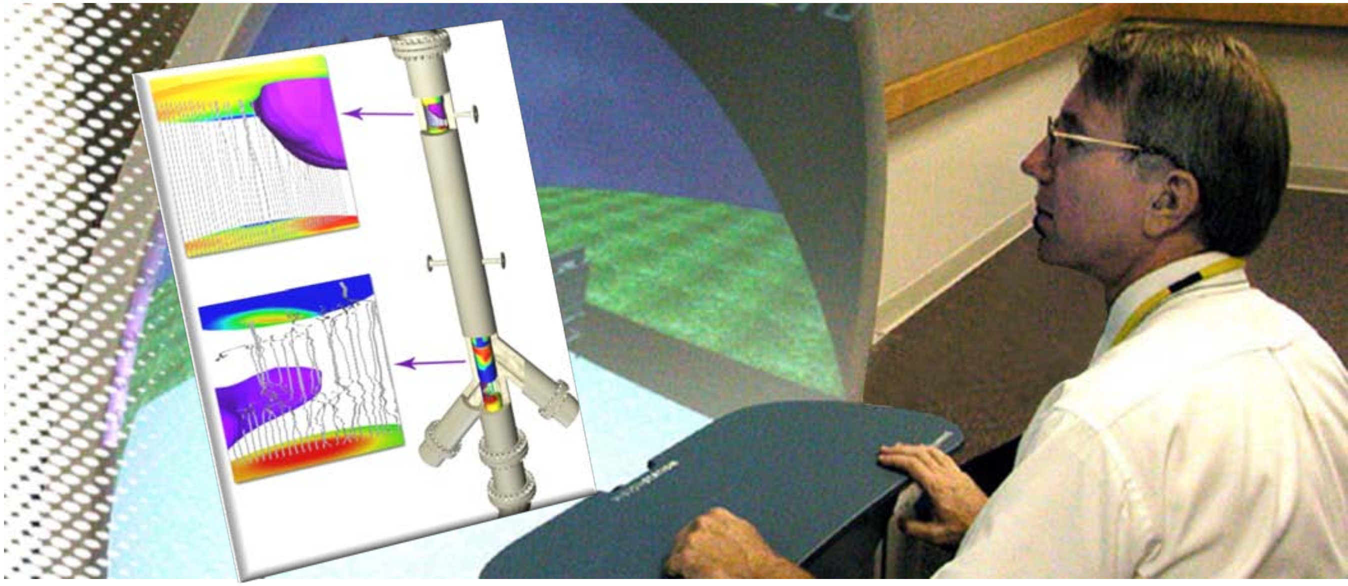
NATIONAL ENERGY TECHNOLOGY LABORATORY



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Multi-Phase Flow Work Shop

May 4-6, 2010

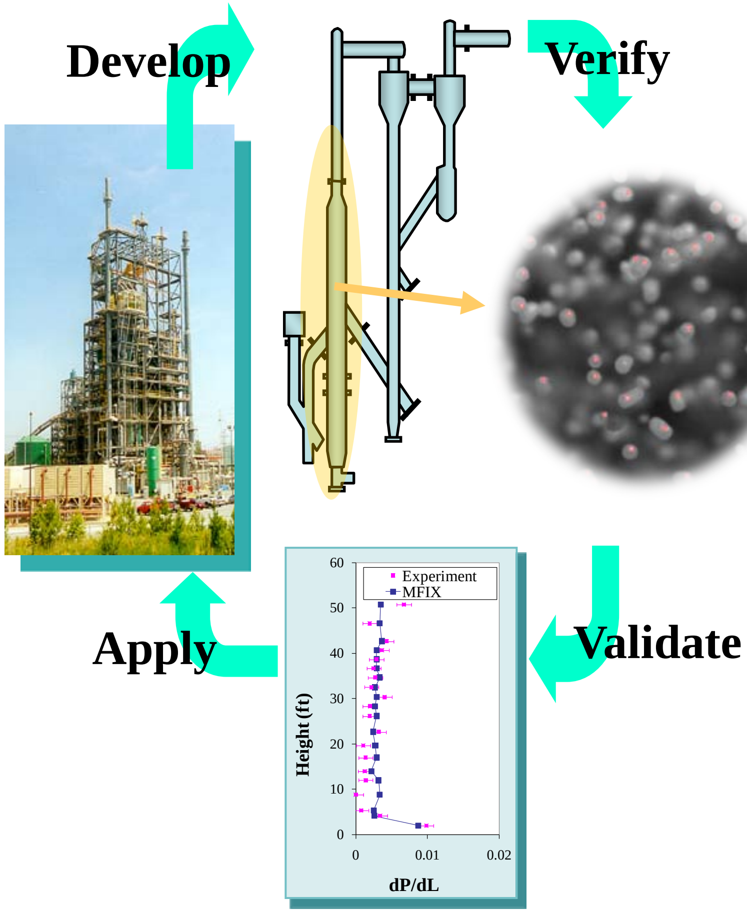
Pittsburgh, PA

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

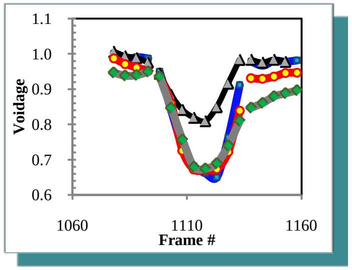
Based upon:
D.K. Casleton's Master's Thesis Electrical Engineering, WVU 2009
D.K. Casleton, L.J. Shadle, and A.A. Ross (2010) Measuring the voidage of a CFB through image analysis, Accepted by Powder Technology 12/11/2009

U.S. DEPARTMENT OF ENERGY

Content



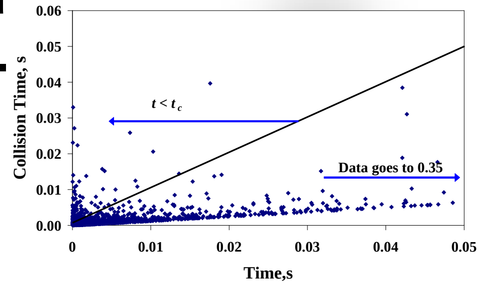
- **Introduction**
- Visualization of Fluid Beds
- Proposed Solution
- Particle Detection
- Particle Tracking
- Concluding Remarks



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 ε_s, TKE, and Granular temperature
  - Cluster size, frequency, *v*, ε_s, TKE, and Granular temperature.
  - Particle Collisions

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

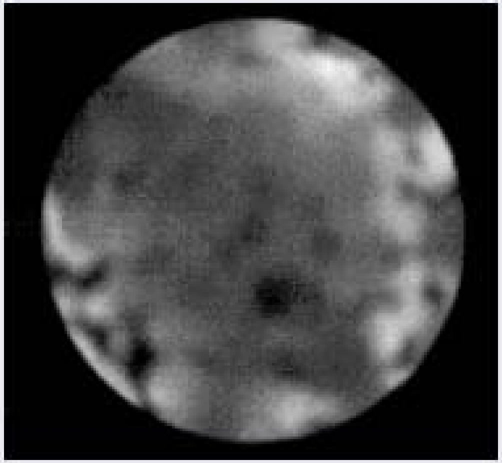
Flow Visualization

- **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.**

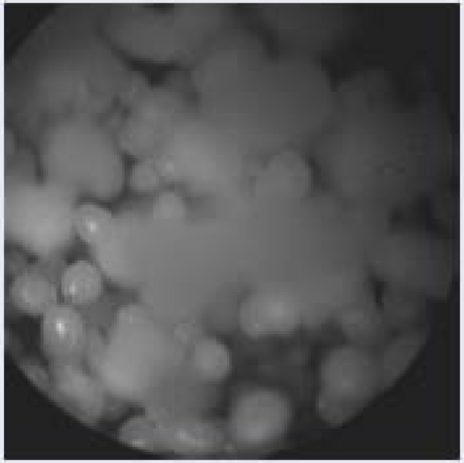
S. Matsuda, H. Hatano, H. Takeuchi, A. T. Pyatenko, and K. Tsuchiya. Motion of individual solid particles in a circulating fluidized bed riser. In M. Kwauk and J. Li, editors, 5th International Conference on Circulating Fluidized Beds, pages 176–181. Science Press, 1996.
yA. Bredebusch, H. Burkhardt, U. Lackermeier, and J. Werther. Application of digital image processing methods for the analysis of flow structures in circulating fluidized beds. In 8th International Symposium on Flow Visualization, 1998.

Internal Imaging

Early technology



Current technology



- **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

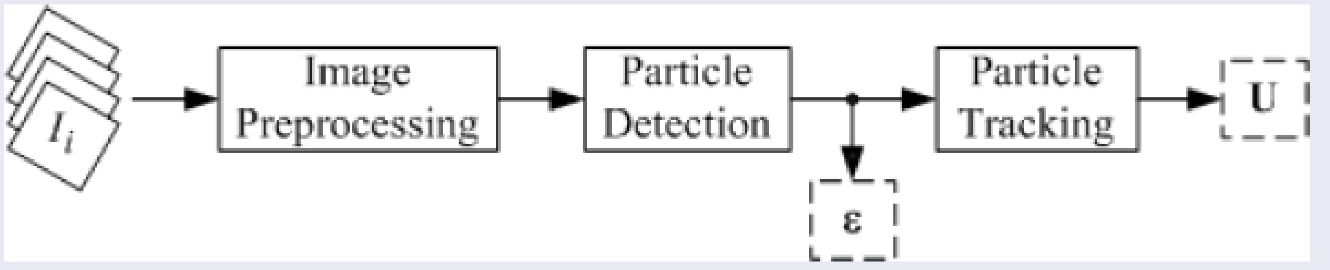
- **No occluding particles.**
- **Background particles can be problematic (same for internal imaging).**
- **Light sources can non-uniformly illuminate the focal plane.**

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.

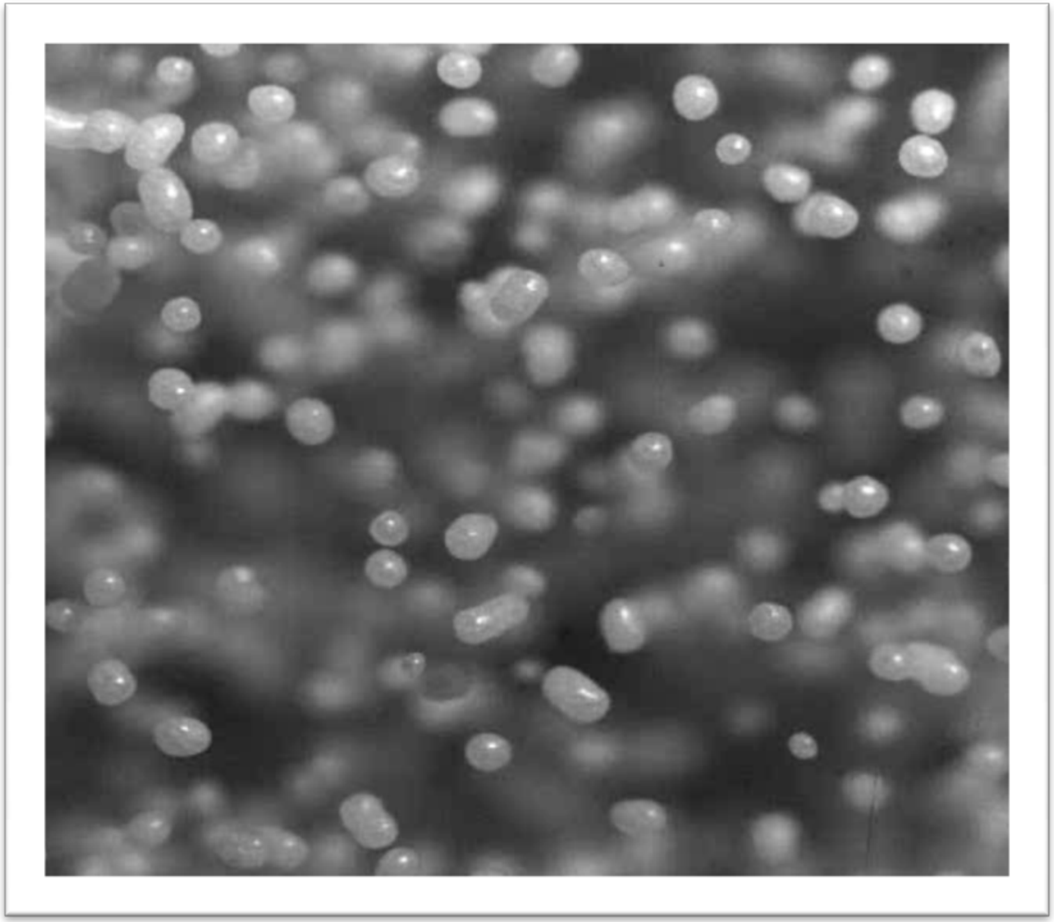
Proposed Approach

System Architecture



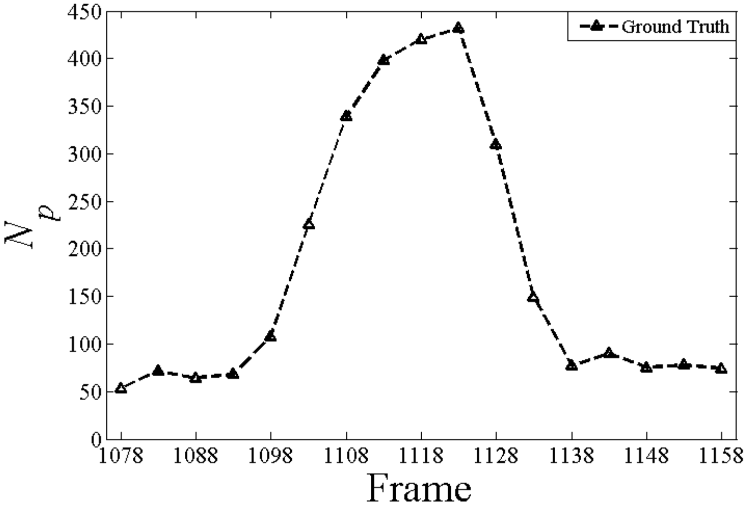
- **Preprocess images to reduce noise and/or enhance features.**
- **Detect particles in each image to determine concentration “ (solids or voidage)**
- **Track multiple particles across successive frames to extract a set of velocities U.**

Evaluation Sequence

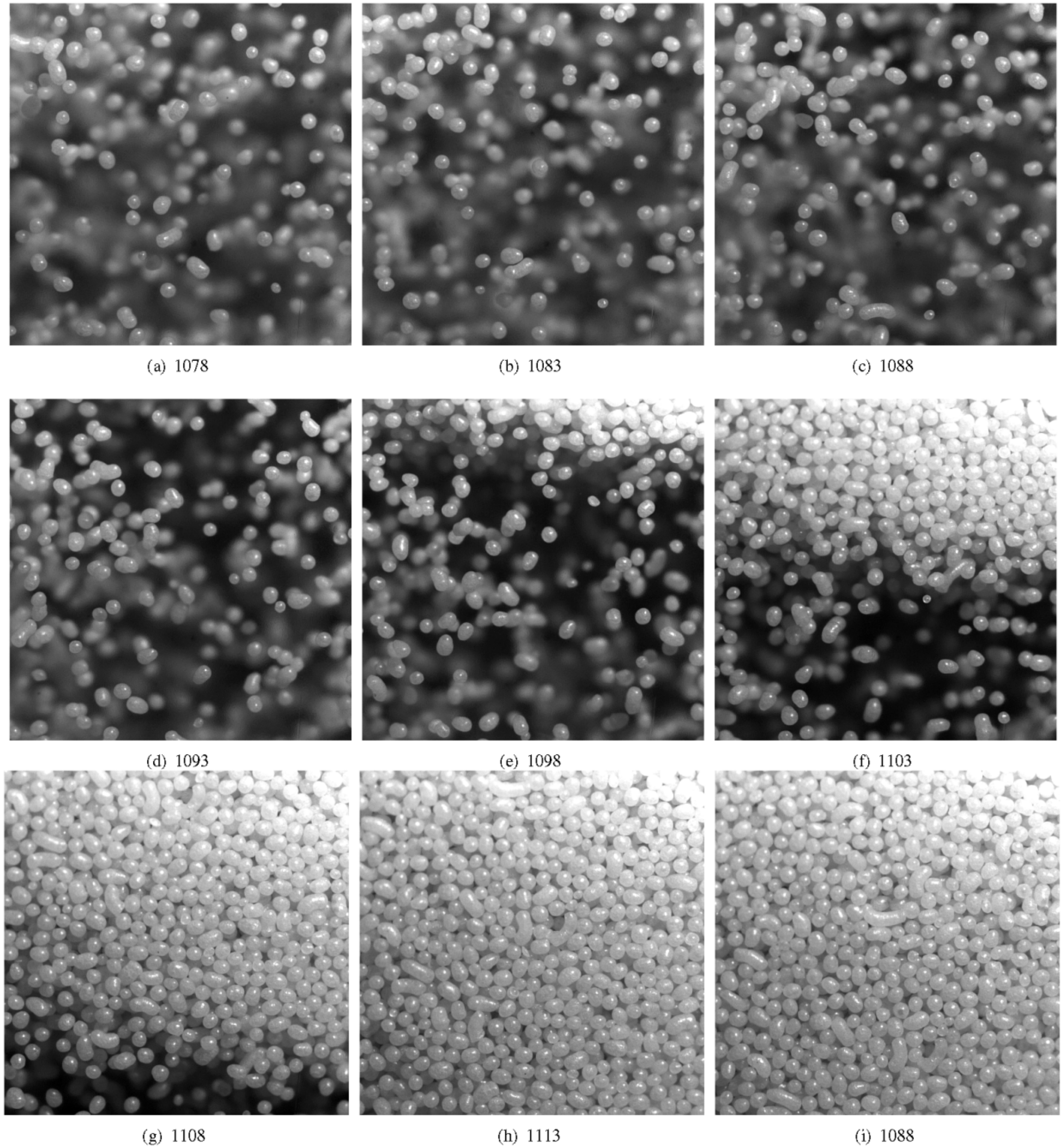


Ground Truth

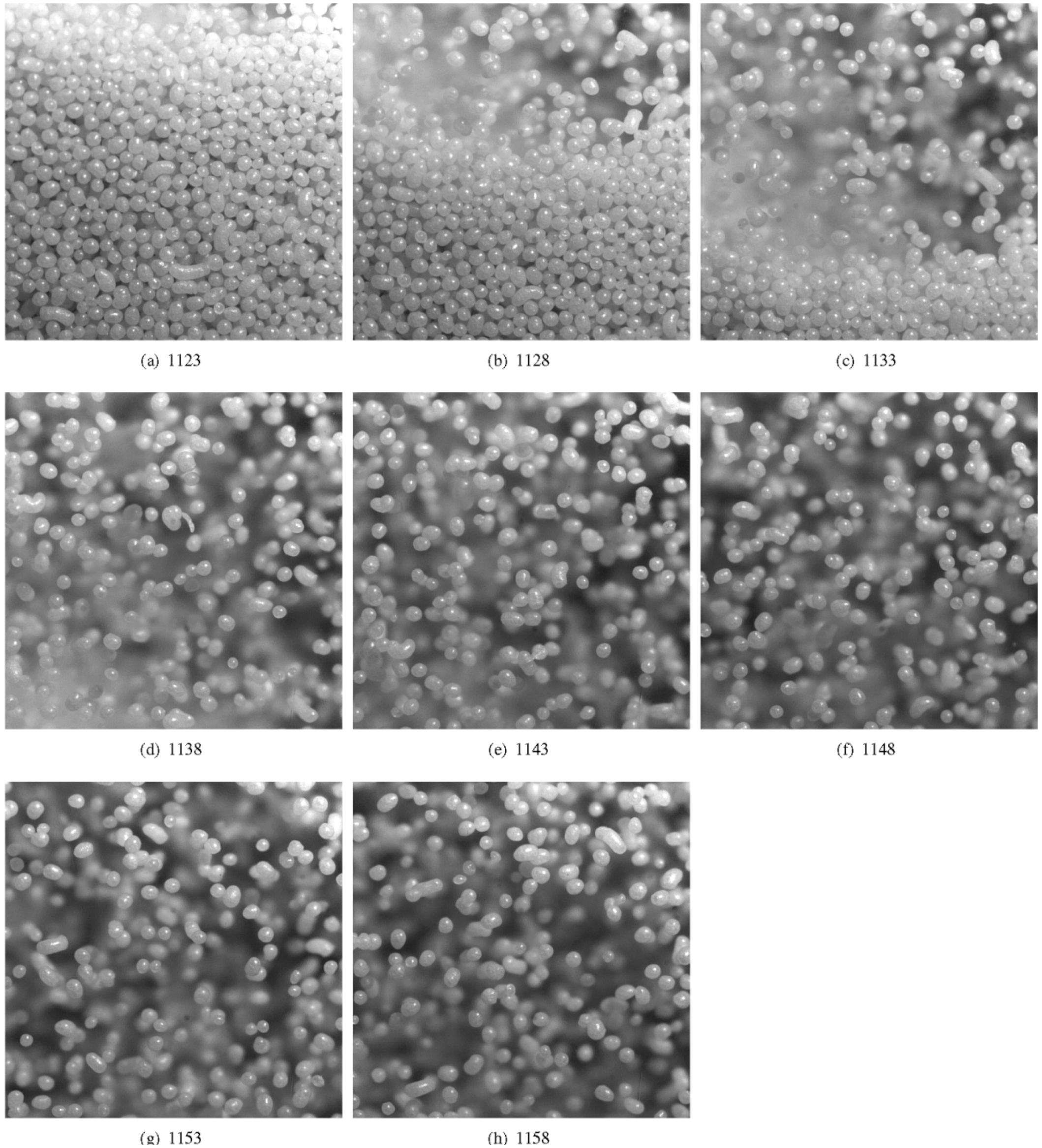
Manually extracted from an image sequence



Dilute Leading up to Dense Cluster



Dense Particle Streamer Leading to Dilute



Intensity-based Approach

- **Apply an intensity threshold on each image.**

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

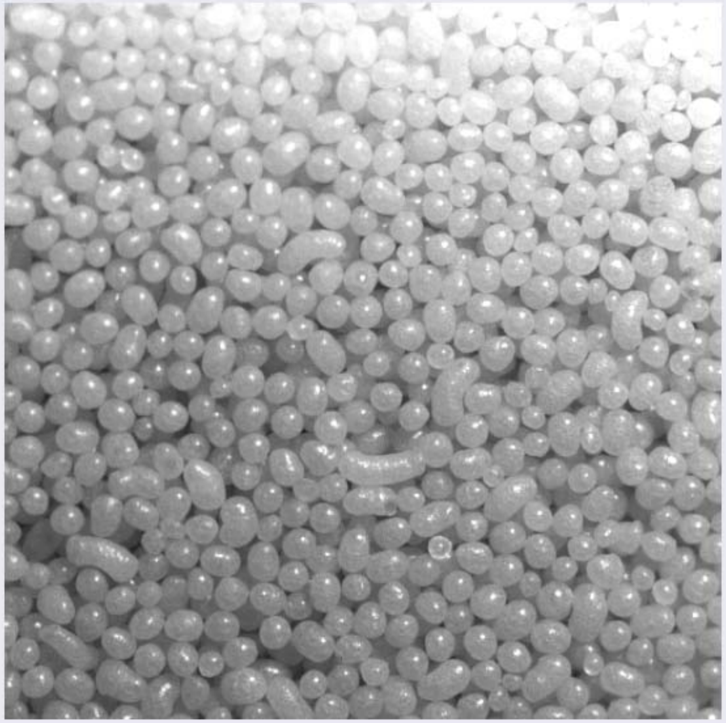
- **Estimate the particle count N_p by assuming spherical particles with mean diameter d_p.**

$$\widehat{N}_p = \frac{4}{\pi d_p^2} \sum_{x \in \mathcal{X}} \sum_{y \in \mathcal{Y}} \delta_I(x,y)$$

Intensity Based Approach - Problem

- **Negligible for dilute flow.**
- **Significant for dense flow.**
- **Could complicate identification process.**

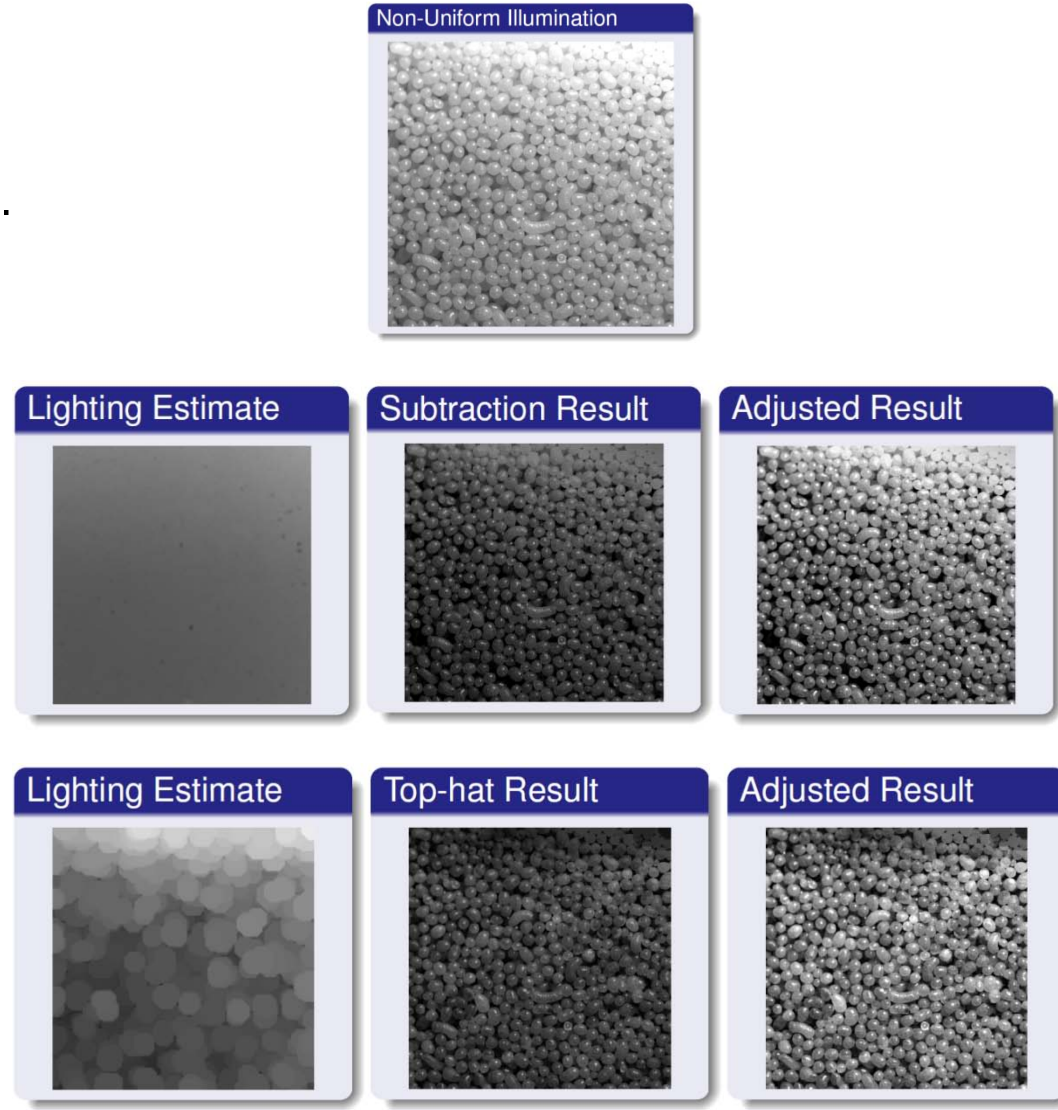
Non-Uniform Illumination



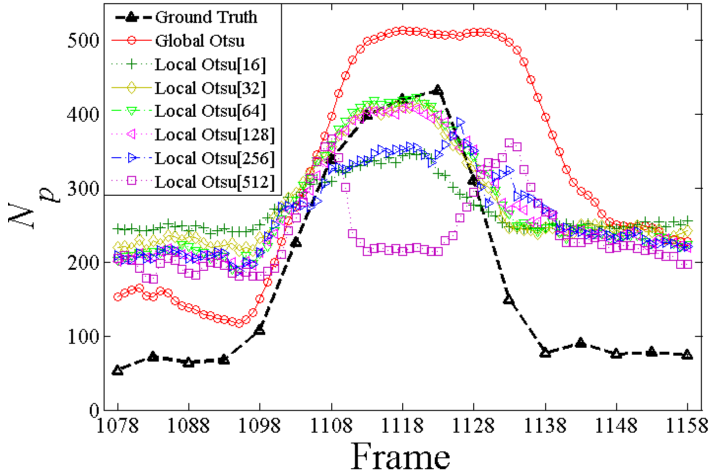
Global or Local Solutions

- **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.

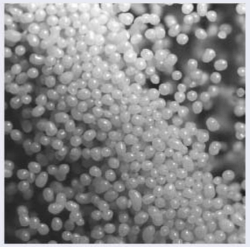
    I D = (I D) D
  - Subtract the estimate from the original.
  - Re-adjust the result to increase the contrast.

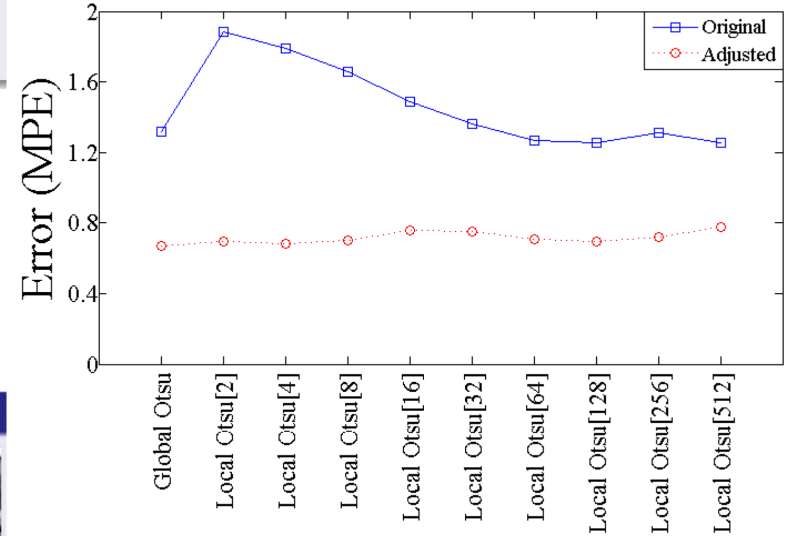


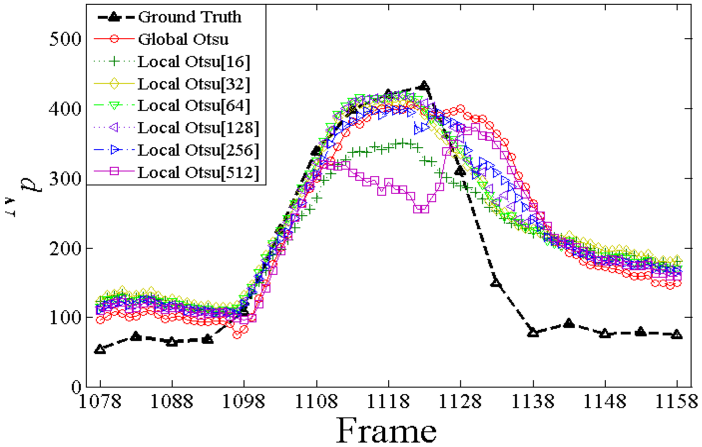
Thresholding on Adjusted images



Original Image



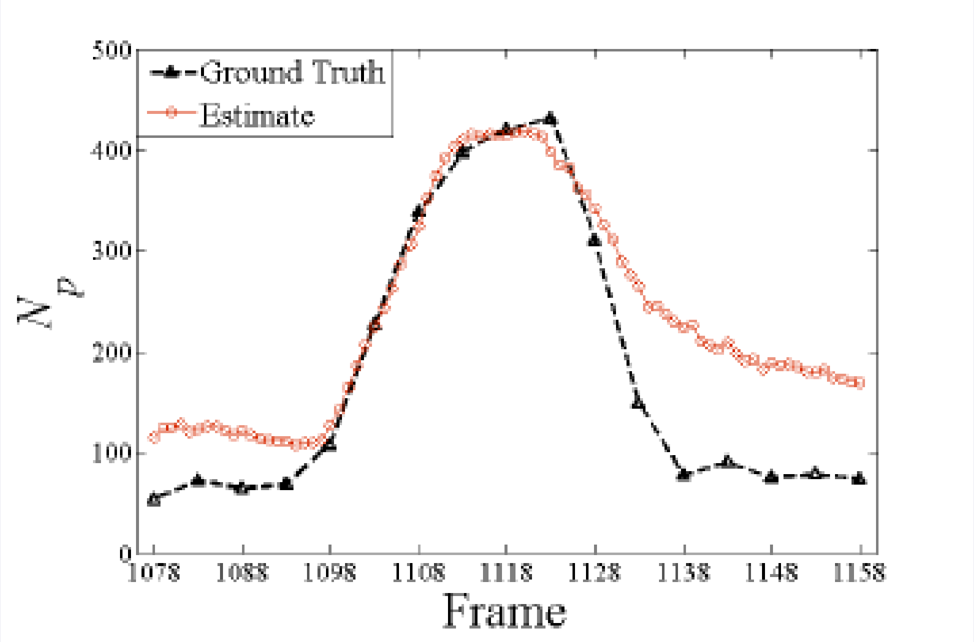




Top-hat Result

Intensity-based Approach

Approximate total particle area



- **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**

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

where $G = ||\nabla I||_2$**.**

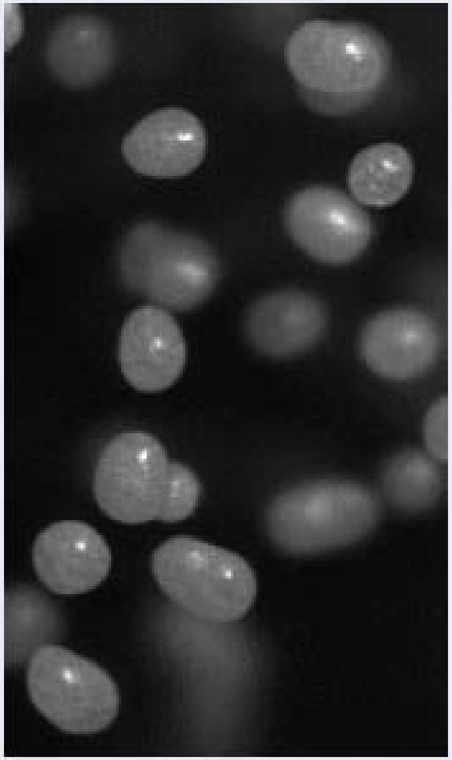
- **Estimate the particle count** N_p **by assuming spherical particles with**

$$\widehat{N}_p = \frac{1}{\pi d_p} \sum_{x \in \mathcal{X}} \sum_{y \in \mathcal{Y}} \delta_G(x,y)$$

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).**

HDPE beads are highly reflective



Specular Highlight Suppression

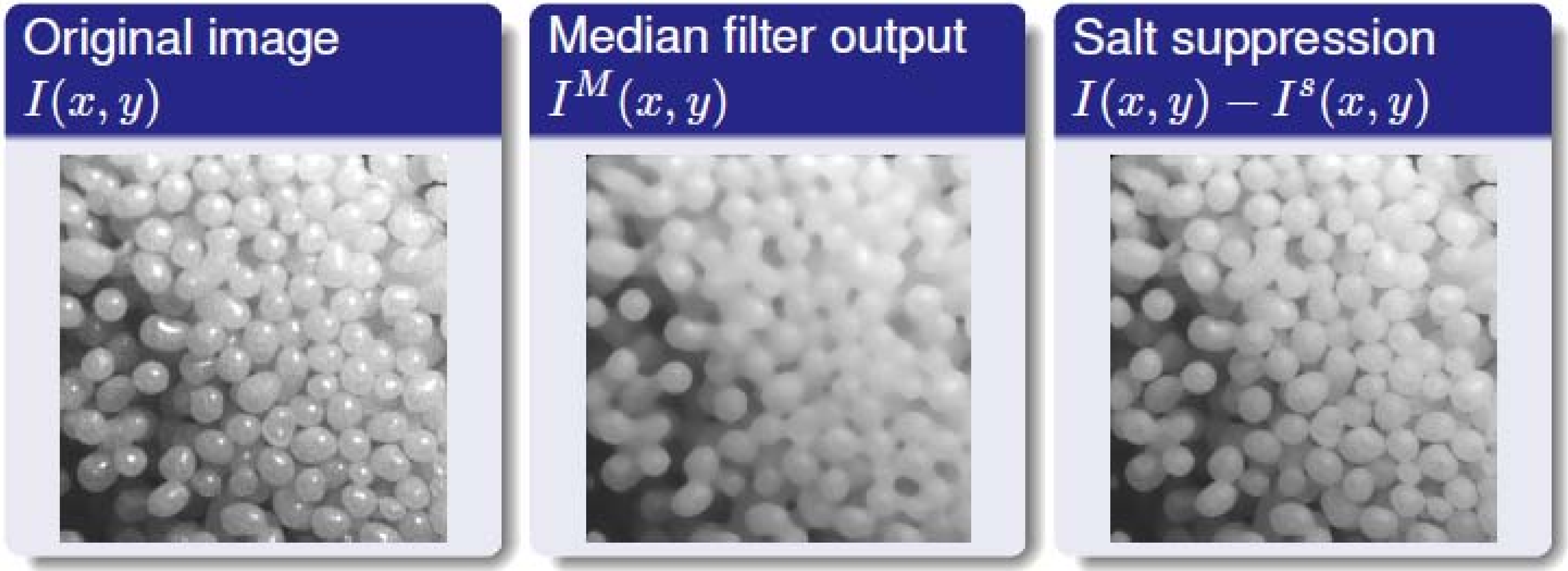
- **Median filter commonly used to reduce salt-and-pepper noise.**
- **Differentiate between the high-intensity noise (salt) and low-intensity noise (pepper).**
- **Let I^M be the result of applying the median filter to an image I.**

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

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

- **Subtracting I^s from I will only suppress the high-intensity noise.**

Specular Highlight Suppression

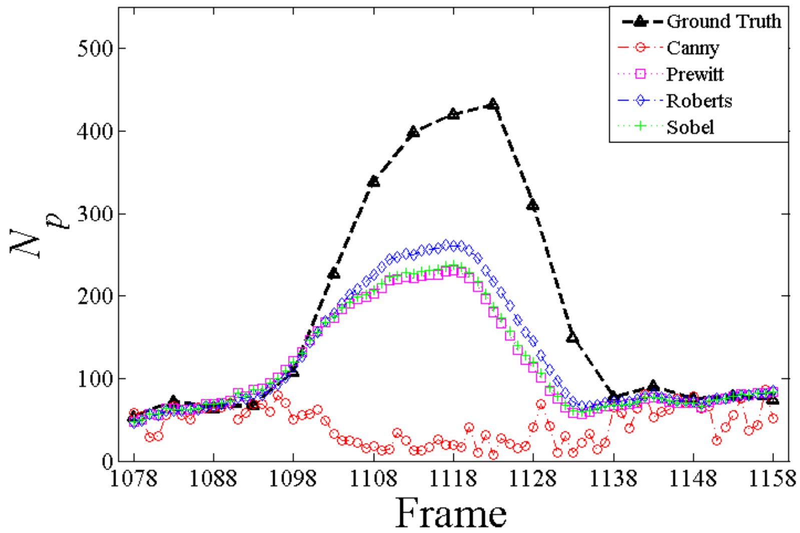


- **The median filter smooths the image (reducing sharpness of edges).**
- **Suppressing only the high-intensity component preserves most of the edge information.**

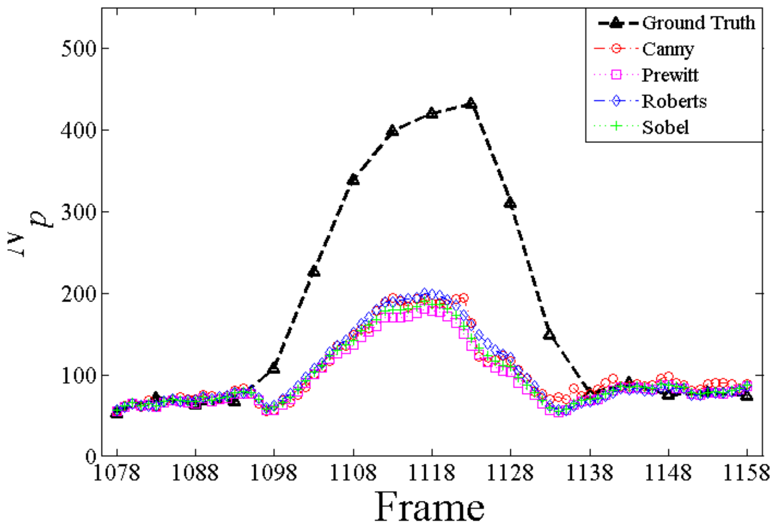
Gradient-Based or Edge Detection

- 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.

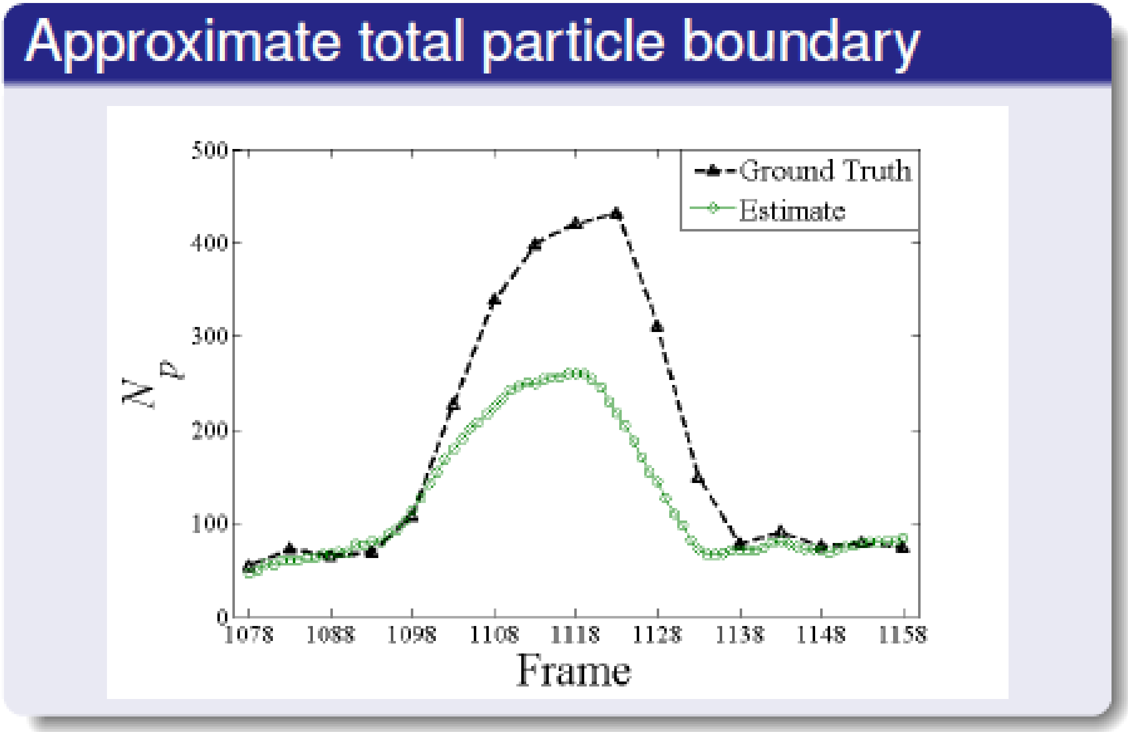
Original Images



Highlight Suppressed Images

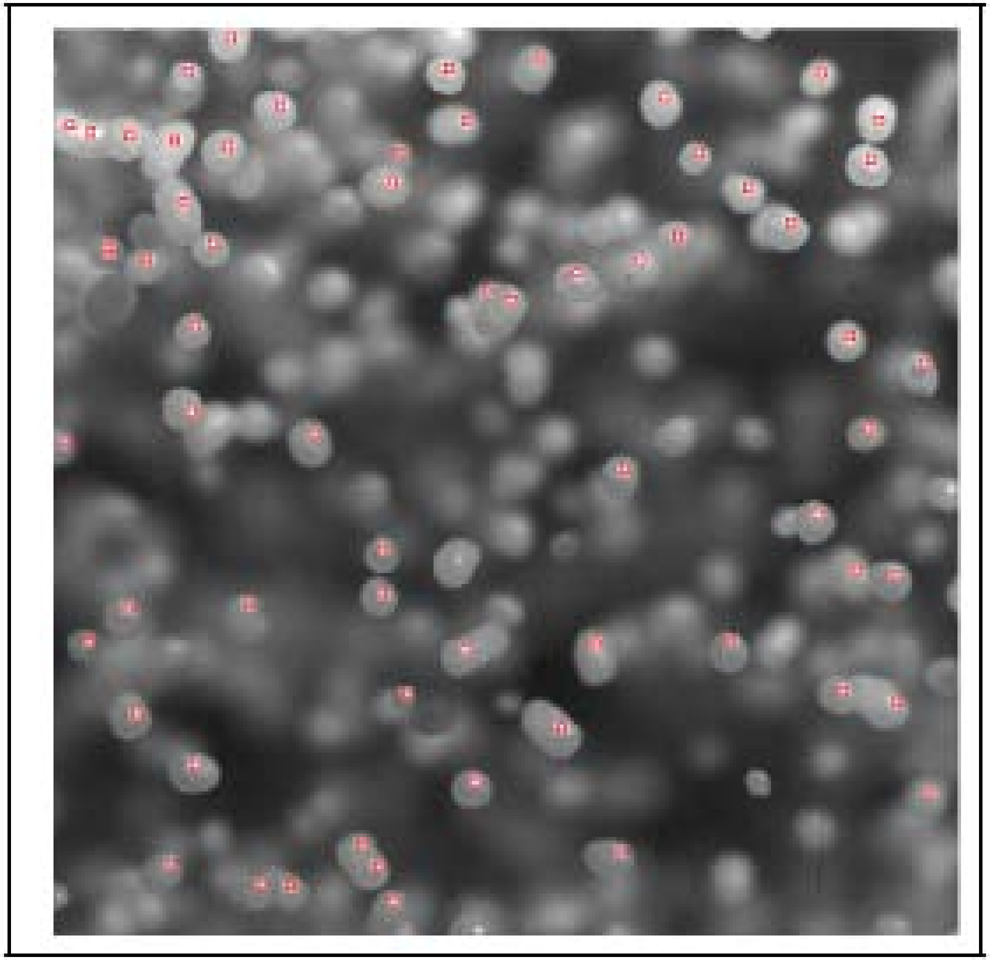


Gradient-based Approach



- **Excellent estimate of the dilute phase (suggests truly spherical particles).**
- **As concentration increases, particle boundary information decreases significantly.**

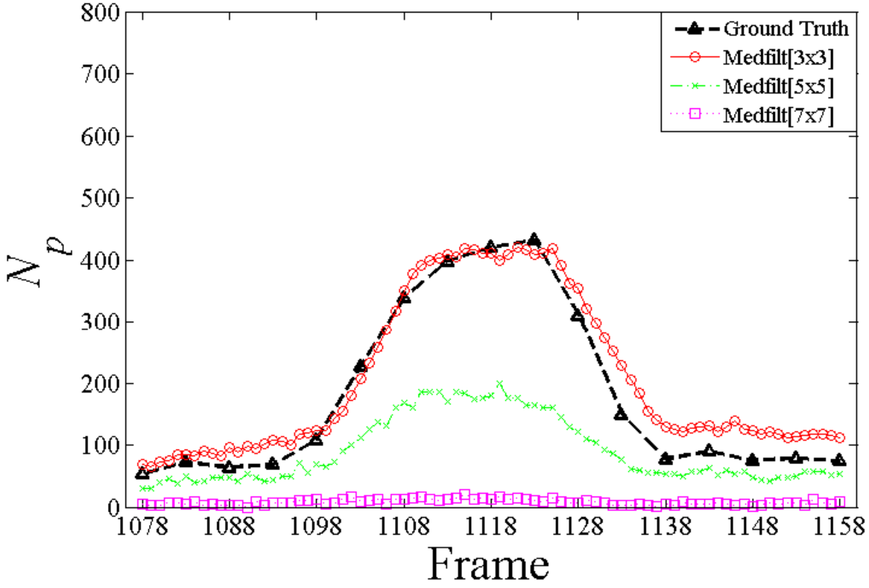
Detected Highlights in the Evaluation Sequence



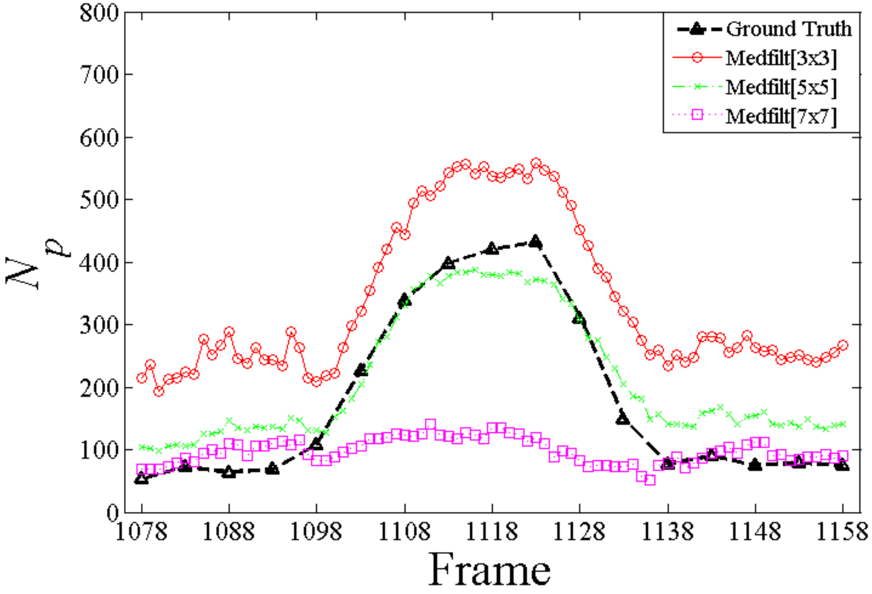
Specularity-based Approach

Effect of image processing

Original Images

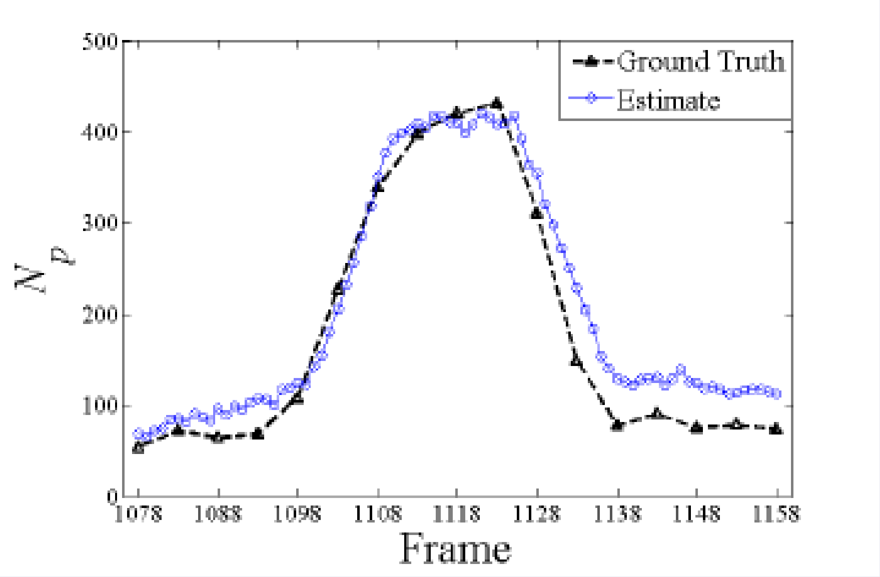


Adjusted Images



Specularity-based Approach

Approximate particle count by specularity count



- **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

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

relative thickness	dense region	dilute region
t	voidage	solids fraction
0.5*dp	22	10
1.0*dp	60	5
1.5*dp	72	3.3

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

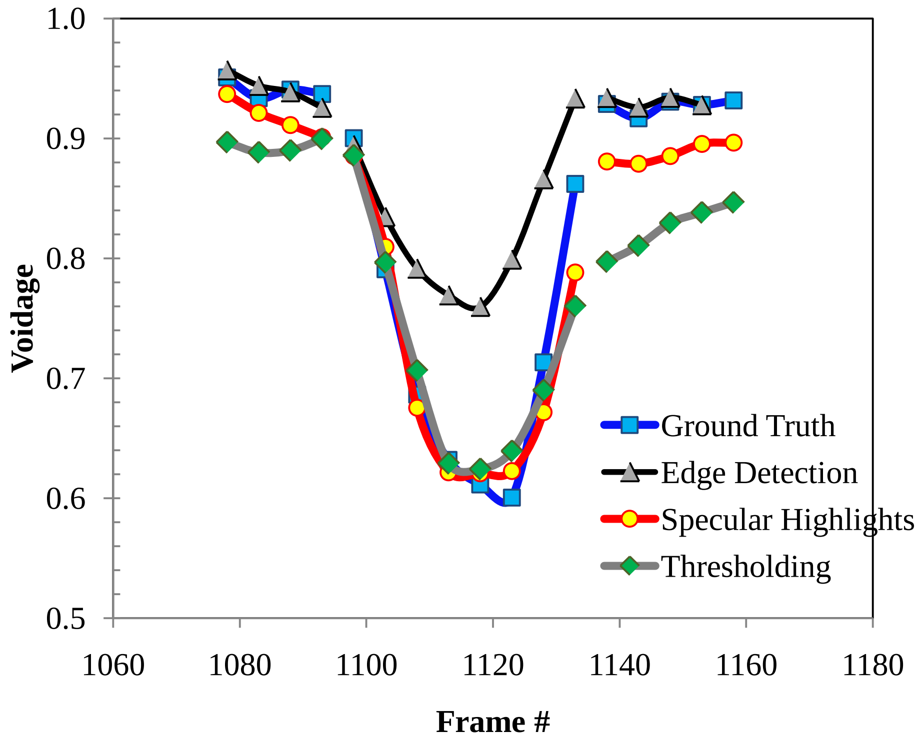
Hoomans, B. P. B. et al, (1996) Chemical Engineering Science 51 (1), 99–118.

$$\varepsilon_v^{\mathrm{O}} = 1 - \frac{\sqrt{2}}{\sqrt{\pi \sqrt{3}}} \psi_p^{\frac{3}{2}}.$$

Reduces to $0.8774 \cdot d_p$

Ouyang, J. and J. H. Li (1999) Chemical Engineering Science 54 (13–14), 2077–2083.

Voidage



Frame #	Mean Void	Bias (void fraction, ε_v)			Precision (95%CL)		
		Specular Highlight	Otsu Threshold	Edge Detection	Specular Highlight	Otsu Threshold	Edge Detection
All	0.835	-0.023	-0.045	0.051	0.009	0.009	0.022
1078–1093	0.941	-0.023	-0.047	0.001	0.014	0.009	0.012
1098–1128	0.725	-0.013	-0.008	0.106	0.020	0.018	0.051
1133–1158	0.927	-0.040	-0.103	0.002	0.007	0.019	0.007

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.