<td>0.61</td>
<td>0.55</td>
</tr>
<tr>
<td>0.6</td>
<td>0.58</td>
<td>0.51</td>
</tr>
<tr>
<td>0.65</td>
<td>0.55</td>
<td>0.48</td>
</tr>
<tr>
<td>0.7</td>
<td>0.53</td>
<td>0.45</td>
</tr>
<tr>
<td>0.75</td>
<td>0.51</td>
<td>0.42</td>
</tr>
<tr>
<td>0.8</td>
<td>0.49</td>
<td>0.4</td>
</tr>
<tr>
<td>0.85</td>
<td>0.47</td>
<td>0.38</td>
</tr>
<tr>
<td>0.9</td>
<td>0.45</td>
<td>0.36</td>
</tr>
<tr>
<td>0.95</td>
<td>0.43</td>
<td>0.34</td>
</tr>
<tr>
<td>1</td>
<td>0.41</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Yang W.C., "Handbook of Fluidization and Fluid-Particle Systems", Marcel Dekker Inc, Madison Avenue, New York 2003
Outline

- Experimental Benchmarking – Spherical Particles
  - 1st Generation Bed
  - 2nd Generation Bed
- Measure the effect of:
  - Bed Height
  - Particle Shape
- Development of numerical models
  - Benchmarking with experimental data
  - Drag model development
  - Implementation into FLUENT
- Qualitative comparisons with Computational Data
  - High-speed camera Images
Effect of Bed Height

Spherical Particles:

\[ \Delta P = 150 \frac{(1 - \varepsilon)^2 \mu}{D_p \varepsilon^3} H V_s + 1.75 \frac{(1 - \varepsilon) \rho_f}{D_p \varepsilon^3} H V_s^2 \]

\[ \Delta P = g (1 - \varepsilon) (\rho_p - \rho_f) H \]
Effect of Particle Shape

- Non-spherical particles had higher voidage fractions ($\varepsilon$)
- Particle bed weights were measured: spherical particles with the same bed heights contained higher mass than the non-spherical particles.
• Higher channeling for non-spherical particles
• Pressure drop due to high velocities

• Channeling caused non-uniform distribution of fluid and solid inside of bed
Outline

- Experimental Benchmarking – Spherical Particles
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Objective

- To develop and validate a computational model that can predict the pressure drop across a packed bed operating with spherical or non-spherical particles

- Use both FLUENT and MFIX to develop the model and compare results
  - FLUENT, a general-purpose CFD code based on the finite volume method on a collocated grid.
  - MFIX (Multiphase Flow with Interphase eXchanges), a solver developed at the Department of Energy’s National Energy Technology Laboratory (NETL) for multiphase flows
Theory

Governing Equations:

- Volume Fraction
  \[ \varepsilon_g + \varepsilon_s = 1 \]

- Continuity Eqn.
  \[ \frac{\partial}{\partial t} (\varepsilon_g \rho_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{v}_g) = 0 \]

- Momentum Eqns.
  \[ \frac{\partial}{\partial t} (\varepsilon_g \rho_g \vec{v}_g) + \nabla \cdot (\varepsilon_g \rho_g \vec{v}_g \vec{v}_g) = \nabla \cdot \overrightarrow{S}_g + \varepsilon_g \rho_g \vec{g} - \overrightarrow{I}_{gs} \]

the rate of momentum transfer between the gas and solid phase per unit volume

\[ \overrightarrow{I}_{gs} = -\varepsilon_s \nabla P_g - F_{gs}(\vec{v}_s - \vec{v}_g) \]

Drag Force
**Spherical Particles**

**Two popular drag models were tested:**

- Gidaspow et al. (1992)

- Syamlal and O’Brien (1989)
Theory

• Gidaspow et al. (1992)

\[
F_{gs} = \begin{cases} 
\frac{3}{4} C_{D-sphere} \rho_g \varepsilon_g \varepsilon_s |v_s - v_g| \varepsilon_g^{-2.65} & \varepsilon_g \geq 0.8 \\
150 \varepsilon_s (1-\varepsilon_g) \mu_g \varepsilon_g d_p^2 + 1.75 \rho_g \varepsilon_s |v_s - v_g| \varepsilon_g d_p & \varepsilon_g < 0.8 
\end{cases}
\]

\[
C_{D-sphere} = \begin{cases} 
24/Re (1 + 0.15 Re^{0.687}) & Re \leq 1000 \\
0.44 & Re > 1000 
\end{cases}
\]

\[
Re = \frac{\varepsilon_g \rho_g |v_s - v_g| d_p}{\mu_g}
\]

\[
v_s = \text{solids velocity} \quad \varepsilon_s = \text{solids volume fraction}
\]
\[
v_g = \text{gas velocity} \quad \varepsilon_g = \text{gas volume fraction}
\]
Theory

- Syamlal and O’Brien (1989)

\[ F_{gs} = \frac{3\varepsilon_s\varepsilon_g \rho_g}{4\nu_t^2 d_p} C_{D-sphere} |\vec{v}_s - \vec{v}_g| \]

\[ C_{D-sphere} = \left(0.63 + 4.8\sqrt{\frac{\nu_t}{Re}}\right)^2 \]

\[ v_t = 0.5 \left(A - 0.06Re + \sqrt{(0.06Re)^2 + 0.12Re(2B - A) + A^2}\right) \]

\[ A = \varepsilon_g^{4.14} \]

\[ B = \begin{cases} 
0.8\varepsilon_g^{1.28} & \varepsilon_g \leq 0.85 \\
\varepsilon_g^{2.65} & \varepsilon_g > 0.85 
\end{cases} \]

\[ Re = \frac{d_p |\vec{v}_s - \vec{v}_g| \rho_g}{\mu_g} \]
Numerical Model

Pressure Outlet

Wall

Velocity Inlet

<table>
<thead>
<tr>
<th>Bed Section</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Void Fraction ($e_g$)</td>
<td>0.37</td>
</tr>
<tr>
<td>Gas Velocity ($v_g$)</td>
<td>5 cm/s</td>
</tr>
</tbody>
</table>
## Numerical Model

<table>
<thead>
<tr>
<th>Grid</th>
<th>Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4800</td>
</tr>
<tr>
<td>2</td>
<td>24200</td>
</tr>
<tr>
<td>3</td>
<td>64400</td>
</tr>
<tr>
<td>4</td>
<td>100625</td>
</tr>
<tr>
<td>5</td>
<td>35420 (Adaptive)</td>
</tr>
</tbody>
</table>
Results

Fluidization (5.5 cm Bed, 1 mm particles)

Spherical
Results

Spherical
Benchmarking with Experiments

Fluidization (5.5 cm bed, 1 mm spherical particles)

Fluidization (5.5 cm Bed, 1 mm particles)

Spherical
Drag Model Development
The rice grains were assumed to ellipsoid in shape.

The Eqn. used to determine the initial terminal velocity:

\[ V_t = \sqrt{\frac{8 \, b \, g \, (\rho_s - \rho_f)}{3 \, C_D \, \rho_f}} \]

where \( V_t \) is the terminal velocity, \( b \) is the mean polar diameter along the y-axis, \( \rho_s \) is the density of rice grain, \( \rho_f \) is the density of air, and \( C_D \) is the drag coefficient initially assumed to be 0.6.

- Rice density 577 kg/m³
- Air density as 1.2 kg/m³
- 3100 frames per second
Drag Model Development

0.01s  0.02s  0.03s  0.04s

5
2.5
0 mm
Drag Model Development
Drag Model Development

<table>
<thead>
<tr>
<th>Boundary No.</th>
<th>Boundary Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Moving Wall</td>
</tr>
<tr>
<td>2</td>
<td>Pressure Outlet</td>
</tr>
<tr>
<td>3</td>
<td>Pressure Outlet</td>
</tr>
<tr>
<td>4</td>
<td>No-Slip Wall</td>
</tr>
</tbody>
</table>
Drag Model Development

Results | Numerical | Experimental
---|---|---
Re | 1058 | 1081
$C_D$ | 0.55 | 0.58
Implementation of Model

\[ C_D = \frac{24}{Re} \left[ 1 + 0.8943Re^{0.3952} \right] + \frac{4.3215}{\left[ 1 + \frac{160.1567}{Re} \right]} \]

Graph showing the relationship between pressure (Pa) and superficial velocity (cm/s) with data points for Exp, FLUENT, and MFIX.
Outline

- Experimental Benchmarking – Spherical Particles
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  - 2nd Generation Bed

- Measure the effect of:
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- Qualitative comparisons with Computational Data
  - High-speed camera Images
Results

Solid-phase volume fraction

Solid particles velocity field
Results

Comparison of bubbling behavior at times $t = 2, 5, 7s$
Results

Gidaspow

![Image of results](image_url)
Summary and Highlights to Date

- Fluidized bed design & experimental setup
  - 1st Generation and 2nd Generation
  - Benchmark tests complete
- Development of computational model
  - Benchmark tests complete
  - Empirical drag model implementation
- High-speed imaging
Anticipated Efforts for the Upcoming Year

- Obtaining Velocity and Drag for Non-Spherical Particles
  - $C_D$ vs. $Re$
  - Various geometry particles
  - Validation with experiments/model

- Implementation of newly acquired shadow sizing system for the:
  - Detection of Non-Spherical Geometries,
  - Particle size
  - Trajectory,
  - Velocity Components
Contact Information

If you have any questions or would be interested in collaboration please contact

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