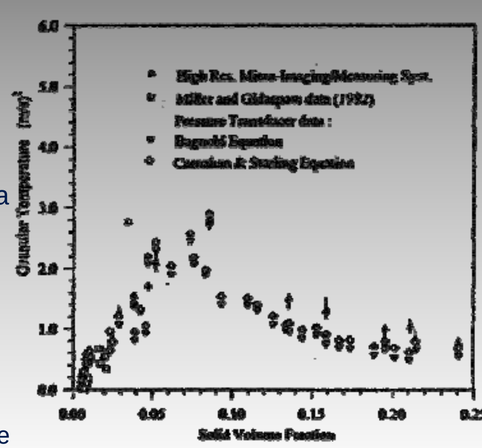
Measurement of Particle Number Density and Volume Fraction in a Fluidized Bed using Shadow Sizing Method

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:

$$PV = Nk_BT$$

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

$$PV = Nk_BT = Nmv_{rms}^2/3$$

$$T = mv_{rms}^2/3k_B$$

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

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Granular Temperature

- From velocity

$$\theta = \frac{1}{3}\left(\sigma_\theta^2 + \sigma_r^2 + \sigma_z^2\right)$$

where: $\sigma_z^2 = \left(u_z - \bar{u}\right)^2$

- u_z is particle velocity

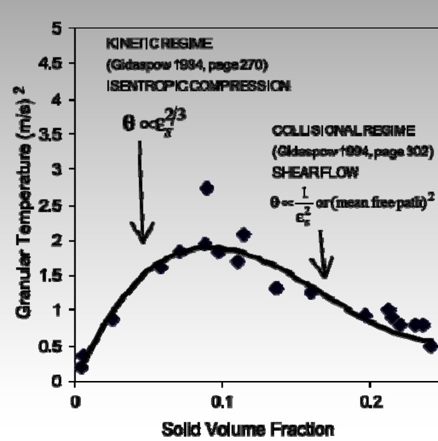
  $\bar{u}$ is the average particle velocity

- From voidage for dilute flows

$$\theta \propto \varepsilon_s^{2/3}$$

- From voidage for dense flows

$$\theta \propto 1/\varepsilon_s^2$$



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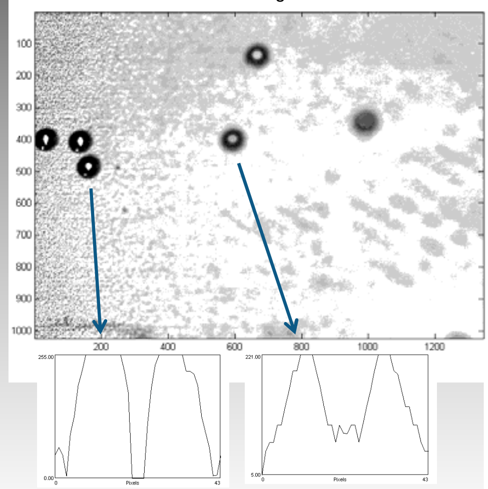
Volume Fraction

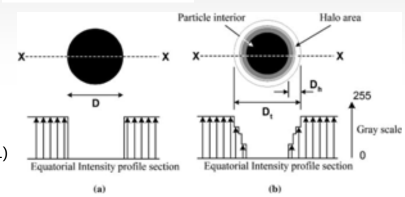
- Solids volume fraction:

$$\varepsilon_s = \frac{nV_p}{Ah}$$

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

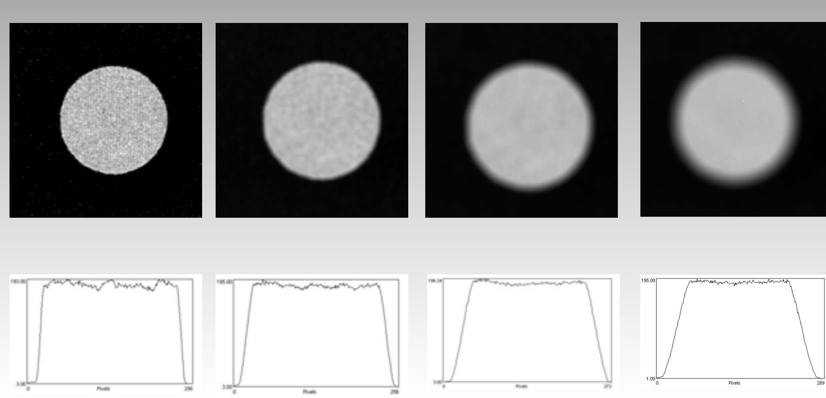
6 Glass beads imaged at FIU 2008





(Lecuona *et al.*, Meas. Sci. Technol., **11,** (2000), 1152-1161)

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

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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
- Ph.D. "Lattice Boltzmann Simulations for Flow and Heat Transfer in Microgeometries," FIU August 2008.
- 2004 – 2007, Verification and Validation of CFD Problems
  - Pulsatile flow in channels, hypersonic flows, laminar/turbulent flames.
- M.S. Thesis: "Finite Volume/Front Tracking Method for multiphase Flows in Constricted Channels," 2003, ITU.

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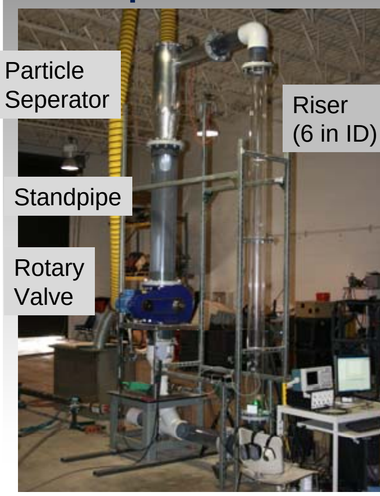
Experimental Setup



Particle Seperator

Riser (6 in ID)

Standpipe

Rotary Valve

Hedland Flowmeter

Air Compressor
(900 cfm at 100psi)

Heat exchanger set-up

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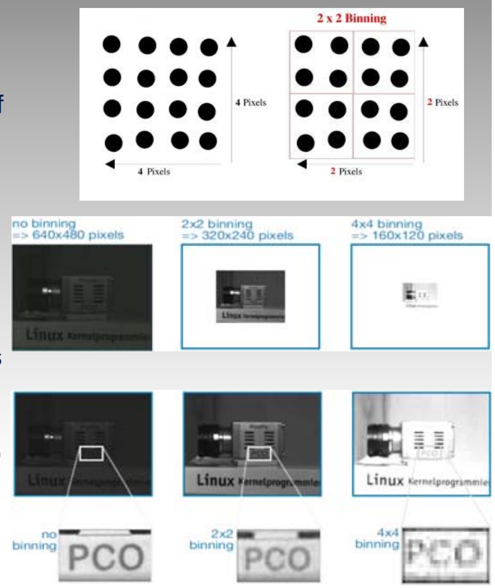
Camera Setup

Digital CCD camera			C8484-05CP
# of Pixels			1344 (H) x 1024 (V)
Effective area			8.67 mm (H) x 6.60 mm (V)
Frame rate	1x1		12.2 frame/s
	Binning	2 x 2	22.3 frame/s
		4 x 4	40.9 frame/s
		8 x 8	68 frame/s
Exposure time			0.02 – 1 s

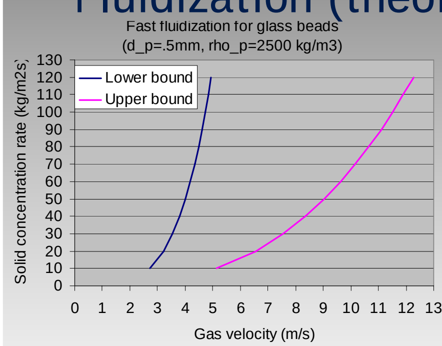
Telecentric Lens	Edmund Optics 55-350
Primary magnification	1X
Horizontal field of view	8.8 mm
Working distance	98 mm – 123 mm
Resolution (MTF Image Space @ F6)	>45% @ 40 lp/mm
Telecentricity	<.1°
Distortion	.5% Max
Depth of field (20% @ 20 lp/mm)	± 0.6mm at F12
Aperture (f/#)	F6 – F25

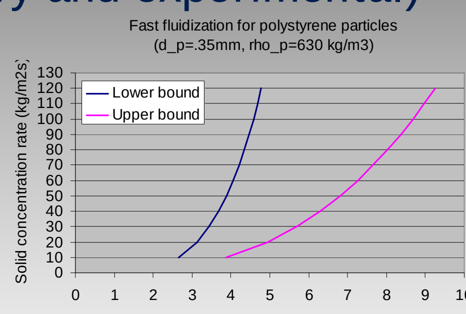
Binning

- 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)





Flow rate (cfm)	Temperature (C°)	Velocity (m/s)	Humidity (RH%)
100	22.0	2.64	59.0
200	35.90	5.79	30.6
300	38.20	8.89	25.2

Flow conditions at the riser inlet

$$U_{tf} = \left(39.8\rho^{-0.311}\,\mathrm{Re}_t^{-0.078}\sqrt{gd_p}\right)^{0.763} J_p^{0.237}$$

$$U_{fd} = \left(21.6\rho^{-0.542}\,Ar^{0.105}\sqrt{gd_p}\right)^{0.649} J_p^{0.351}$$

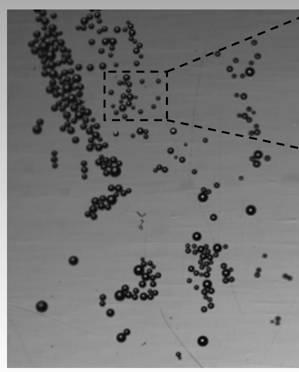
$$Ar = \frac{\rho(\rho_p - \rho)gd_p^3}{\mu^2}$$

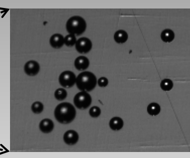
$$\mathrm{Re}_t = \frac{\rho U_{pt} d_p}{\mu} \qquad U_{pt}^{1.4} = 0.072\frac{d_p^{1.6}(\rho_p - \rho)g}{\rho^{0.4}\mu^{0.6}}$$

Image Processing

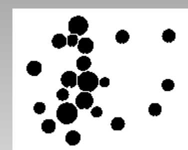
(NIH ImageJ – Freeware by National Institutes of Health)

Image of particles on glass to demonstrate image processing

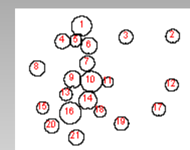




Region of interest (1.19x0.92 mm)



Binary > Fill holes > Watershed



Particle analyzer

$$\varepsilon_s = \frac{\sum_i^n V_i}{Ah}$$

n = 21
A= 0.158 mm^2
h = 1 mm

$$\varepsilon_s = 0.99\%$$

Polystyrene particles
D_p =0.3 – 0.4 mm

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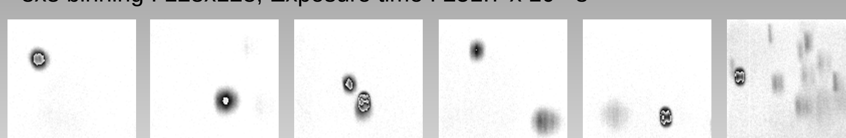
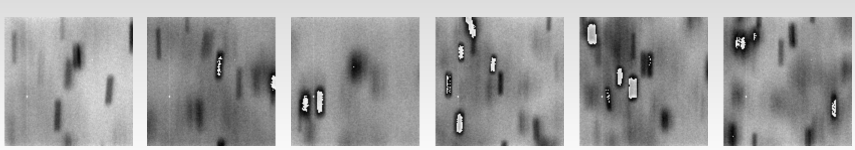
Images of Polystyrene Particles in the Riser

8x8 binning : 128x128, Exposure time : 251.7 x 10^{-3} s



Q= 150 CFM,



Q= 180 CFM,

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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 µs of exposure time.
  - Will require external triggering using a pulse generator.
- Postprocessing with intensity graduation

Airlock rotary valve blades

Particle feed mechanism

Pulse generator