GASIFICATION TRANSPORT: A MULTIPHASE CFD APPROACH & MEASUREMENTS

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Outline

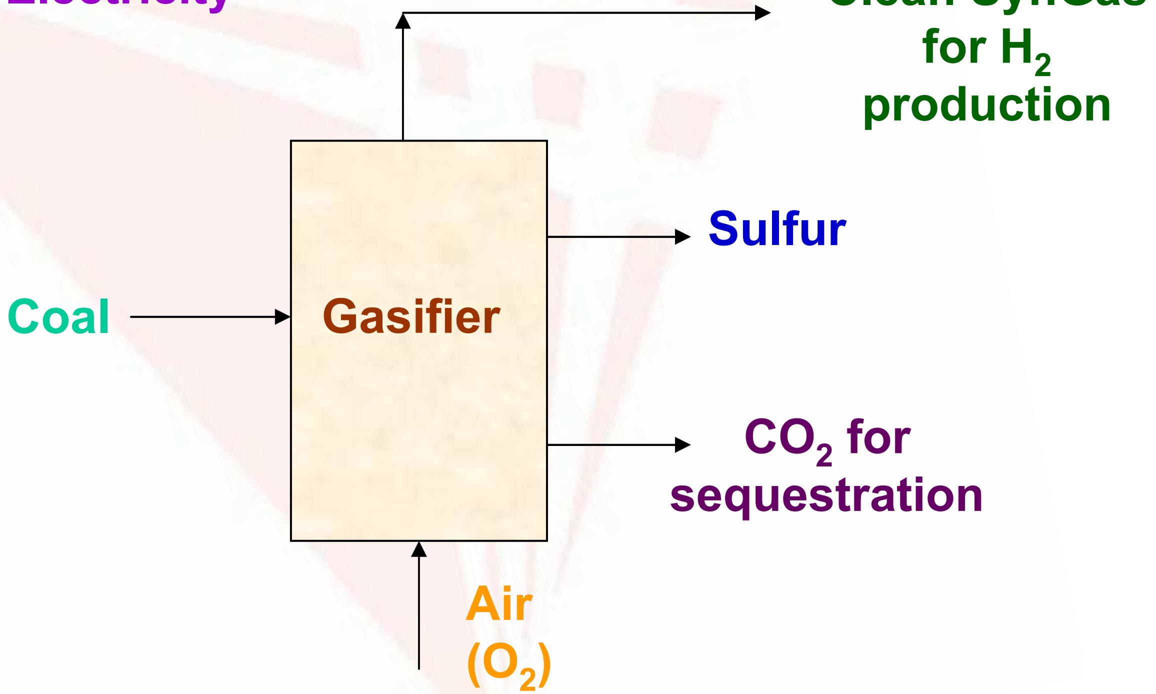
- Introduction
- Measurement of dispersion coefficients in IIT 2-D Circulating Fluidized Bed
- Measurement and computation of dispersion coefficients in the IIT riser
- Computation of clusters and mass transfer coefficients in the PSRI riser

PART I

INTRODUCTION

Background

- FutureGen was a one billion dollar, ten year project to create world's first coal based, zero emission electricity and hydrogen plant (Rita Bajura, 2004). It was canceled by DOE on January 29, 2008.
- H_2 (from natural gas) in Molten Carbonate Fuel Cell → Waste heat
  75% efficiency → Electricity



- Our concept utilizes heat for the gasifier from fuel cell (Clearwater Conference; 2007 UCR Review Meeting)

Background (Continued)

- Gasifier needs substantial improvement to increase its efficiency.
- Reliable design of a gasifier requires the knowledge of dispersion and mass transfer coefficients, which are known to vary by several orders of magnitude (Gidaspow et al. (2004); Breault (2006)).

Dispersion Coefficients

- The physical definition of dispersion coefficients is based on the kinetic theory of gases. For diffusion of gases or particles, the diffusivity is defined as the mean free path times the average velocity

$$D = L \; x \; \overline{C}$$

- The mean free path is obtained from the average velocity and collision time

$$L = \overline{C} \; x \; \tau$$

- Therefore, the dispersion matrix can be defined as the Reynolds stresses times the collision time

$$D_p = \overline{CC} \; x \; \tau$$

Dispersion Coefficients

$$D_L(a) = \overline{v'(a)^2}\, T_L$$

where,

$\overline{v'(a)^2}$ **= mean square particle fluctuating velocity corresponding to normal Reynolds stress**

$T_L = \int_0^\infty R_L(\vec{a},t')dt' = \int_0^\infty \frac{\overline{v'(t)v'(t+t')}}{\overline{v'^2}}dt'$ **= Lagrangian integral time scale**

$v'(t)$ **= Largrangian velocity fluctuations**

$R_L(\vec{a},t') = \frac{\overline{v'(t)v'(t+t')}}{\overline{v'^2}}$ **= particle autocorrelation**

$T_L \approx T_E$ **= Eulerian integral time scale approximately equals Lagrangian integral time scale**

Hinze, H. O., 1959. Turbulence. McGraw-Hill, New York

PART II

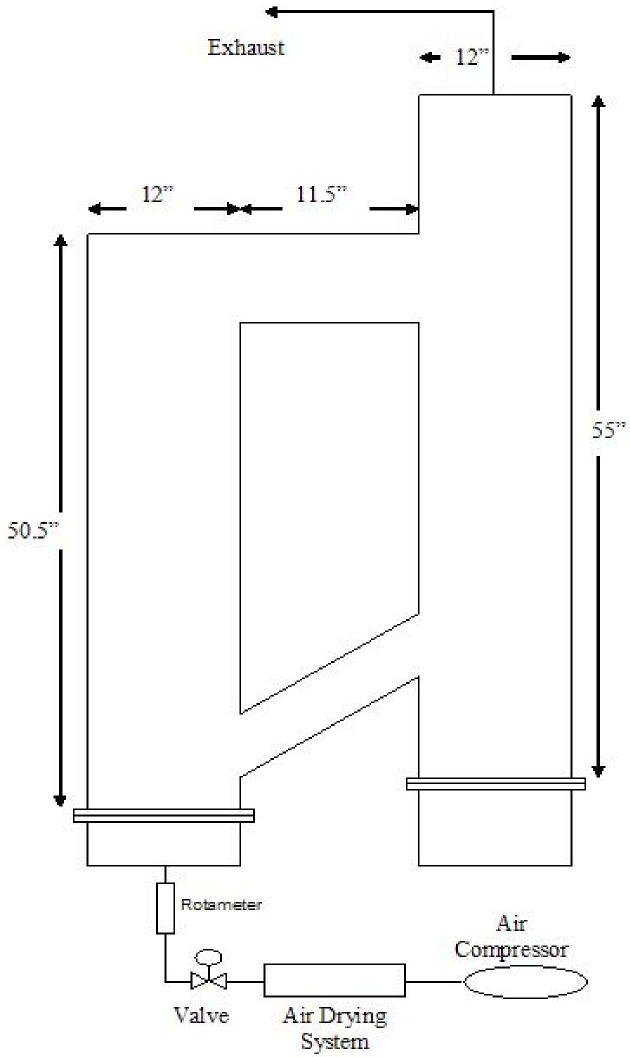
MEASUREMENT OF DISPERSION COEFFICIENTS IN IIT 2-D CIRCULATING FLUIDIZED BED

Theory

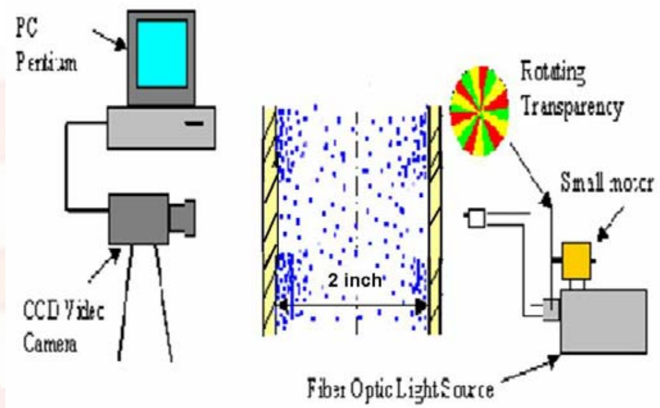
- The dispersion coefficient is a measure of the quality of mixing. We have identified two types of solids dispersion coefficients:
  1. Those due to random particle oscillations, “laminar” type
  2. Those due to cluster or bubble motion, “turbulent” type

- The Particle Image Velocimetry (PIV) method described in Tartan et al. (2003) was used to measure the velocities and stresses of the 75 μm FCC particles and 1093 μm particles in the IIT 2-dimensional CFB and IIT riser, respectively. The measurements of instantaneous particle velocities enabled us to calculate the granular temperatures and solids dispersion coefficients using the auto-correlation technique described in Jiradilok et al (2006).

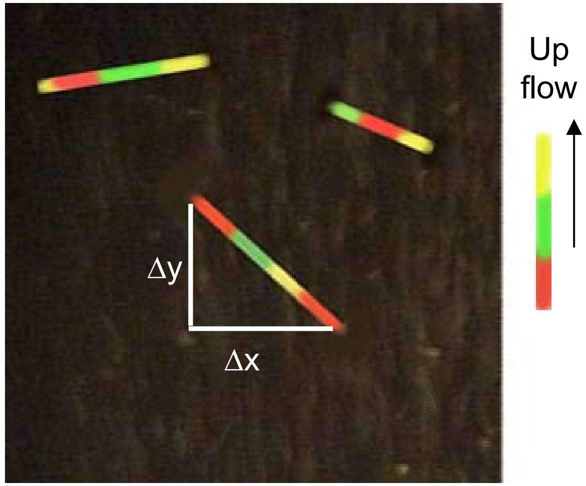
Experimental Setup



IIT 2-dimensional circulating fluidized bed

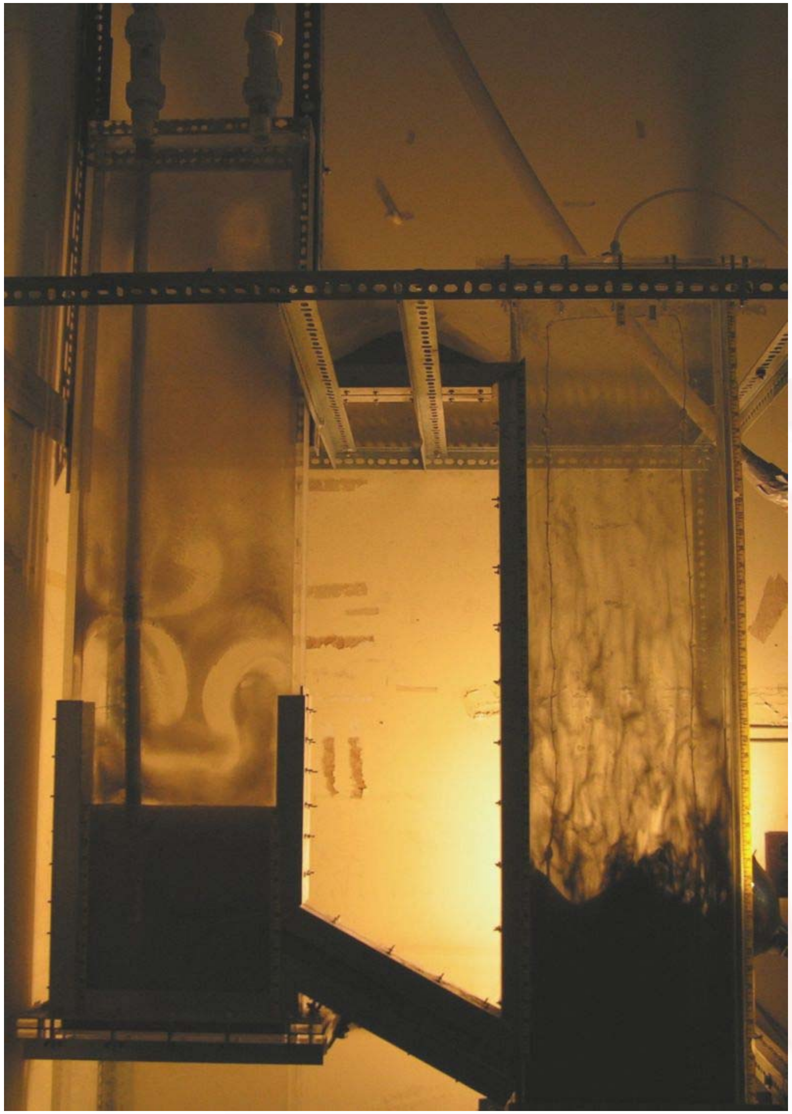


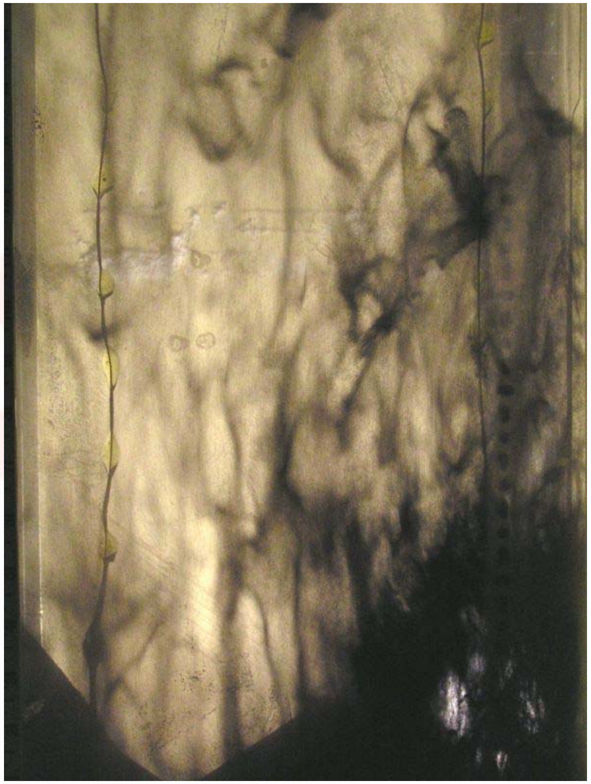
Particle image velocity measurement system



Typical streak images captured by CCD camera

2-D Circulating Fluidized Bed





Circulating fluidized bed showing clusters formed by 75 µm FCC particles

Particle Image Velocimetry (PIV) Method

The exposure time noted from the CCD camera settings helps us measure the instantaneous velocities. The frame speed of 30 frames per second gives the time internal between continuous frames. Instantaneous radial and axial velocities are calculated as,

$$c_x(r,t) = \frac{\Delta L}{t}\sin\alpha$$

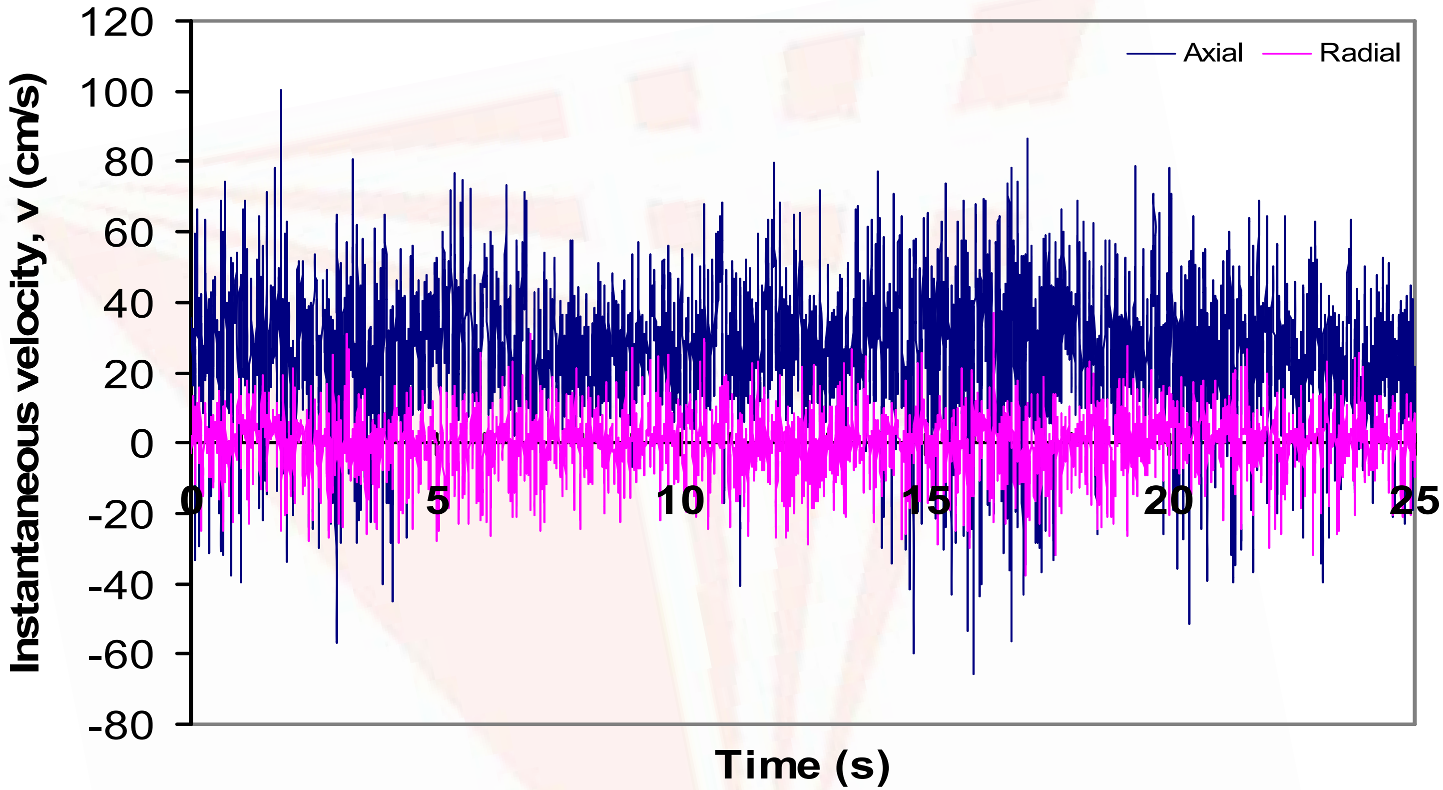
$$c_y(r,t) = \frac{\Delta L}{t}\cos\alpha$$

Hydrodynamic velocity, i.e. average of instantaneous velocities in each frame, is given by

$$v_i(r,t) = \frac{1}{n}\sum_{k=1}^{n} c_{ik}(r,t)$$

HORIZONTALLY AT THE CENTER, AT A HEIGHT OF 69.85 CM

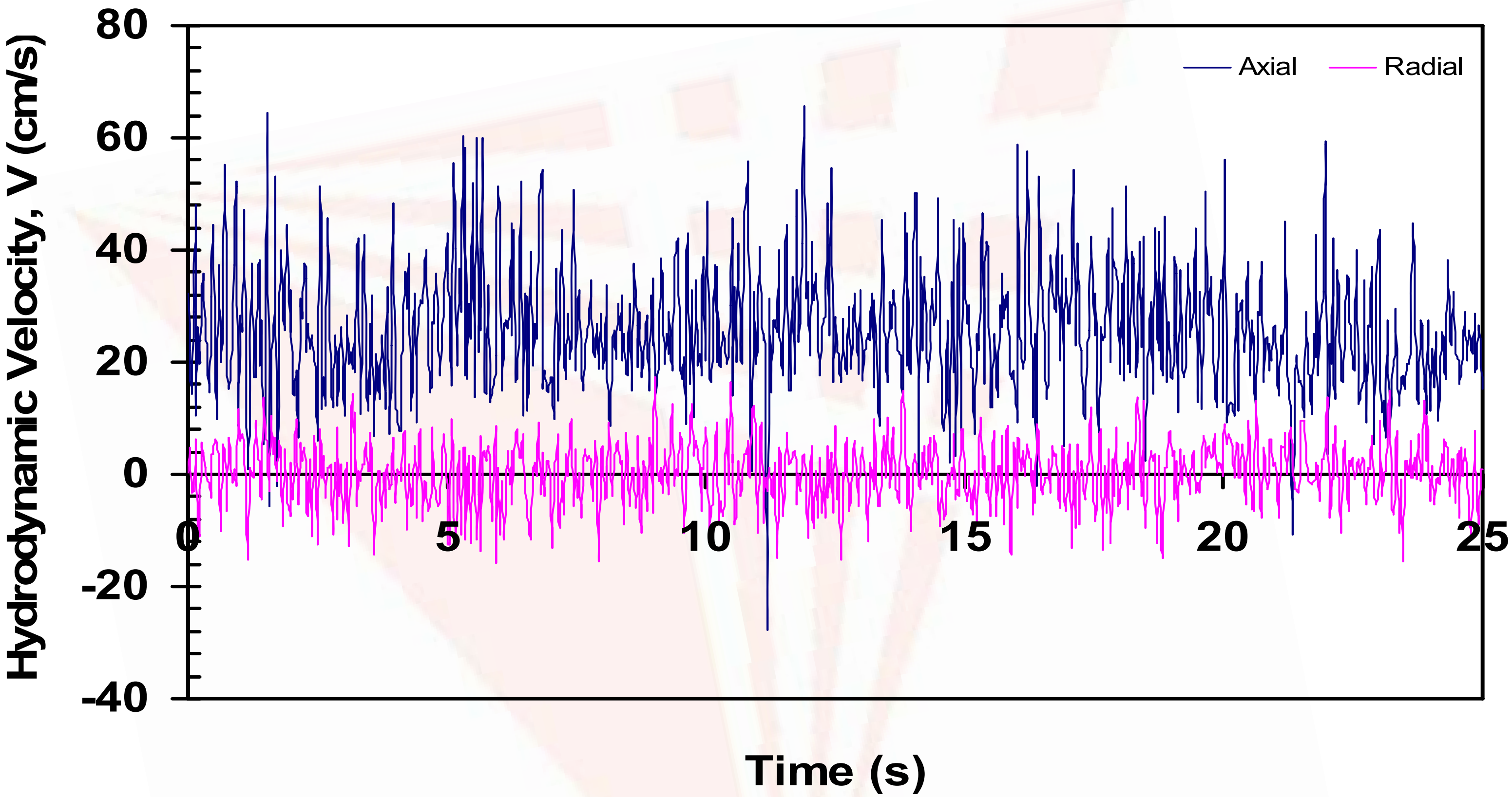
Instantaneous Velocities



Oscillation of instantaneous velocity in radial and axial directions obtained by CCD camera technique at a measuring height of 69.85 cm

$$\left(\overline{c_r} = 0.06 cm/s \quad , \quad \overline{c_a} = 23.21 cm/s \right)$$

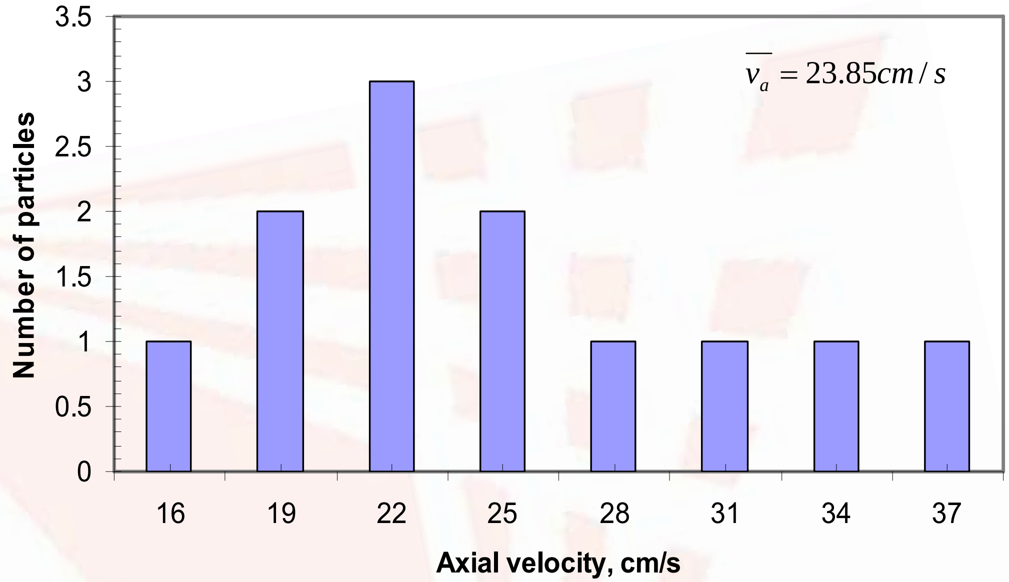
Hydrodynamic Velocities

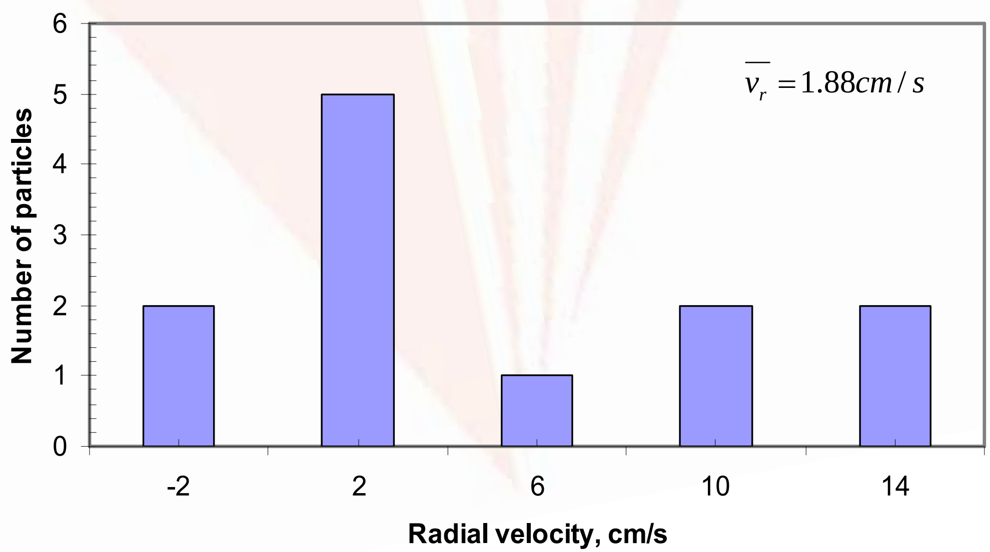


Oscillation of hydrodynamic velocity in radial and axial directions obtained by CCD camera technique at a measuring height of 69.85 cm

$$(\overline{V_r} = 0.295 cm/s, \ \overline{V_a} = 25.68 cm/s)$$

Typical Instantaneous Velocity Distribution in a Frame



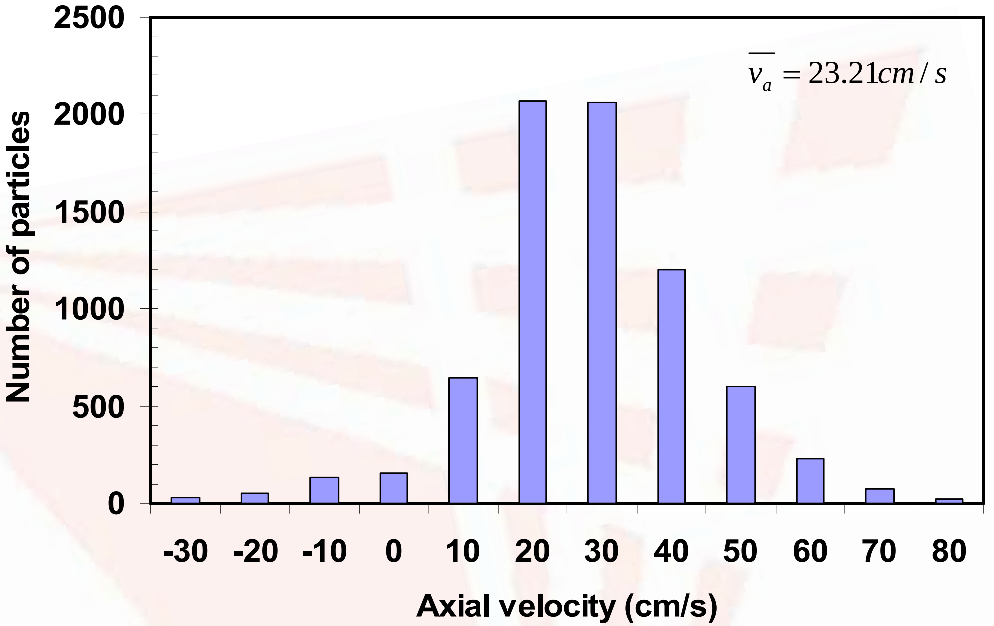


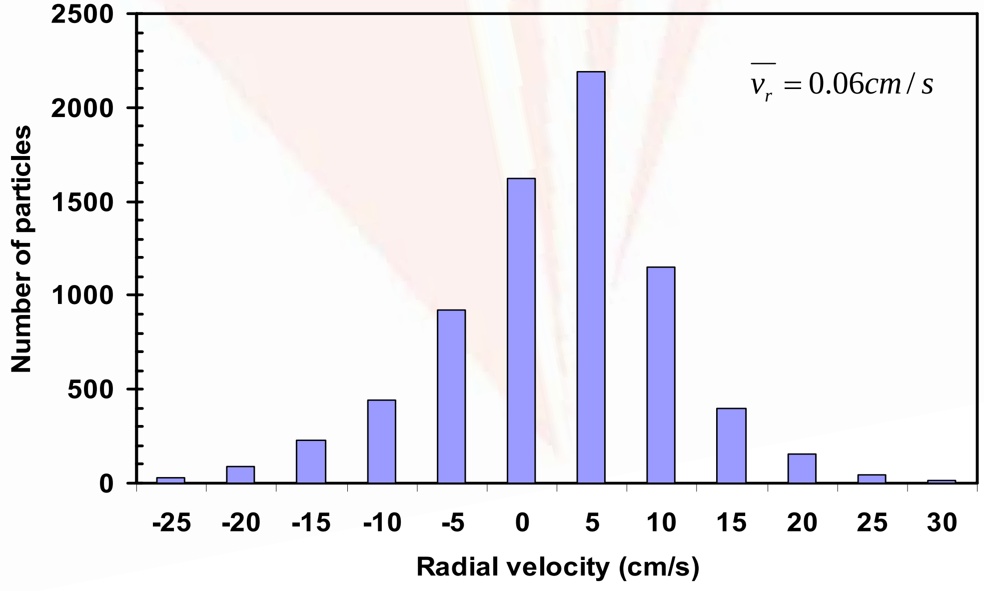
H = 69.85 cm

U_g = 46.67 cm/s

t = 1/250 s

Overall Instantaneous Velocity Distribution



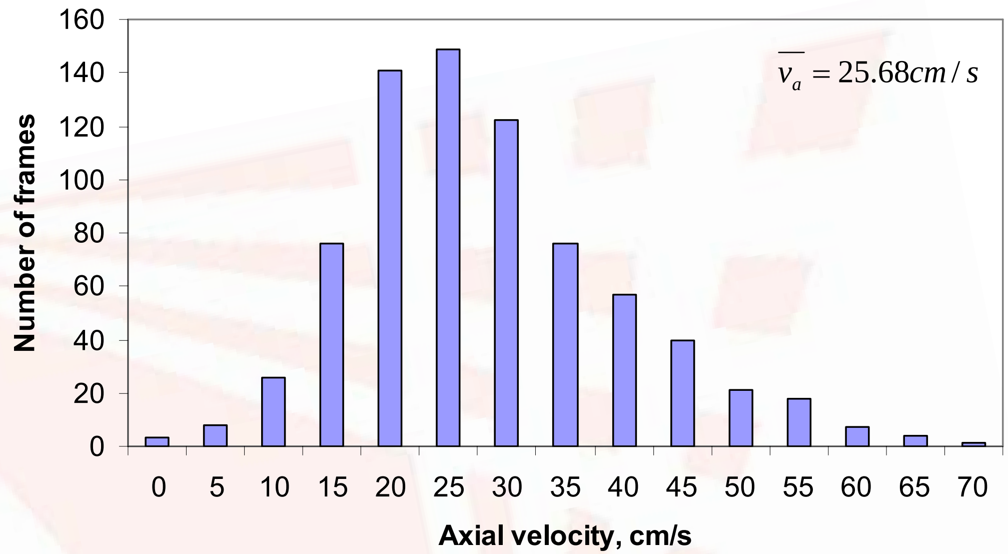


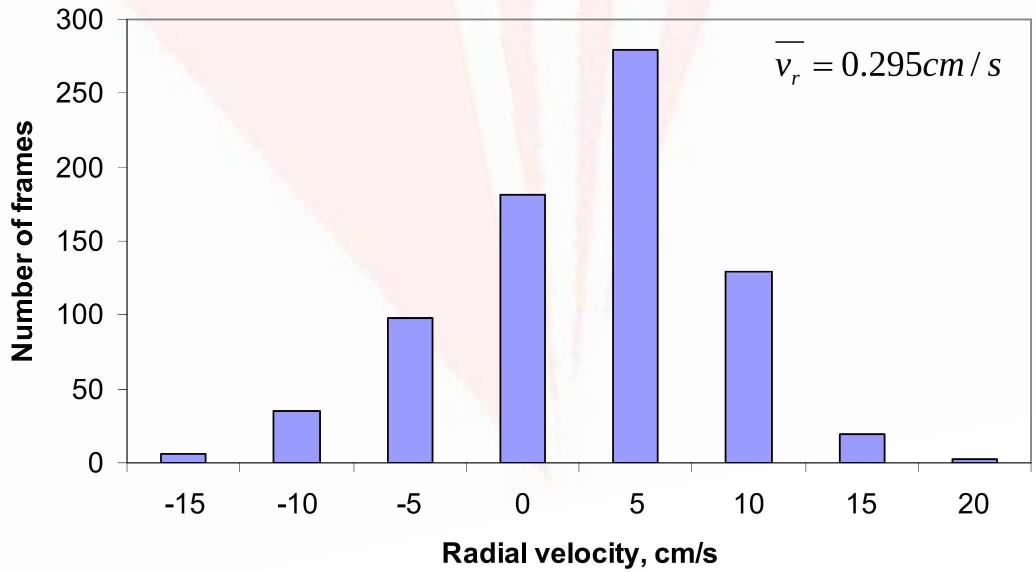
H = 69.85 cm

U_g = 46.67 cm/s

t = 1/250 s

Hydrodynamic Velocity Distribution





H = 69.85 cm

U_g = 46.67 cm/s

t = 1/250 s

Reynolds Stresses

Laminar Normal Reynolds Stress

$$< C_i C_i > (r,t) = \frac{1}{n}\sum_{k=1}^{n}(c_{ik}(r,t) - v_i(r,t))(c_{ik}(r.t) - v_i(r,t))$$

$$v_i(r,t) = \frac{1}{n}\sum_{k=1}^{n} c_{ik}(r,t)$$

Turbulent Normal Reynolds Stress

$$< V_i V_i > (r) = \frac{1}{m}\sum_{k=1}^{m}(v_{ik}(r,t) - \bar{v}_i(r))(v_{ik}(r,t) - \bar{v}_i(r))$$

$$\bar{v}_i(r) = \frac{1}{m}\sum_{k=1}^{m} v_{ik}(r,t)$$

where, "n" is the number of particles per unit volume,
"c" is instantaneous particle velocity in i-direction,
"v" is hydrodynamic velocity in i-direction,
"r" is any position,
"I" is x, y or z direction,
"m" is the total number of frames over a given time period
v_i is the mean particle velocity

Laminar Granular Temperature

$$\theta_{Laminar}(r,t) = \frac{1}{3}\left[< C_x C_x > + < C_y C_y > + < C_z C_Z >\right]$$

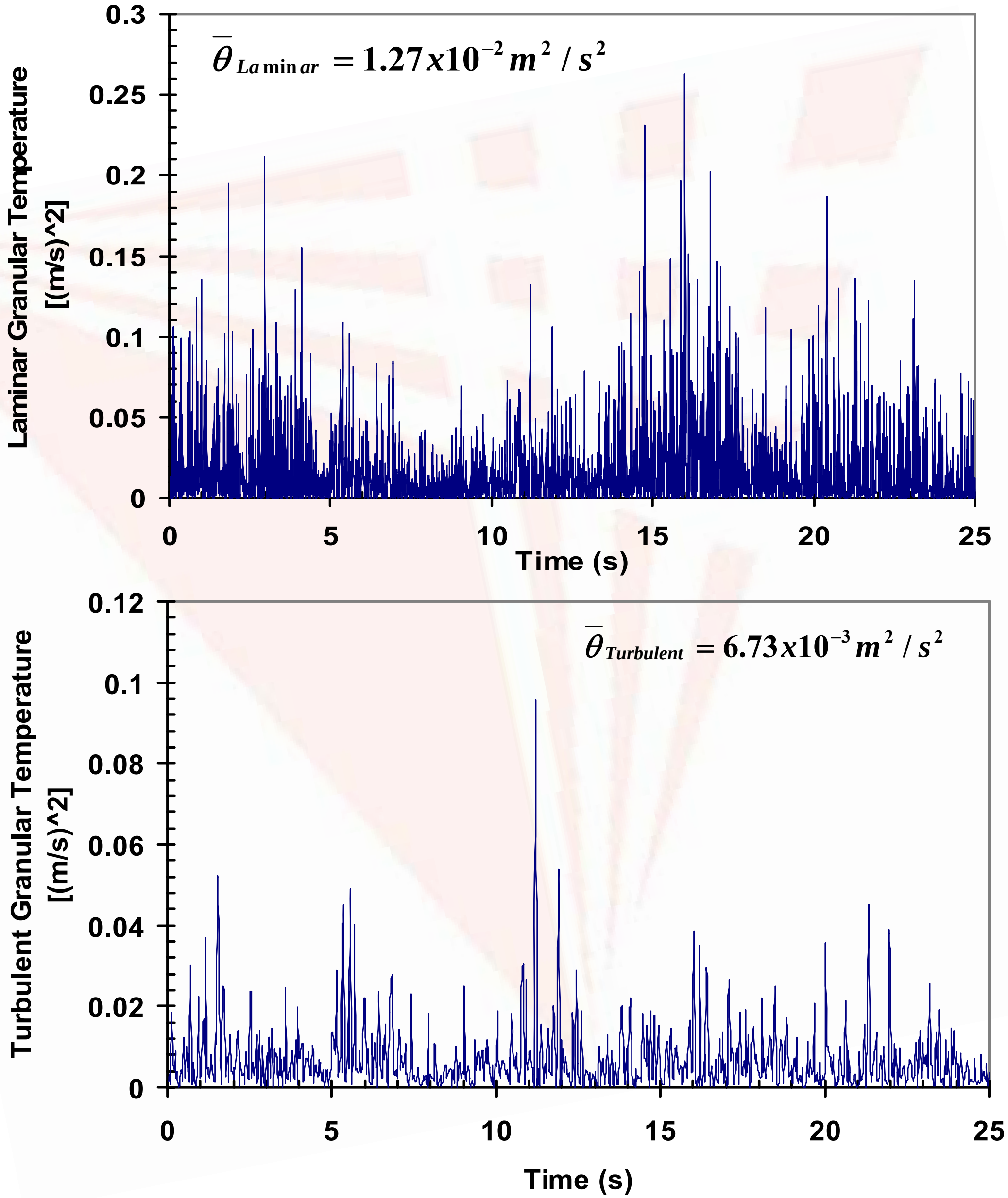
$$\theta_{Laminar}(r,t) \cong \frac{1}{3}\left[< C_y C_y > + 2 < C_x C_x >\right]$$

Turbulent Granular Temperature

$$\theta_{Turbulent}(r,t) = \frac{1}{3}\left[< V_x V_x > + < V_y V_y > + < V_z V_Z >\right]$$

$$\theta_{Turbulent}(r,t) \cong \frac{1}{3}\left[< V_y V_y > + 2 < V_x V_x >\right]$$

Variation in Granular Temperature



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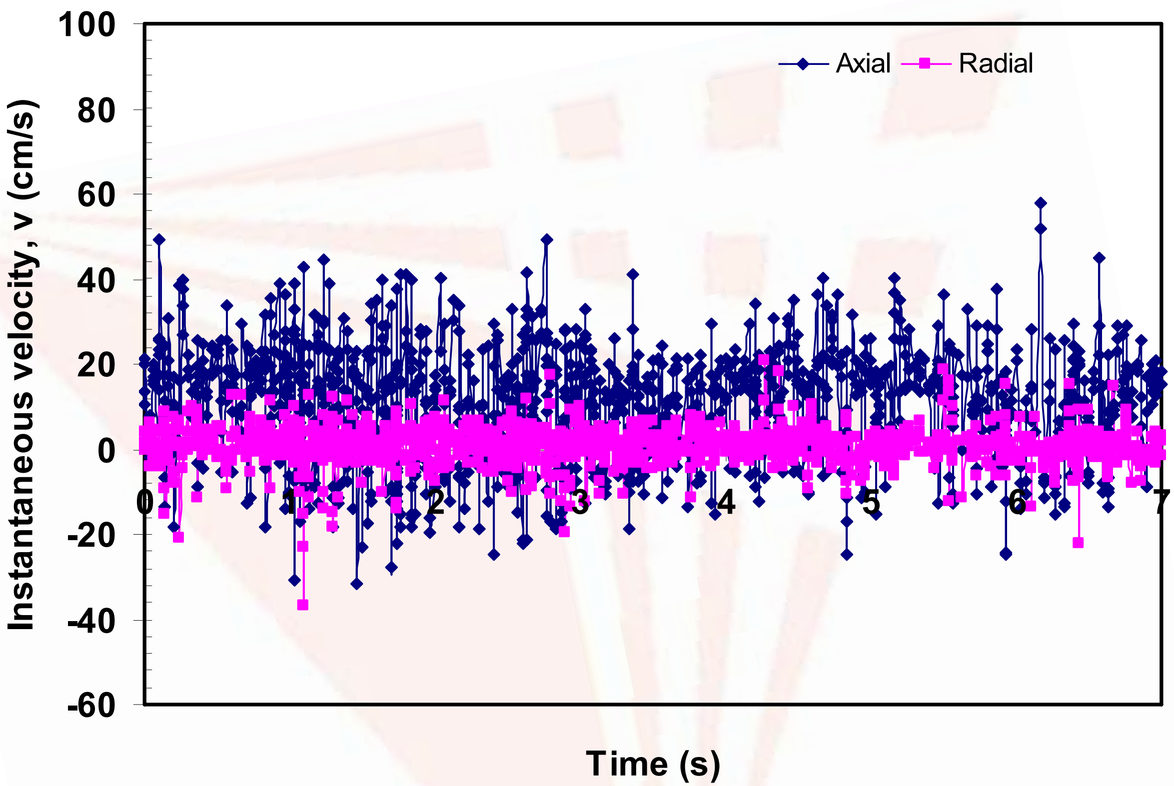
HORIZONTALLY NEAR THE RIGHT WALL,

AT A HEIGHT OF 69.85 CM

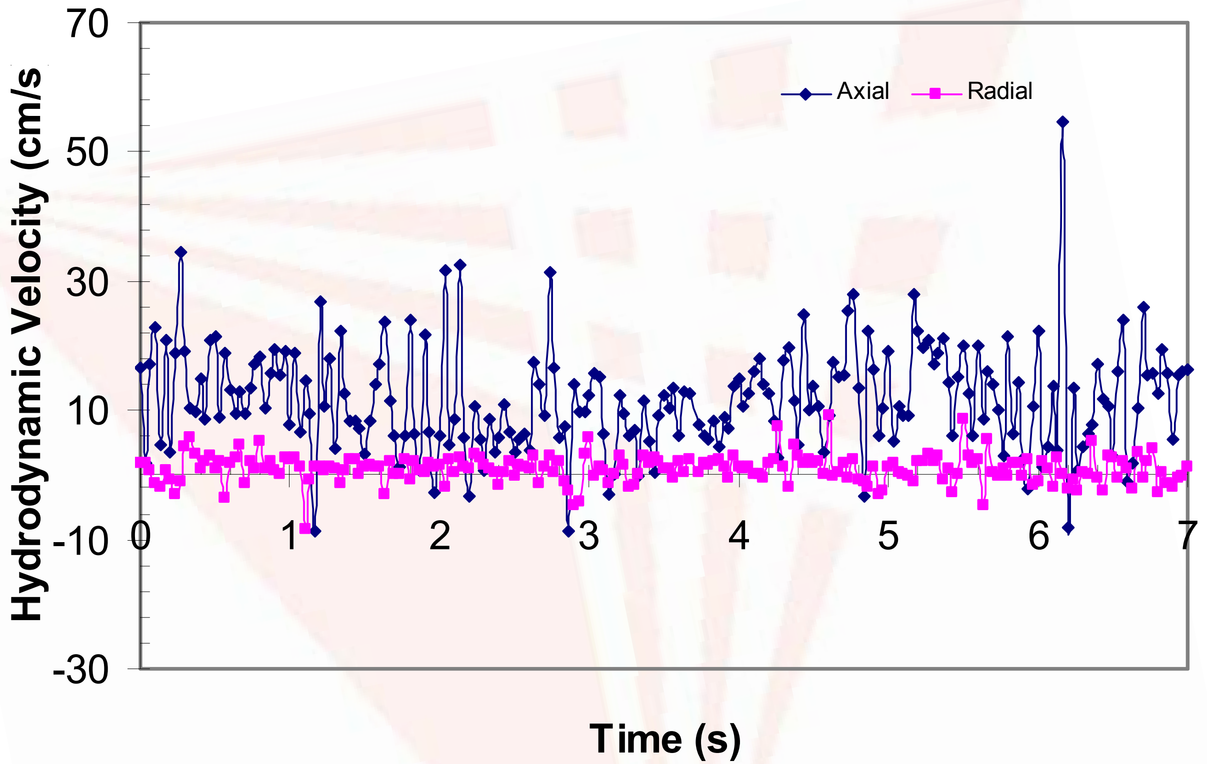
Instantaneous Velocities



Oscillation of instantaneous velocity in radial and axial directions obtained by CCD camera technique, near the right wall, at a measuring height of 69.85 cm

($\overline{c_r} = 0.95 cm/s$, $\overline{c_a} = 10.50 cm/s$)

Hydrodynamic Velocities



Oscillation of hydrodynamic velocity in radial and axial directions obtained by CCD camera technique, near the right wall, at a measuring height of 69.85 cm

$$\left(\overline{V_r} = 0.92 cm/s \;,\; \overline{V_a} = 11.73 cm/s \right)$$

Overall Instantaneous Velocity Distribution

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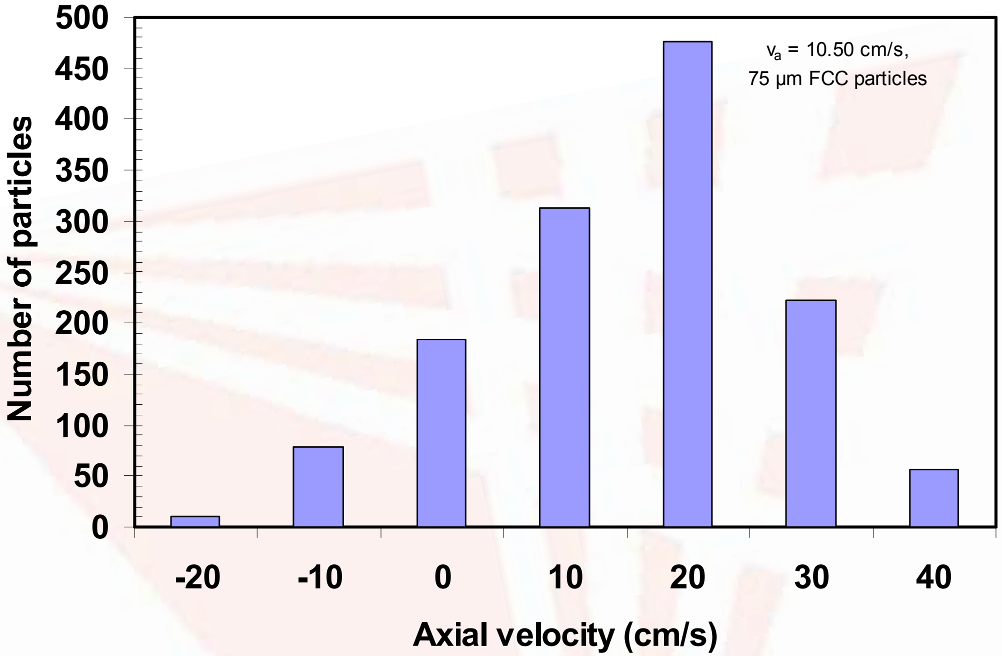
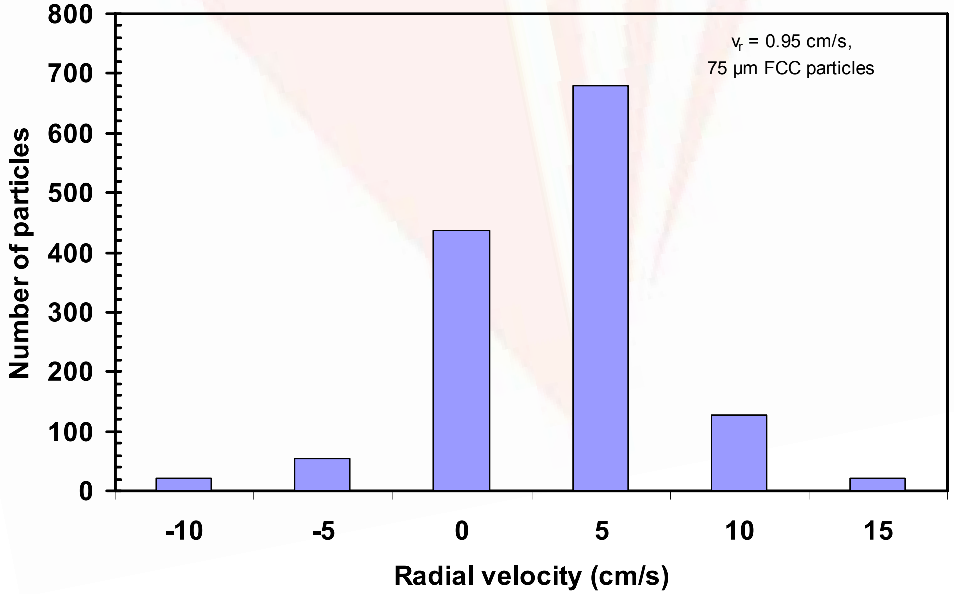


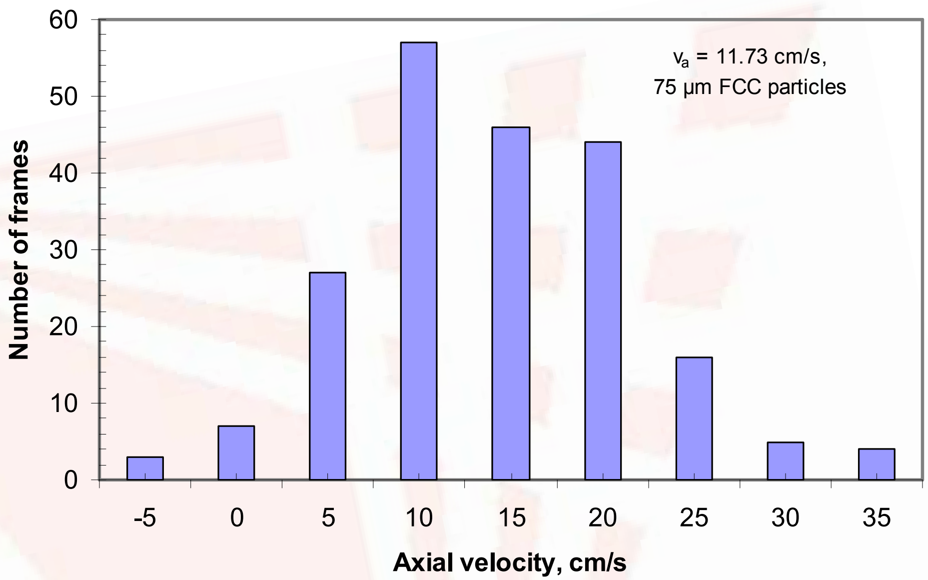


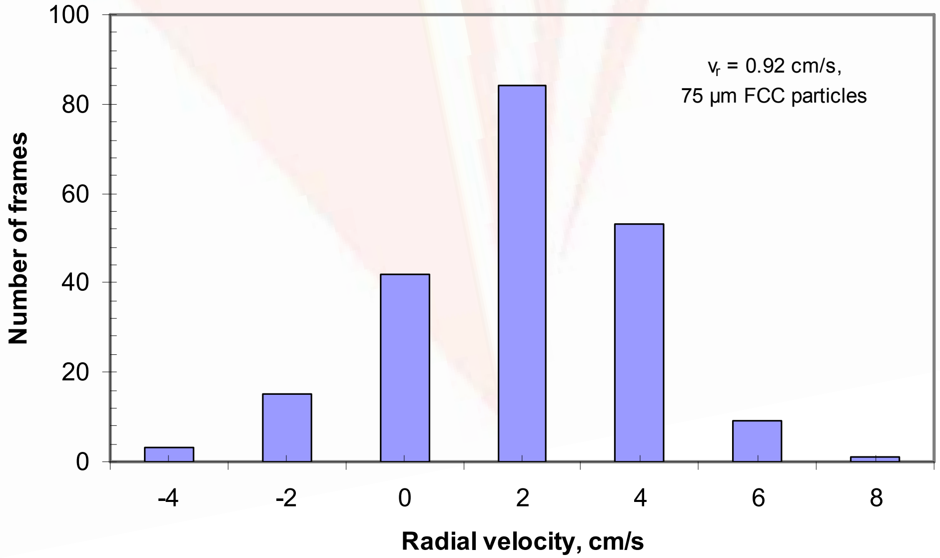
H = 69.85 cm

U_g = 46.67 cm/s

t = 1/250 s

Hydrodynamic Velocity Distribution



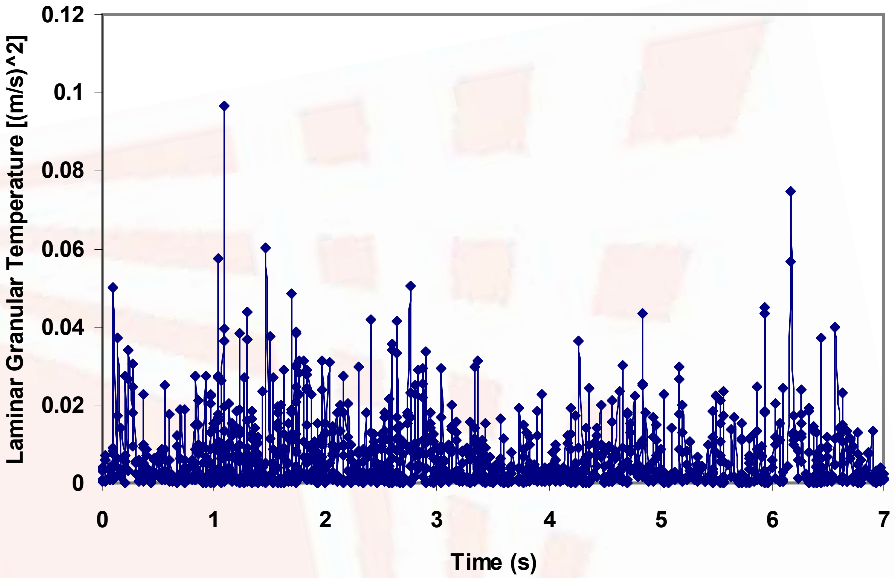


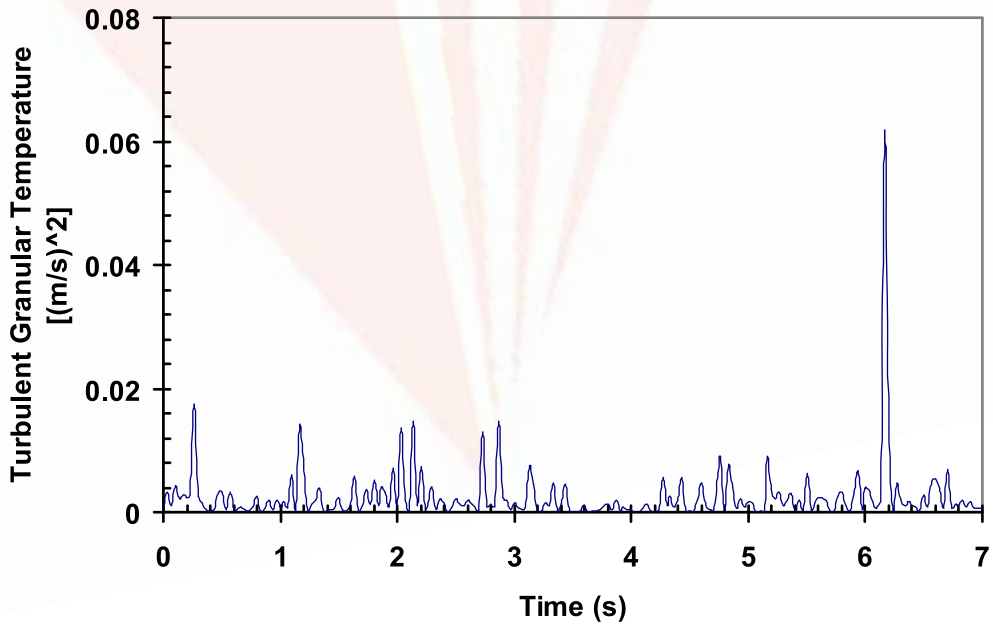
H = 69.85 cm

U_g = 46.67 cm/s

t = 1/250 s

Variation in Granular Temperature

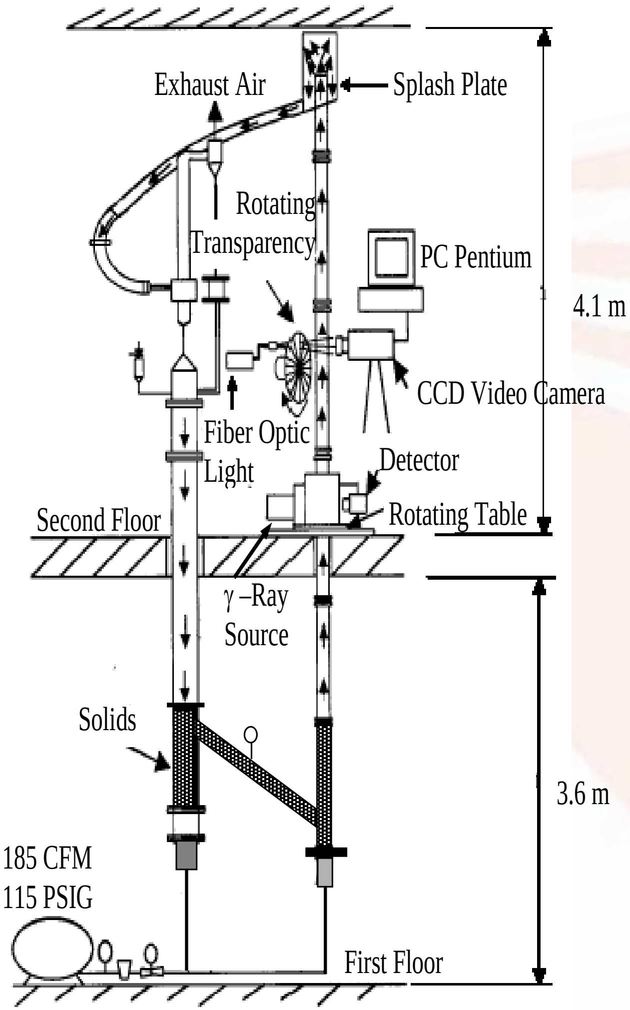




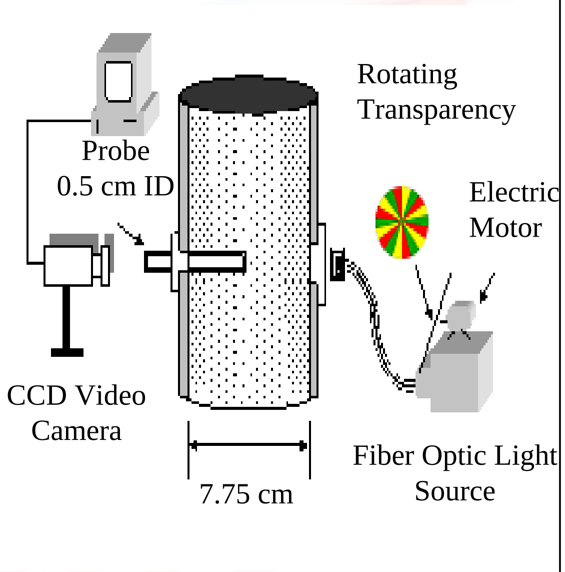
PART III

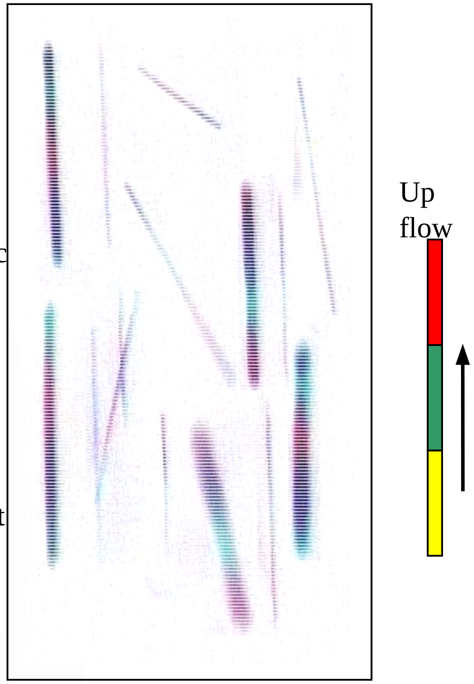
MEASUREMENT AND COMPUTATION OF DISPERSION COEFFICIENTS IN THE IIT RISER

IIT Riser



IIT riser with splash plate and fluidized downcomer to obtain high flux

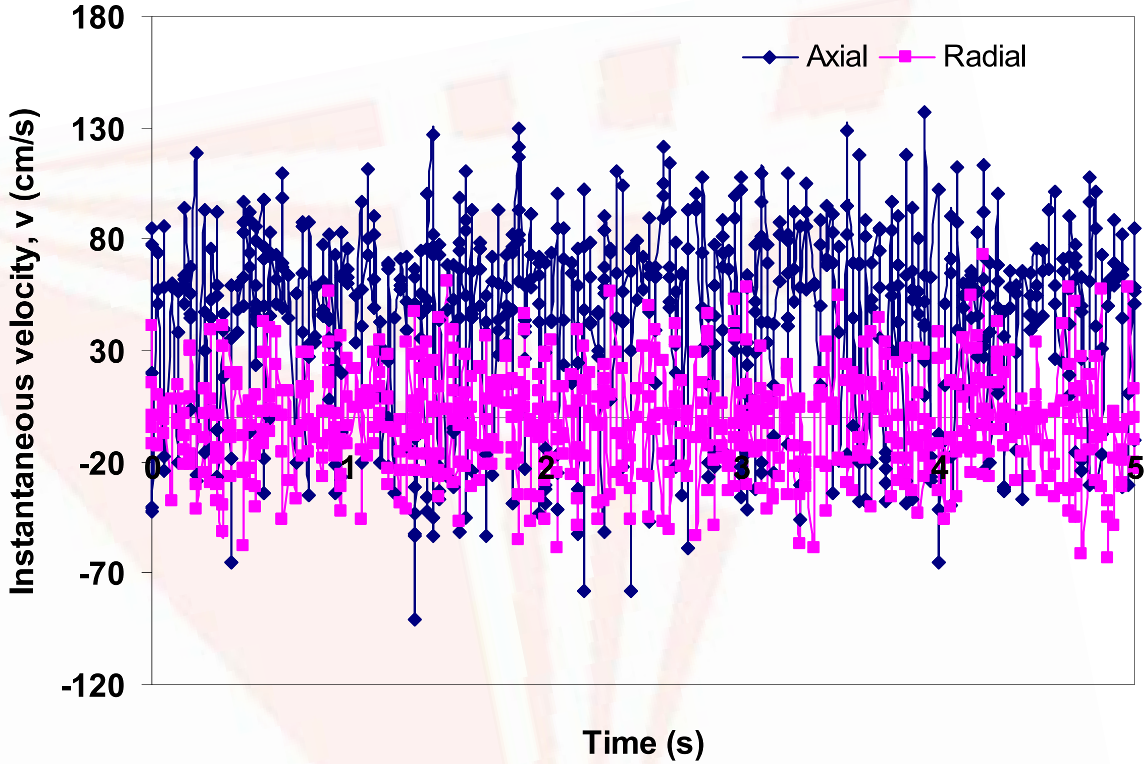




Particle image velocity measurement system with probe and typical streak images captured by the CCD camera. (Gidaspow et al. (2004))

Median particle size	1.093 mm
Particle density	2.985 g/cc

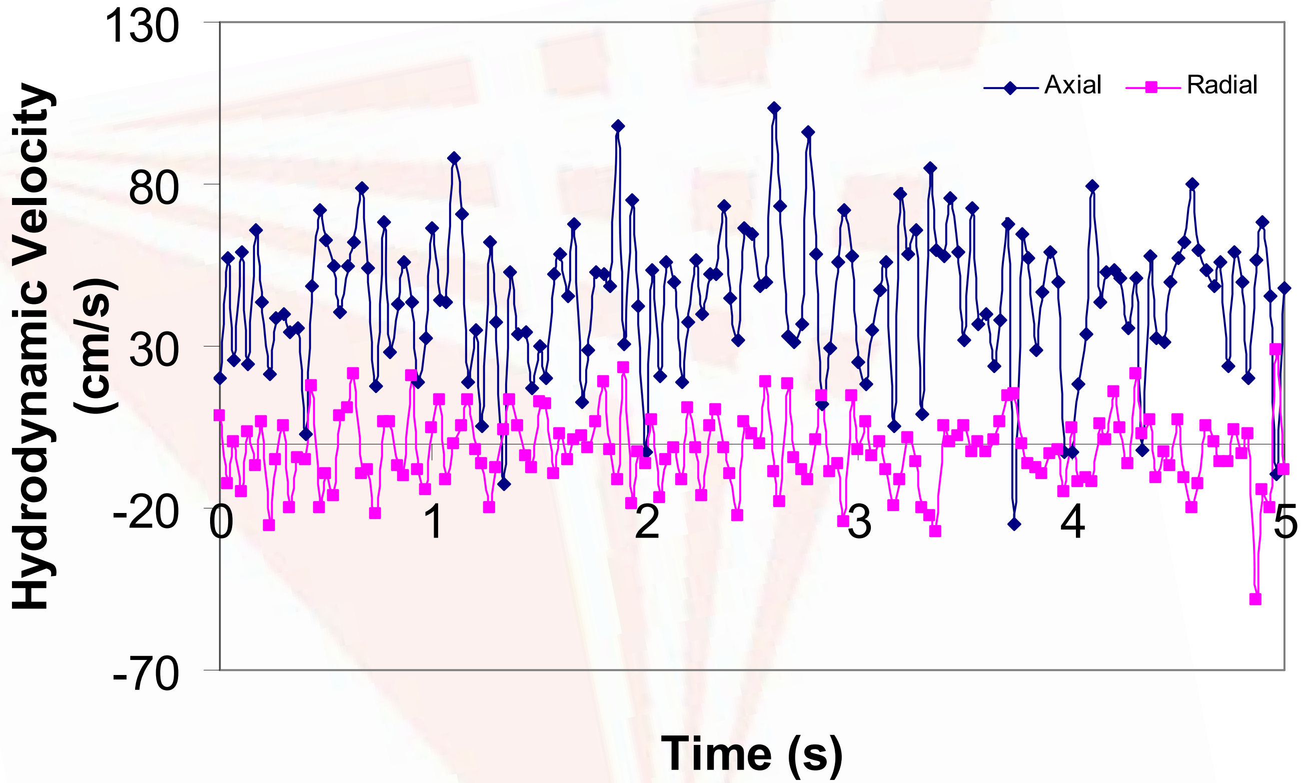
Instantaneous Velocities



Oscillation of instantaneous velocity in radial and axial directions obtained by CCD camera technique at a measuring height 4.5 m

($\overline{c_r} = -1.93 cm/s$, $\overline{c_a} = 43.9 cm/s$)

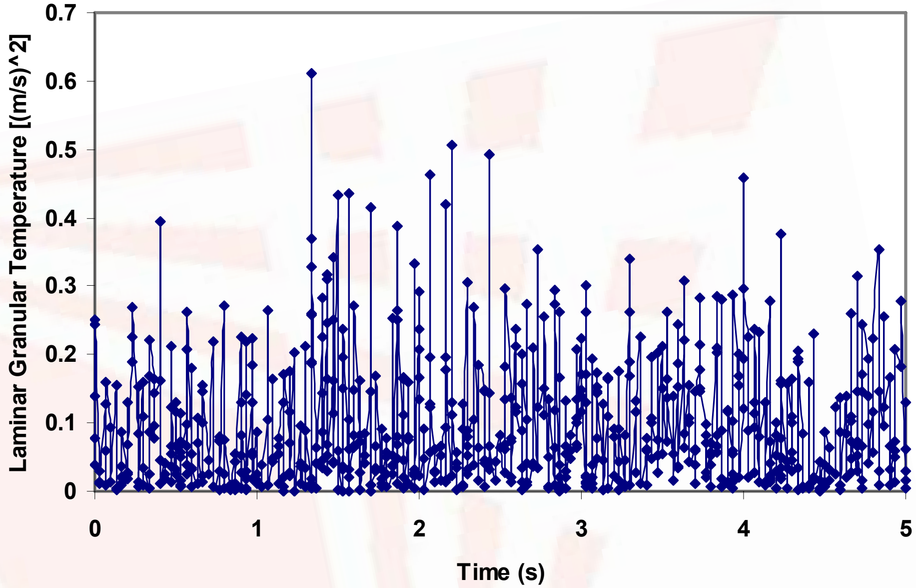
Hydrodynamic Velocities

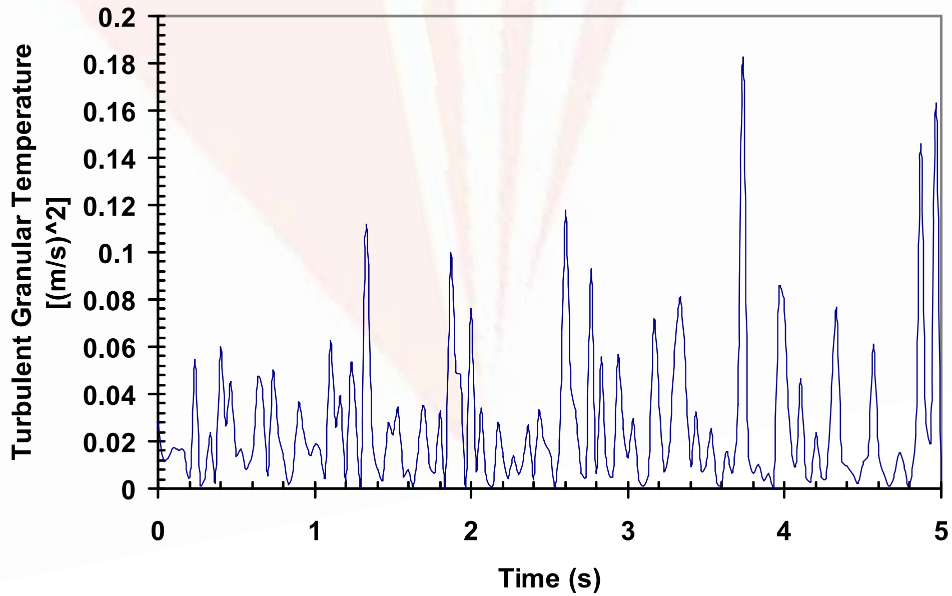


Oscillation of hydrodynamic velocity in radial and axial directions obtained by CCD camera technique at a measuring height 4.5 m

($\overline{V_r} = -2.38 cm/s$, $\overline{V_a} = 44.9 cm/s$)

Variation in Granular Temperature with Time





Measured laminar and turbulent granular temperatures

Granular Temperature, m^2/s^2			
System	Radial Position	Laminar due to individual particle oscillations	Turbulent due to cluster oscillations
2-D CFB, 75 μm FCC particles	Center	1.27×10^{-2}	6.73×10^{-3}
2-D CFB, 75 μm FCC particles	Right Wall	6.67×10^{-3}	2.54×10^{-3}
IIT Riser, 1093 μm	Wall	9.48×10^{-2}	2.61×10^{-2}

Mixing is on the level of particles

Dispersion Coefficients

Measured axial and radial solids dispersion coefficients

Dispersion Coefficient, m^2/s				
System	Radial Position	Type	Axial	Radial
2-D CFB, 75 μm FCC particles	Center	Laminar	3.21×10^{-4}	7.66×10^{-5}
2-D CFB, 75 μm FCC particles	Center	Turbulent	1.77×10^{-4}	3.78×10^{-5}
2-D CFB, 75 μm FCC particles	Right Wall	Laminar	2.64×10^{-4}	2.26×10^{-5}
2-D CFB, 75 μm FCC particles	Right Wall	Turbulent	1.09×10^{-4}	5.63×10^{-6}
IIT Riser, 1093 μm	Wall	Laminar	1.99×10^{-3}	8.64×10^{-4}
IIT Riser, 1093 μm	Wall	Turbulent	5.65×10^{-4}	2.26×10^{-4}

Mixing is on the level of particles

Gamma Ray Densitometer: Theory of Operation

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The Beer-Lambert law is the mathematical basis for the gamma ray densitometer technique to analyze the experimental data. This technique is in agreement with the concept that the reading of the transmitted gamma ray can be described as a linear function of the porosity of the system. According to Beer-Lambert law, the intensity of the transmitted radiation is given by:

$$I = I_0 e^{-k\rho l}$$

The solids volume fraction is calculated directly from a natural logarithm of intensity. From Seo & Gidaspow (1987), we get,

$$-\ln\left(\frac{I}{I_0}\right) = (A_s - A_g)\varepsilon_s + A_g = V$$

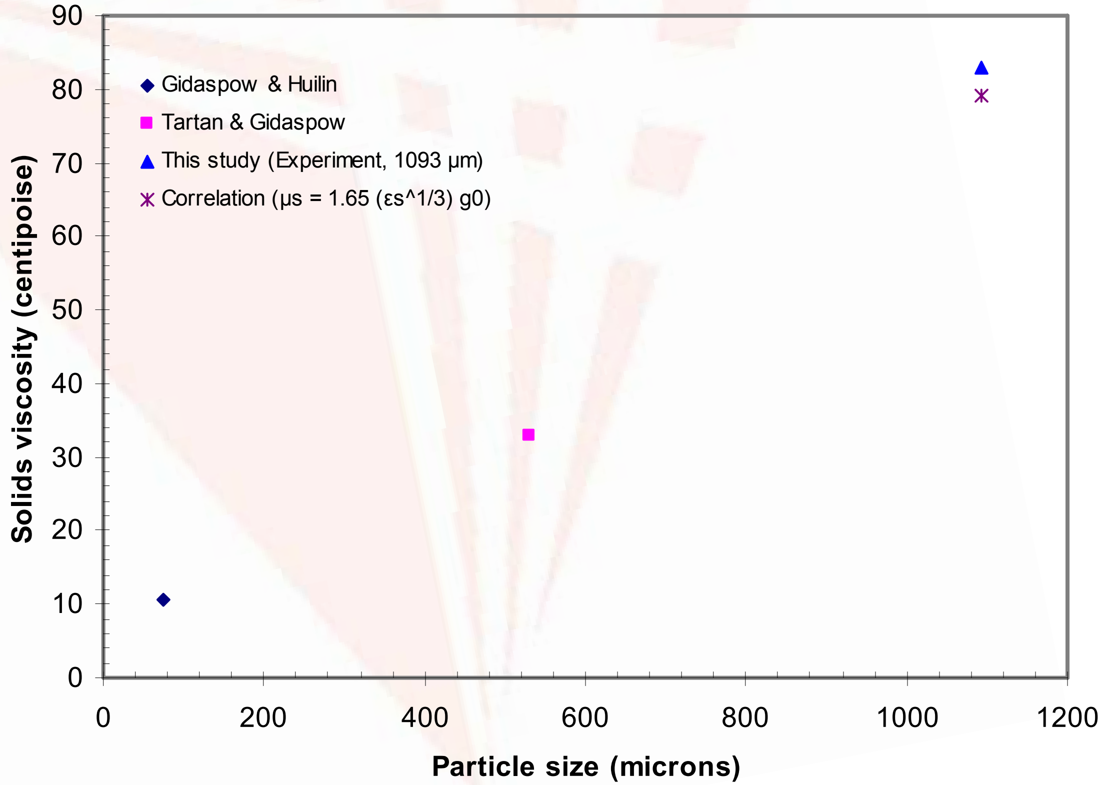
Voltage data were taken using National Instruments' data collection system. Data were taken at a height of 4.3 m in the IIT riser.

Effect of Particle Size on Solids Viscosity

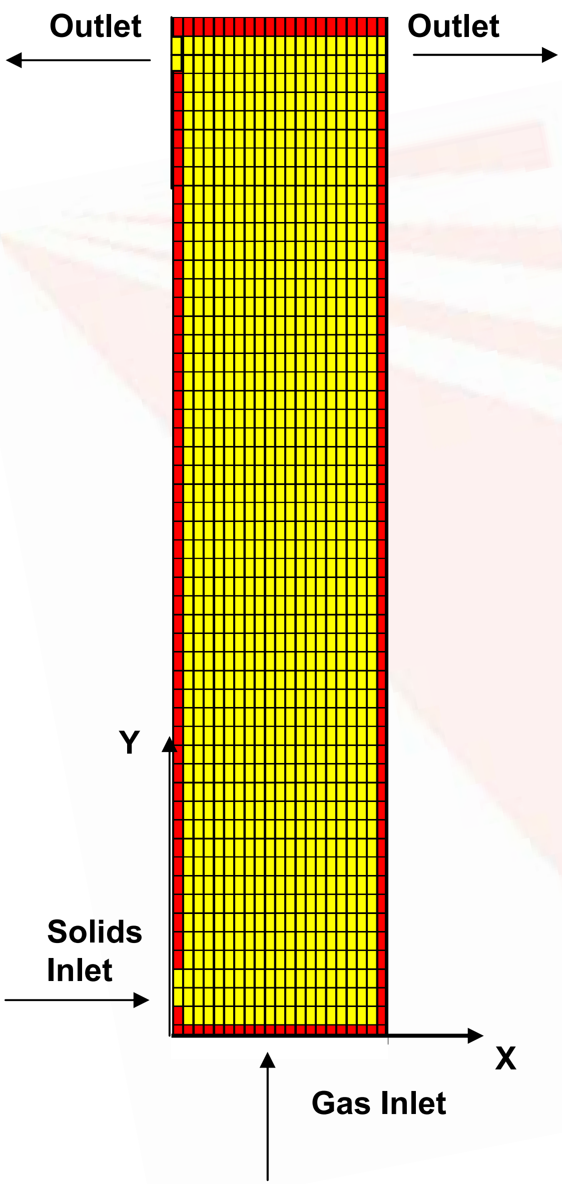
$$\mu_s = \frac{2\mu_{s_{dil}}}{(1+e)g_0}\left[1+\frac{4}{5}(1+e)g_o\varepsilon_s\right]^2 + \frac{4}{5}\varepsilon_s^2\rho_s d_s g_o(1+e)\sqrt{\frac{\theta}{\pi}}$$

$$g_o = \left[1-\left(\frac{\varepsilon_s}{\varepsilon_{s,\max}}\right)^{1/3}\right]^{-1}$$

$$\mu_{s_{dil}} = \frac{5\sqrt{\pi}}{96}\rho_p d_p \theta^{1/2}$$



Computational Simulation Domain for IIT Riser



Inlet conditions	
Solid mass flux, kg/m^2-s	**251**
Superficial gas velocity, m/s	**14**
Solids volume fraction	**0.65**
Outlet conditions	
Continuous outflow	
Boundary conditions	
Solid phase (Johnson and Jackson, 1987)	
Gas phase $v_{x,w}=v_{y,w}=0$	

Hydrodynamic Kinetic Theory Model

Continuity Equations

$$\frac{\partial(\rho_g \varepsilon_g)}{\partial t} + \nabla \cdot (\rho_g \varepsilon_g v_g) = 0$$

$$\frac{\partial(\rho_s \varepsilon_s)}{\partial t} + \nabla \cdot (\rho_s \varepsilon_s v_s) = 0$$

Momentum Equations

$$\frac{\partial(\rho_g \varepsilon_g v_g)}{\partial t} + \nabla \cdot (\rho_g \varepsilon_g v_g v_g) = -\nabla P + \nabla \cdot \overline{\overline{\tau}}_g - \beta_B (v_g - v_s) + \rho_g g$$

$$\frac{\partial(\rho_s \varepsilon_s v_s)}{\partial t} + \nabla \cdot (\rho_s \varepsilon_s v_s v_s) = -\nabla P_s + \nabla \cdot \overline{\overline{\tau}}_s + \beta_B (v_g - v_s) + \varepsilon_s (\rho_s - \rho_g) g$$

Fluctuating Energy Equation for Particles ($\theta = 1/3 \cdot \langle C^2 \rangle$)

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\varepsilon_s \rho_s \theta) + \nabla \cdot (\varepsilon_s \rho_s v_s \theta)\right] = \left(-\nabla P_s \overline{\overline{I}} + \overline{\overline{\tau}}_s\right) : \nabla v_s + \nabla \cdot (\kappa_s \nabla \theta) - \gamma_s$$

Constitutive Equations

1) Definitions

$$\varepsilon_g + \varepsilon_s = 1$$

2) Gas Pressure

$$P_g = \rho_g \tilde{R} T_g$$

3) Stress Tensor (*i* = gas or solid)

$$\overline{\overline{\tau}}_i = 2\mu_i \overline{\overline{D}}_i + \left(\lambda_i - \frac{2}{3}\mu_i\right) tr(\overline{\overline{D}}_i)\overline{\overline{I}}$$

with $\overline{\overline{D}}_i = \frac{1}{2}\left[\nabla v_i + (\nabla v_i)^T\right]$

$$P_s = \rho_s \varepsilon_s \theta \left[1 + 2(1+e) g_o \varepsilon_s\right]$$

$$\mu_s = \frac{2\mu_{s_{dil}}}{(1+e) g_0}\left[1 + \frac{4}{5}(1+e) g_o \varepsilon_s\right]^2 + \frac{4}{5}\varepsilon_s^2 \rho_s d_s g_o (1+e)\sqrt{\frac{\theta}{\pi}}$$

$$\lambda_s = \frac{4}{3}\varepsilon_s^2 \rho_s d_s g_o (1+e)\sqrt{\frac{\theta}{\pi}}$$

where, g_o is the radial distribution function and μ_{sdil} is the particle phase dilute viscosity.

$$g_o = \left[1 - \left(\frac{\varepsilon_s}{\varepsilon_{s,\max}}\right)^{1/3}\right]^{-1}$$

Hydrodynamic Kinetic Theory Model (Continued)

$$\mu_{s_{dil}} = \frac{5\sqrt{\pi}}{96}\rho_p d_p \theta^{1/2}$$

1) Granular Conductivity of Fluctuating Energy

$$\kappa = \frac{2}{(1+e)g_0}\left[1 + \frac{6}{5}(1+e)g_o\varepsilon_s\right]^2 \kappa_{dil} + 2\varepsilon_s^2 \rho_s d_s g_o (1+e)\sqrt{\frac{\theta}{\pi}}$$

where, $\kappa_{dil} = \frac{75\sqrt{\pi}}{384}\rho_s d_s \theta^{1/2}$

2) Collisional Energy Dissipation

$$\gamma_s = 3(1-e^2)\varepsilon_s^2 \rho_s g_o \theta\left(\frac{4}{d_s}\sqrt{\frac{\theta}{\pi}} - \nabla \cdot v_s\right)$$

3) Gas–Solid Drag Coefficient

$$\beta_B = 150\frac{\varepsilon_s^2 \mu_g}{\varepsilon_g^2 d_p^2} + 1.75\frac{\rho_g \varepsilon_s |v_g - v_s|}{\varepsilon_g d_p} \qquad \varepsilon_g < 0.8$$

$$\beta = \frac{3}{4}C_d \frac{\rho_g \varepsilon_s |\upsilon_g - \upsilon_s|}{d_p}\varepsilon_g^{-2.65} \qquad \varepsilon_g \geq 0.8$$

where,

$$C_d = \frac{24}{\mathrm{Re}_p}\left[1 + 0.15\,\mathrm{Re}_p^{0.697}\right] \quad \text{for} \quad \mathrm{Re}_p < 1000$$

$$C_d = 0.44 \quad \text{for} \quad \mathrm{Re}_p \geq 1000$$

$$\mathrm{Re}_p = \frac{\varepsilon_g \rho_g d_p |v_g - v_s|}{\mu_g}$$

Boundary Conditions for Particle Phase (Johnson and Jackson, 1987)

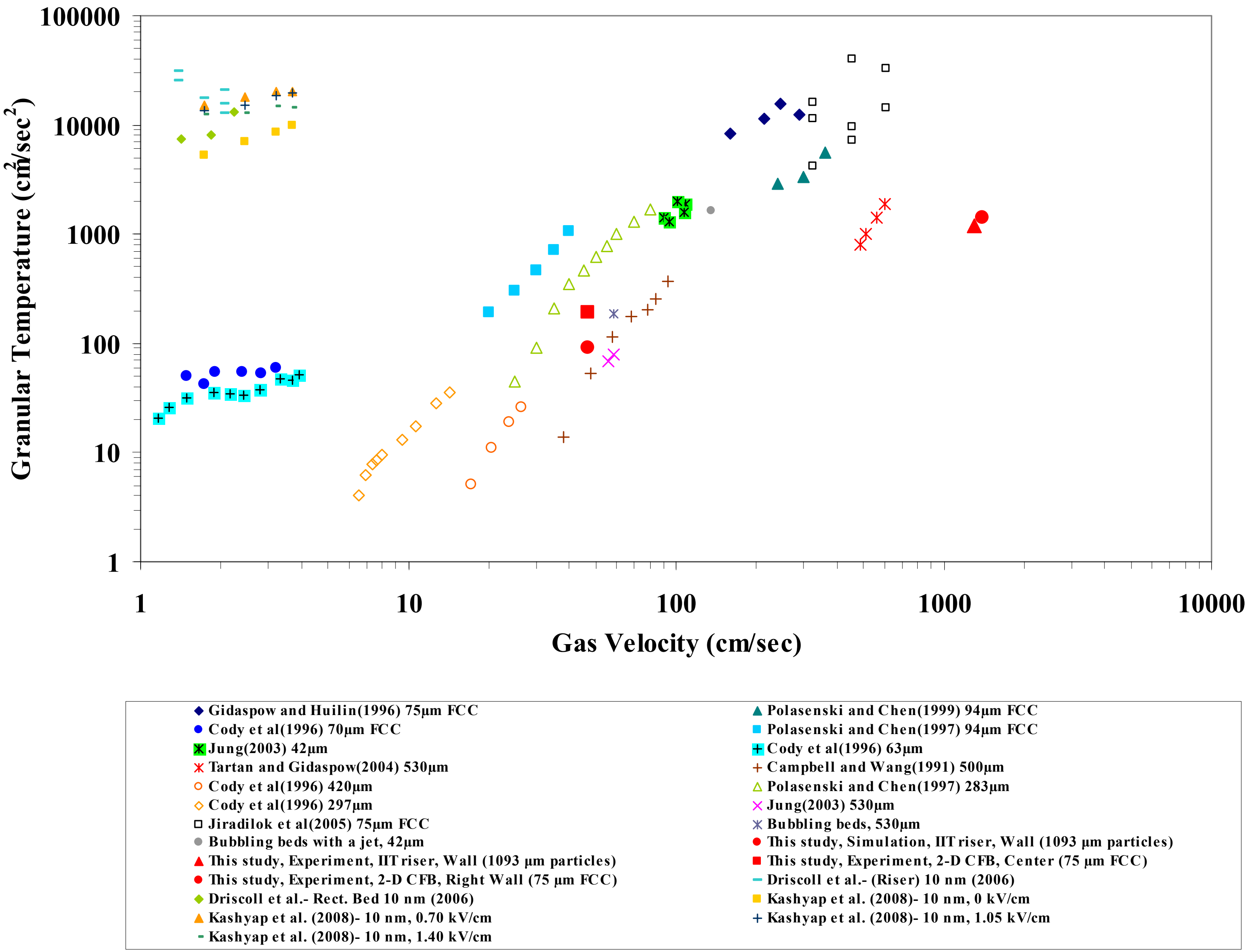
1) Velocity

$$\vec{u}_{s,w} = -\frac{6\mu_s \varepsilon_{s,\max}}{\sqrt{3}\pi\phi\rho_s \varepsilon_s g_0 \sqrt{\theta}}\frac{\partial \vec{v}_{s,w}}{\partial n}$$

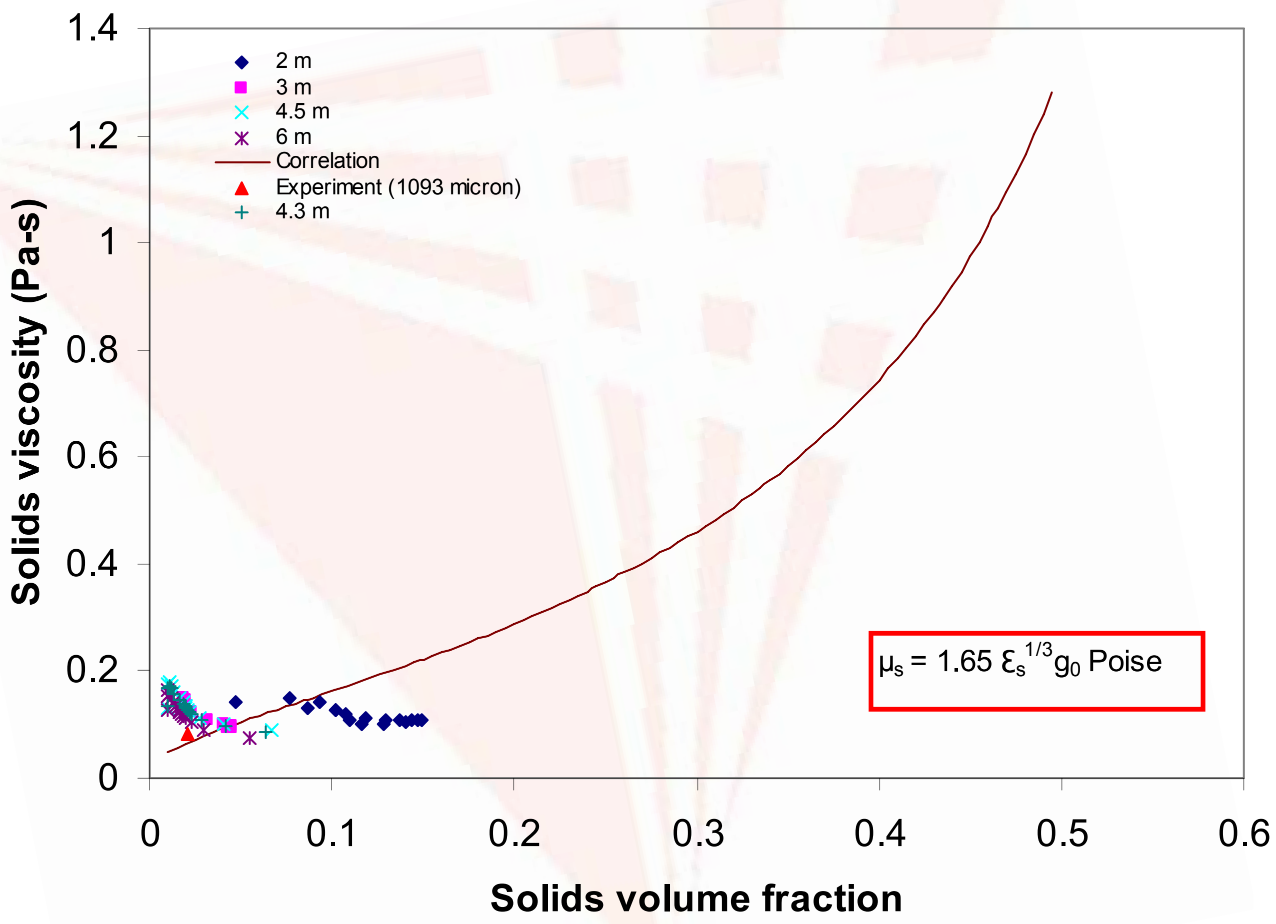
2) Granular Temperature

$$\theta_w = -\frac{\kappa\theta}{\gamma_w}\frac{\partial\theta}{\partial n} + \frac{\sqrt{3}\pi\phi\rho_s \varepsilon_s \vec{v}_{s,slip}^{\,2} g_0 \theta^{3/2}}{6\varepsilon_{s,\max}\gamma_w} \qquad \text{where} \qquad \gamma_w = \frac{\sqrt{3}\pi(1-e_w^2)\varepsilon_s \rho_s g_0 \theta^{3/2}}{4\varepsilon_{s,\max}}$$

Comparison of Granular Temperatures



Solids Viscosity as a Function of Solids Volume Fraction



Comparison of Axial Solids Dispersion Coefficients

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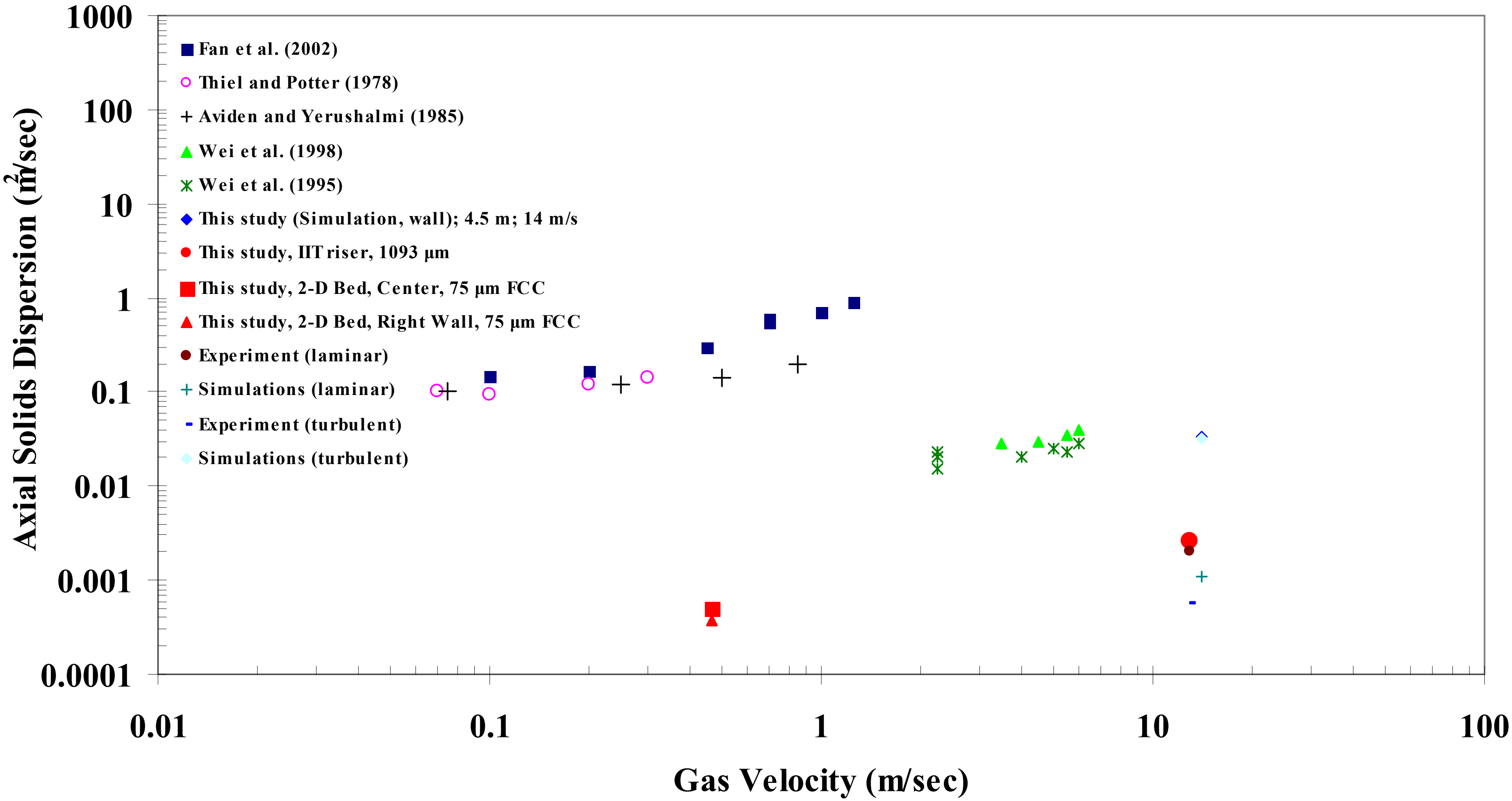
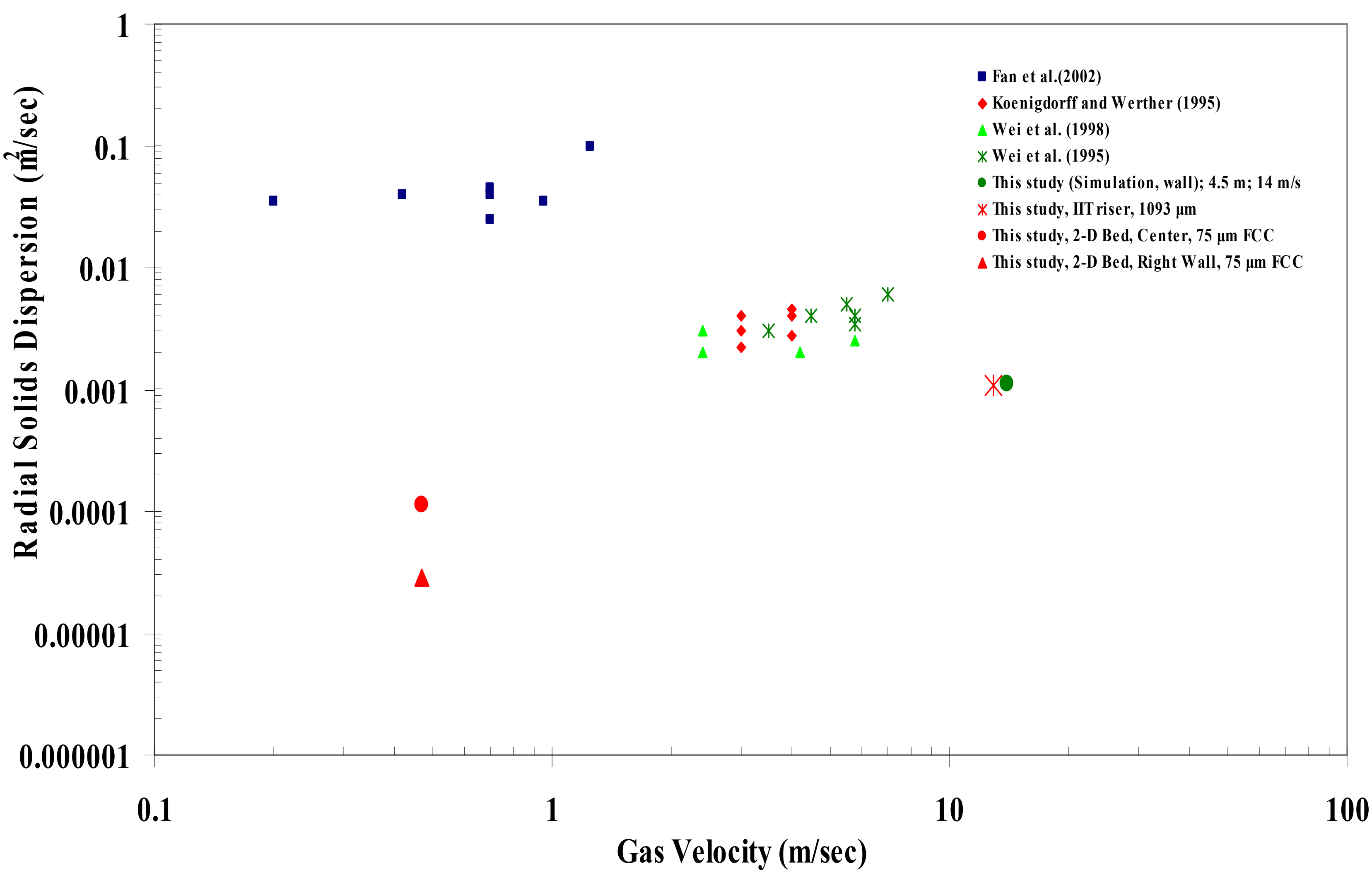
$$D_L(a) = \overline{v'(a)^2} T_L$$



Comparison of Radial Solids Dispersion Coefficients



PART IV

COMPUTATION OF CLUSTERS AND MASS TRANSFER COEFFICIENTS IN THE PSRI RISER

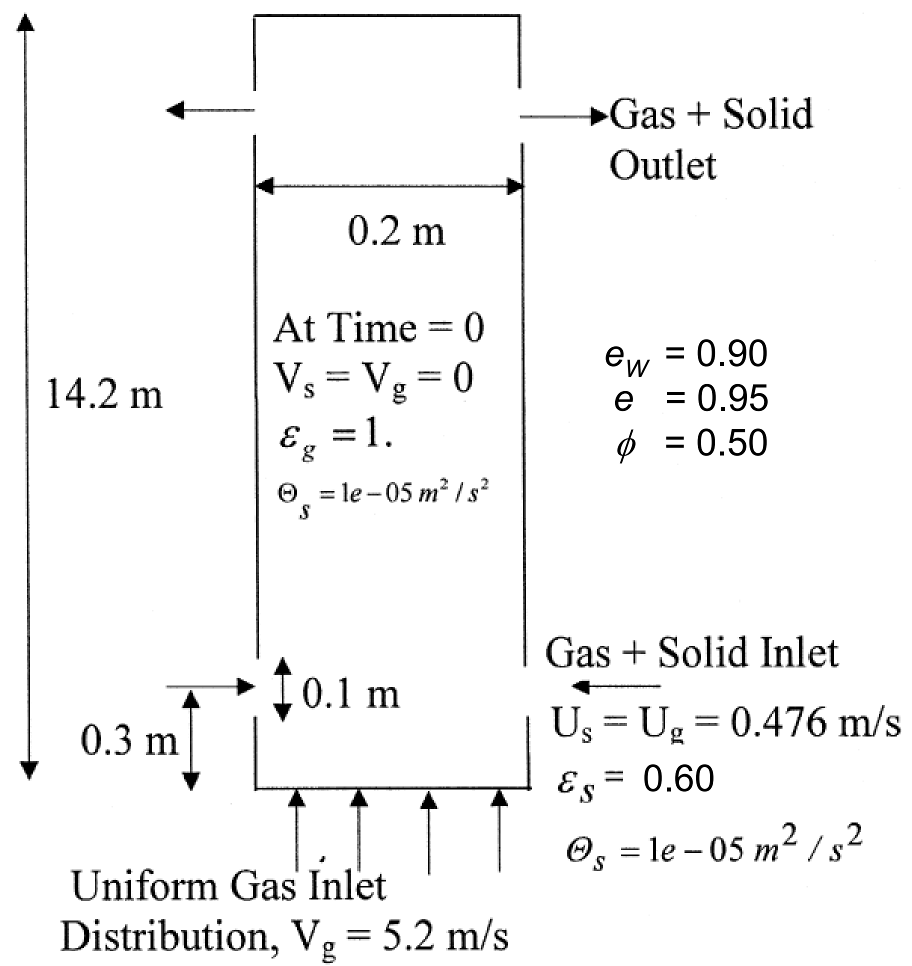
Model descriptions:

Models >

- **2D**
- **Unsteady state**
- **Eulerian (Euler-Euler)**

Materials >

- **Air**
  - **Density 1.2 kg/m^3**
  - **Viscosity 2.0×10^{-05} m2/s**
- **FCC**
  - **Density 1,712 kg/m^3**
  - **Diameter 76 μm**



Schematic drawing of a simplified riser used in this study (Benyahia et al. (2000))

System Geometry

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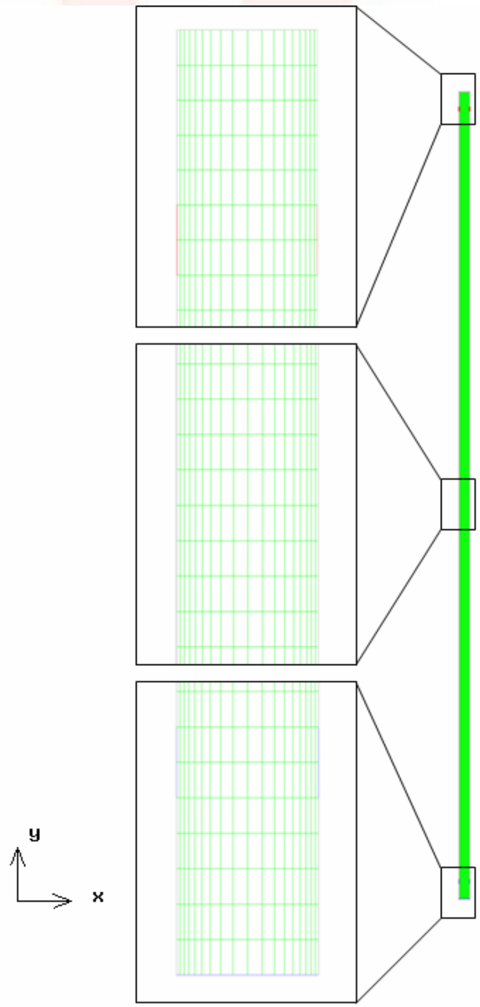
Model descriptions:

Solution procedures >

- GAMBIT
- FLUENT 6.2.16
- Computational domain
  - 19 non-uniform grids radially
  - 285 uniform grids axially
- Real time 40 seconds



FLUENT®
The Right Answer in CFD

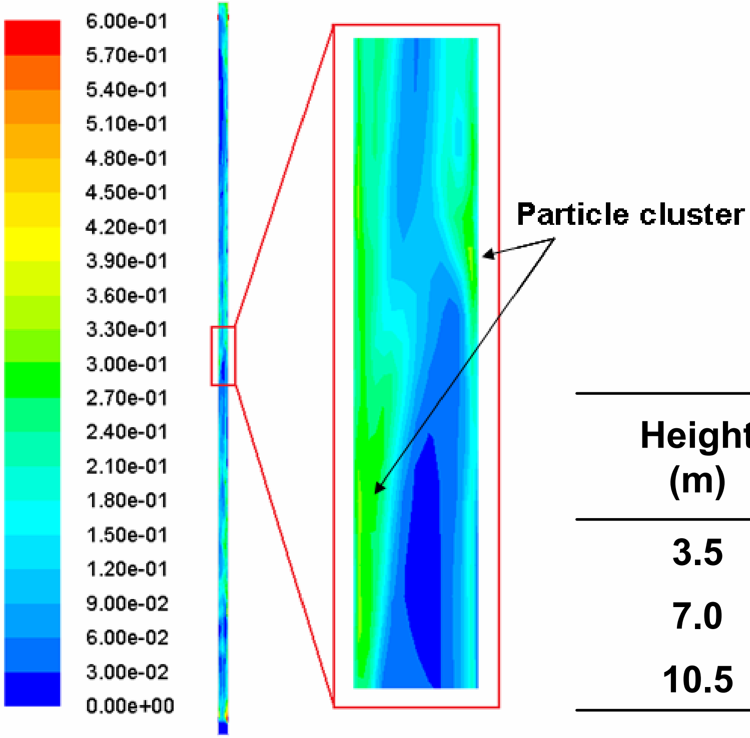
Computational domain of a simplified riser used in this study

Results and discussion:

Particle cluster diameter

$$Cluster\ diameter = Characteristic\ length = \frac{D_x(r)}{Oscillating\ velocity}$$

$$Oscillating\ velocity = \sqrt{\overline{v'_x v'_x(r)}}$$



Height (m)	Oscillating velocity (m/s)	Particle cluster diameter (m)
3.5	0.224	0.0101
7.0	0.259	0.0095
10.5	0.243	0.0087

The computed information on particle cluster diameter at three different heights of the riser

Granular Temperature and Dispersion Coefficient

A comparison of computed laminar, turbulent and total granular temperatures and turbulent kinetic energy at three different heights

Height (m)	Granular temperature (m^2/s^2)			Turbulent kinetic energy (m^2/s^2)
	Larminar	Turbulent	Total	
3.5	0.016	1.841	1.857	2.785
7.0	0.028	2.273	2.300	3.450
10.5	0.027	2.010	2.036	3.055

A comparison of computed axial and radial dispersion coefficients at three different heights

Height (m)	Solid dispersion coefficients (m^2/s)		Gas dispersion coefficients (m^2/s)	
	Axial	Radial	Axial	Radial
3.5	1.959	0.002	3.959	0.017
7.0	3.644	0.003	3.983	0.018
10.5	2.118	0.002	2.856	0.020

Results and discussion:

Computation from chemical reaction

Ozone decomposition reaction →

$$2O_{3(g)} \rightarrow 3O_{2(g)}$$

Sh → concept of additive resistances

Integration of the conservation of ozone species equation over time and over the riser radius gives the one dimensional steady state balance →

$$v_y \frac{dC_{O_3}}{dY} = -KC_{O_3}\varepsilon_s$$

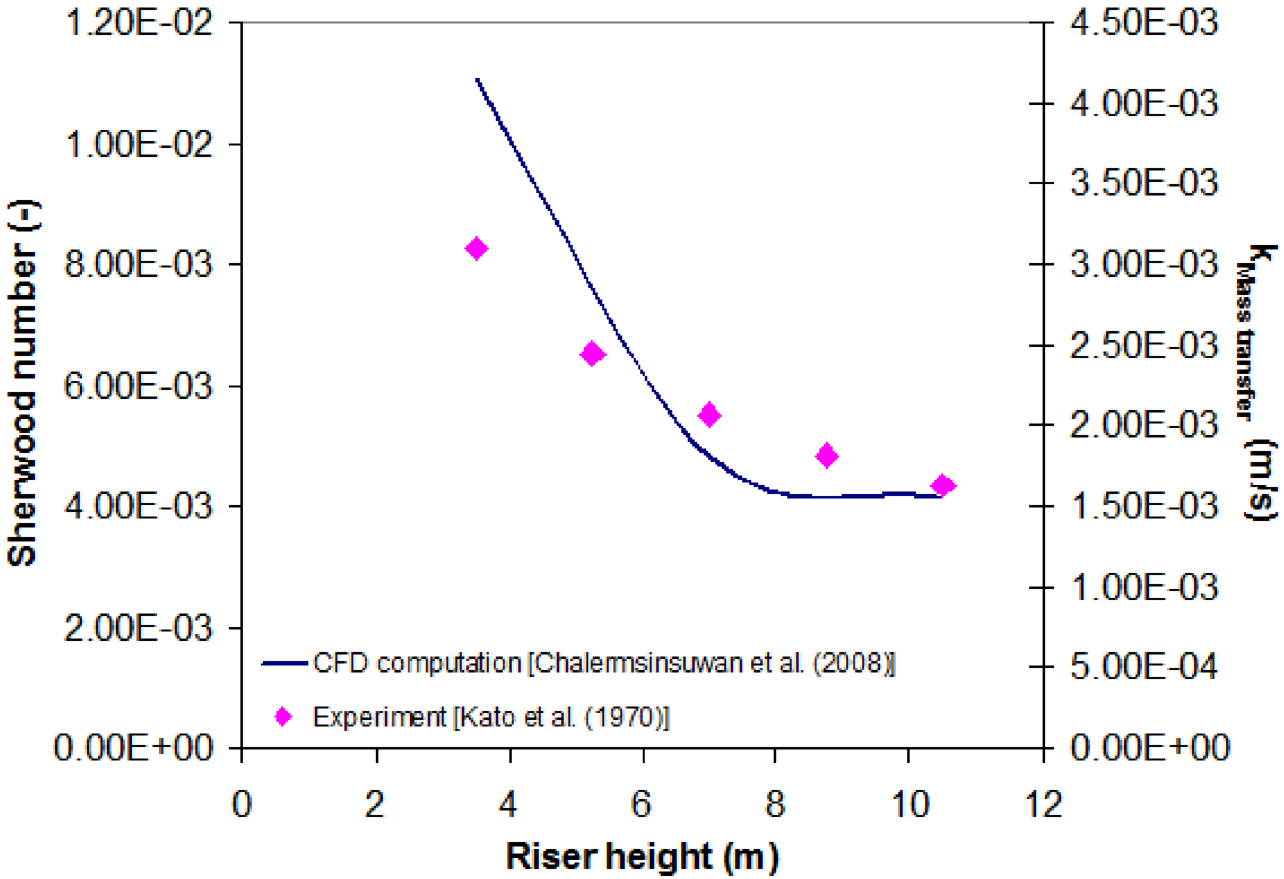
$$\ln C_{O_3} = \ln C_{O_3,0} - \frac{K\varepsilon_s}{v_y} Y$$

$$\frac{1}{K} = \frac{1}{k_{mass\ transfer}} + \frac{1}{k_{reaction}}$$

Sherwood number, $$Sh = \frac{k_{mass\ transfer}\, d_p}{D}$$

Computation of Mass Transfer Coefficients

- **Example: Simulation of PSRI riser with $k_{reaction}$ = 39.6 s^{-1}**



Low mass transfer coefficients in PSRI riser with $k_{reaction}$ = 39.6 s^{-1}

Conclusions

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- We developed a technique for the measurement and CFD computation of axial and radial dispersion coefficients.
- We explained the low mass transfer coefficients in fluidized beds by performing CFD simulations.
- Time averaged particle velocity profiles for 1093 μm particles in the IIT riser and 75 μm FCC particles in the 2 dimensional circulating fluidized bed (CFB), describing movement of particles in axial and radial directions, were obtained successfully.
- Laminar axial and radial Reynolds stresses were measured in the IIT riser and the 2 dimensional CFB using instantaneous particle velocities. Turbulent Reynolds stresses were obtained by time-averaging hydrodynamic velocities. Laminar and turbulent granular temperatures were measured using Reynolds stresses. Laminar granular temperatures were higher than the turbulent granular temperatures for both the 1093 μm particles and 75 μm FCC particles. Hence, mixing is mostly on the level of particles, not clusters. The granular temperatures for both the particles are in reasonable agreement with the values from the literature.

Conclusions

- Laminar and turbulent solids dispersion coefficients for 1093 µm particles and 75 µm FCC particles, in axial and radial directions were obtained using the auto-correlation method.
- A Beer-Lambert law based gamma ray densitometer technique was successfully used to measure the solids volume fractions of 1093 µm particles in the riser. Combined with the particle velocity distribution data, the solids volume fraction data were further used to calculate the kinetic theory based solids viscosity.
- The standard kinetic theory model described in Gidaspow's 1994 book, Multiphase Flow and Fluidization, Academic Press and available in M-FIX and commercial codes e.g. FLUENT, with Johnson and Jackson boundary conditions, was used to model circulation of 1093 µm particles in the IIT riser. The standard drag correlation was used, without modification.
- Sherwood numbers of the order of 10^{-3} were obtained for a circulating fluidized bed, using the kinetic theory CFD code.

Conclusions (Continued)

- A Beer-Lambert law based gamma ray densitometer technique was successfully used to measure the solids volume fractions of 1093 μm particles in the riser. Combined with the particle velocity distribution data, the solids volume fraction data were further used to calculate the kinetic theory based solids viscosity. As expected from the formula, the solids viscosity increased with the increase in particle size. The particle viscosities obtained from kinetic theory measurements at a solids volume fraction of 2% are 10.5, 33 and 83 centipoises for 75 μm FCC, 530 μm glass beads and 1093 μm particles, respectively.
- The standard kinetic theory model described in Gidaspow's 1994 book, Multiphase Flow and Fluidization, Academic Press and available in M-FIX and commercial codes e.g. FLUENT, with Johnson and Jackson boundary conditions, was used to model circulation of 1093 μm particles in the IIT riser. The standard drag correlation was used, without modification.
- Sherwood numbers of the order of 10^{-3} were obtained for a circulating fluidized bed, using the kinetic theory CFD code.

Thank You!