Measurement of Particle Number Density and Volume Fraction in a Fluidized Bed using Shadow Sizing Method

Seckin Gokaltun, Ph.D
David Roelant, Ph.D
Applied Research Center
FLORIDA INTERNATIONAL UNIVERSITY

Objective

- 2006 Roadmap Task D1 & D2:
  - Detailed CFB data at ~.15m ID
  - Non-intrusive probes

- Generate detailed experimental data to develop a new mathematical analysis procedure for defining cluster formation by utilizing granular temperature.
  - Measure void fraction
  - Obtain granular temperature
  - Demonstrate nonintrusive probe to collect void fraction data
Granular Temperature

**Granular theory**

- From the ideal gas law:
  
  \[ PV = Nk_B T \]

  where \( k_B \) is the Boltzmann constant and the absolute temperature, thus:

  \[ PV = Nk_B T = Nmv_{rms}^2 / 3 \]

  \[ T = mv_{rms}^2 / 3k_B \]

  \[ v_{rms}^2 = \sum_{i=1}^{n} v_i^2 \]

  is the root-mean-square velocity

**Kinetic theory**

- Assumptions:
  - Very large number of particles (for valid statistical treatment)
  - Distance among particles much larger than molecular size
  - Random particle motion with constant speeds
  - Elastic particle-particle and particle-walls collisions (no loss of energy)
  - Molecules obey Newton Laws

---

Granular Temperature

- From velocity
  
  \[ \theta = \frac{1}{3} (\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \]

  where:

  \[ \sigma_i^2 = (u_i - \bar{u})^2 \]

  - \( u_i \) is particle velocity

  \[ \bar{u} \] is the average particle velocity

- From voidage for dilute flows
  
  \[ \theta \propto \varepsilon_s^{2/3} \]

- From voidage for dense flows
  
  \[ \theta \propto 1/\varepsilon_s \]
Volume Fraction

- Solids volume fraction:
  \[ \varepsilon_s = \frac{nV_p}{Ah} \]

- \( n \): the number of particles
- \( V_p \): is the volume of single particle
- \( A \): the view area
- \( h \): the depth of view


Intensity Graduation Profile
(distance calibration for particle halo)

1 mm outside DOF  2 mm outside DOF  3 mm outside DOF  4 mm outside DOF
Progress to Date - Summary

• Lab set up in 2007 and glass beads (~500μ) imaged in 2008 with results shown June 11, 2008.

• Unable to achieve dense flow in our system with these glass beads so several modifications were made to the system in March 2009 to allow dense flow.

• New researcher, Dr. Seckin Gokaltun, chosen to lead lab research March 1, 2009 after no cost extension

• Images and videos collected in April 2009

• Improvements to camera and use of PIV mode planned for May 2009

Seckin Gokaltun - Research Background

• 2007 - Present: “Modeling Multi-phase Flow in Pipelines for Conditions Leading to Plugging and Effectiveness of Technologies for Unplugging,” Florida International University


• 2004 - 2007, Verification and Validation of CFD Problems
  • Pulsatile flow in channels, hypersonic flows, laminar/turbulent flames.

Experimental Setup

- Particle Separator
- Standpipe
- Rotary Valve
- Riser (6 in ID)
- Hedland Flowmeter
- Heat exchanger set-up
- Air Compressor (900 cfm at 100psi)

Camera Setup

<table>
<thead>
<tr>
<th>Digital CCD camera</th>
<th>C8484-05CP</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Pixels</td>
<td>1344 (H) x 1024 (V)</td>
</tr>
<tr>
<td>Effective area</td>
<td>8.67 mm (H) x 6.60 mm (V)</td>
</tr>
<tr>
<td>Frame rate</td>
<td>1x1, 2x2, 4x4, 8x8</td>
</tr>
<tr>
<td>Binning</td>
<td>12.2 frame/s, 22.3 frame/s, 40.9 frame/s, 68 frame/s</td>
</tr>
<tr>
<td>Exposure time</td>
<td>0.02 - 1 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Telecentric Lens</th>
<th>Edmund Optics 55-350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary magnification</td>
<td>1X</td>
</tr>
<tr>
<td>Horizontal field of view</td>
<td>8.8 mm</td>
</tr>
<tr>
<td>Working distance</td>
<td>98 mm - 123 mm</td>
</tr>
<tr>
<td>Resolution (MTF Image Space @ F6)</td>
<td>&gt;45% @ 40 lp/mm</td>
</tr>
<tr>
<td>Telecentricity</td>
<td>&lt;.1°</td>
</tr>
<tr>
<td>Distortion</td>
<td>.5% Max</td>
</tr>
<tr>
<td>Depth of field (20% @ 20 lp/mm)</td>
<td>± 0.6mm at F12</td>
</tr>
<tr>
<td>Aperture (f/#)</td>
<td>F6 - F25</td>
</tr>
</tbody>
</table>
Binning

- Binning is the combination of two or more CCD image sensor pixels to form a new “super-pixel” prior to readout and digitizing.
- 2x2 binning: Each new pixel received contains all the light from the 4 original pixels.
  - This makes that pixel 4 times brighter
- Improves signal-to-noise-ratio (less read noise events)
- Improves frame rate.

Inlet Flow Conditions for Fast Fluidization (theory and experimental)

<table>
<thead>
<tr>
<th>Flow rate (cfm)</th>
<th>Temperature (°C)</th>
<th>Velocity (m/s)</th>
<th>Humidity (RH%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>22.0</td>
<td>2.64</td>
<td>59.0</td>
</tr>
<tr>
<td>200</td>
<td>35.90</td>
<td>5.79</td>
<td>30.6</td>
</tr>
<tr>
<td>300</td>
<td>38.20</td>
<td>8.89</td>
<td>25.2</td>
</tr>
</tbody>
</table>

Flow conditions at the riser inlet
**Image Processing**  
(NIH ImageJ - Freeware by National Institutes of Health)  
Image of particles on glass to demonstrate image processing

![Image of particles on glass](image)

- Region of interest (1.19x0.92 mm)
- Binary > Fill holes
- > Watershed
- Particle analyzer

\[ \varepsilon_s = \frac{\sum V_i}{A h} \]
\[ n = 21 \]
\[ A = 0.158 \text{ mm}^2 \]
\[ h = 1 \text{ mm} \]
\[ \varepsilon_s = 0.99\% \]

Polystyrene particles  
\( D_p = 0.3 - 0.4 \text{ mm} \)

**Images of Polystyrene Particles in the Riser**

- 8x8 binning: 128x128, Exposure time: 251.7 x 10^{-3} s
- Q= 150 CFM,
- Q= 180 CFM,
Future Work

- Prevent polystyrene particles from clogging the airlock blades
- Upgrade camera to higher resolution and lower exposure time
- Implement PIV mode:
  - To obtain full resolution (1344x1024) of current camera vs. 128x128.
  - To acquire a pair of images at 200 ns intervals and 150.1 \( \mu \)s of exposure time.
  - Will require external triggering using a pulse generator.
- Postprocessing with intensity graduation