Comparing Methods to Extract Solids Fraction From High Speed Images of Polyethylene Beads in a Fluidized Bed Riser

Based upon:
D.K. Casleton’s Master’s Thesis Electrical Engineering, WVU 2009
Content

• Introduction
• Visualization of Fluid Beds
• Proposed Solution
• Particle Detection
• Particle Tracking
• Concluding Remarks
Validation

Motivation

- Modeling is a cost effective approach to designing new, more efficient CFBs.
- Accuracy of CFD models must be validated empirically.
- Cold-flow CFB gives researchers easy access to the flow stream.
- Particle material can be chosen to behave similarly to material used in industrial applications.

Criteria

- **Level 1 Macro-scale**
  - Axial pressure profile
  - Riser bed-density
  - Dynamic transfer functions

- **Level 2 Meso-scale**
  - Riser radial distribution
  - Streamer size, freq. and v.
  - Pressure fluctuations

- **Level 3 Micro-scale**
  - Dispersed particle $\varepsilon_s$, TKE, and Granular temperature
  - Cluster size, frequency, $v$, $\varepsilon_s$, TKE, and Granular temperature.
  - Particle Collisions

\[
\tau_c = E(t) \approx \frac{V}{N \pi d_p^2 \sqrt{(v_i - v_m)^2}}
\]
Flow Visualization

- Visualizing the flow of fluid beds is not a new problem.
- Research exists in the literature for both internal and externally visualization techniques.
- Early applications gave only qualitative observations.
- Quantitative data has been extracted using digital image processing techniques.


Internal Imaging

- Early applications: particle velocities manually extracted from the dilute phase; particle concentrations estimated in both dilute and dense phases.
- Advances in borescope technology and high-powered lighting have greatly improved visual content.
- Probe physically impedes the flow, possibly changing its behavior.
External Imaging

- No occluding particles.
- Background particles can be problematic (same for internal imaging).
- Light sources can non-uniformly illuminate the focal plane.
Proposed Solution

• Given a video sequence, extract information on the particle concentration.
  – Requires knowledge of in-focus particles (located on focal plane).

• Given a video sequence, extract information on the particle velocities.
  – Must know the location of every in-focus particle.
  – Particles must be tracked across successive frames.
Proposed Approach

- Preprocess images to reduce noise and/or enhance features.
- Detect particles in each image to determine concentration " (solids or voidage)
- Track multiple particles across successive frames to extract a set of velocities U.
Evaluation Sequence

Ground Truth
Manually extracted from an image sequence
Dilute Leading up to Dense Cluster
Dense Particle Streamer Leading to Dilute
Intensity-based Approach

• Apply an intensity threshold on each image.

\[ \delta_I(x, y) = \begin{cases} 
1 & \text{if } I(x, y) \geq T_I \\ 
0 & \text{if } I(x, y) < T_I 
\end{cases} \]

• Estimate the particle count \( N_p \) by assuming spherical particles with mean diameter \( d_p \).

\[ \hat{N}_p = \frac{4}{\pi d_p^2} \sum_{x \in X} \sum_{y \in Y} \delta_I(x, y) \]
Intensity Based Approach - Problem

- Negligible for dilute flow.
- Significant for dense flow.
- Could complicate identification process.
Global or Local Solutions

• **Global Solution: Temporal Mean**
  - Estimate the lighting by finding the temporal mean for all pixels.
  - Subtract the estimate from the original.
  - Re-adjust the result to increase the contrast.

• **Local Solution: Top-hat Transformation**
  - Estimate the lighting by morphologically opening the image I by the structuring element D.
    
    \[ I \hat{D} = (I \cdot D) \cdot D \]
  - Subtract the estimate from the original.
  - Re-adjust the result to increase the contrast.
Thresholding on Adjusted images

Original Image

Top-hat Result

Error (MPE)
Intensity-based Approach

- Background particles can be brightly illuminated, overestimating the concentration.
- Images must be preprocessed to reduce effect of non-uniform illumination.
Gradient-based Approach

- Apply a threshold on each gradient image

\[ \delta_G(x, y) = \begin{cases} 
1 & \text{if } G(x, y) \geq T_G \\
0 & \text{if } G(x, y) < T_G 
\end{cases} \]

where \( G = ||\nabla I||_2 \).

- Estimate the particle count \( N_p \) by assuming spherical particles with

\[ \hat{N}_p = \frac{1}{\pi d_p} \sum_{x \in \mathcal{X}} \sum_{y \in \mathcal{Y}} \delta_G(x, y) \]
Specular Highlights

- Seemingly all in-focus particles have highlights.
- Can also be found on out-of-focus particles.
- Problematic for edge detection methods (gradient along particle surface).
Specular Highlight Suppression

- Median filter commonly used to reduce salt-and-pepper noise.
- Differentiate between the high-intensity noise (salt) and low-intensity noise (pepper).
- Let $I^M$ be the result of applying the median filter to an image $I$.

$$I^D(x, y) = I(x, y) - I^M(x, y) \quad (1)$$

$$I^s(x, y) = \begin{cases} 
I^D(x, y) & \text{if } I^D(x, y) > 0 \\
0 & \text{if } I^D(x, y) < 0 
\end{cases} \quad (2)$$

- Subtracting $I^s$ from $I$ will only suppress the high-intensity noise.
Specular Highlight Suppression

- The median filter smooths the image (reducing sharpness of edges).
- Suppressing only the high-intensity component preserves most of the edge information.
Gradient-Based or Edge Detection

- Original and Adjusted Images perform well in dilute regions.
- Not influenced by non-uniform illumination.
- Some improvement found by suppressing specular highlight.
- Poor performance in Dense region.

![Graphs showing performance comparison between Original Images and Highlight Suppressed Images](image-url)
Gradient-based Approach

- Excellent estimate of the dilute phase (suggests truly spherical particles).
- As concentration increases, particle boundary information decreases significantly.
Detected Highlights in the Evaluation Sequence
Specularity-based Approach

Effect of image processing

Original Images

Adjusted Images

![Graphs showing original and adjusted images]
Specularity-based Approach

- Estimate particle count by number of specular highlights detected.
- Reasonable estimates of both dilute and dense phase.
- Suffers from multiple highlights for large (non-spherical) particles and highlights on some out-of-focus particles.
Voidage Estimates

\[ \varepsilon_v = 1 - \frac{V_p}{V_T} = 1 - \frac{1/6 \cdot \pi d_p^2}{l \cdot w \cdot t}. \]

\[ \varepsilon_v^H = 1 - \frac{2}{\sqrt{\pi \sqrt{3}}} \psi_p^{\frac{3}{2}}. \]


<table>
<thead>
<tr>
<th>relative thickness</th>
<th>dense region</th>
<th>dilute region</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>voidage</td>
<td>solids fraction</td>
</tr>
<tr>
<td>0.5*dp</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>1.0*dp</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>1.5*dp</td>
<td>72</td>
<td>3.3</td>
</tr>
</tbody>
</table>

\[ \varepsilon_v^O = 1 - \frac{\sqrt{2}}{\sqrt{\pi \sqrt{3}}} \psi_p^{\frac{3}{2}}. \] Reduces to 0.8774 \cdot d_p
### Voidage

<table>
<thead>
<tr>
<th>Frame #</th>
<th>Mean Void</th>
<th>Specular Highlight</th>
<th>Otsu Threshold</th>
<th>Edge Detection</th>
<th>Specular Highlight</th>
<th>Otsu Threshold</th>
<th>Edge Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>0.835</td>
<td>-0.023</td>
<td>-0.045</td>
<td>0.051</td>
<td>0.009</td>
<td>0.009</td>
<td>0.022</td>
</tr>
<tr>
<td>1078–1093</td>
<td>0.941</td>
<td>-0.023</td>
<td>-0.047</td>
<td>0.001</td>
<td>0.014</td>
<td>0.009</td>
<td>0.012</td>
</tr>
<tr>
<td>1098–1128</td>
<td>0.725</td>
<td>-0.013</td>
<td>-0.008</td>
<td>0.106</td>
<td>0.020</td>
<td>0.018</td>
<td>0.051</td>
</tr>
<tr>
<td>1133–1158</td>
<td>0.927</td>
<td>-0.040</td>
<td>-0.103</td>
<td>0.002</td>
<td>0.007</td>
<td>0.019</td>
<td>0.007</td>
</tr>
</tbody>
</table>
Summary

• **Dilute region** \((\varepsilon > 0.93)\)
  – Gradient-based or edge detection method was most accurate

• **Dense region** \((\varepsilon < 0.93)\)
  – Plagued by particle-particle contact, particle overlap, and obscuration of particle edges
  – Intensity-based or Otsu’s thresholding method was superior

• **With light background**
  – edge detection technique cannot identify the higher particle counts
  – Use Otsu thresholding method for this discrimination
**Summary** (Continued)

- **With image quality info and solids concentration—**
  - bias corrected analysis can be quite accurate with precision better than 3%
- **Without information on image quality,**
  - the bias correction using the specular highlight particle detection method was significantly more accurate
  - For the specular highlight method, a bias based upon voidage alone can offer some additional improvement in accuracy over uncorrected analysis.