Fundamentals Fluidization II

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Motivation

"Granular materials are ubiquitous in nature and are the second-most manipulated material in industry (the first one is water)…"

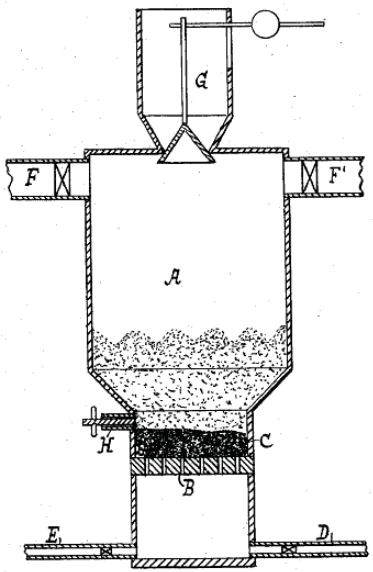
- Richard et al, *Nature*, 2005

"…the virtues of the fluidized-bed reactor drove its competitors from the market."

- Fogler, *Elements of Chemical Reaction Engineering*, 1998

OUTLINE

- Fluidization Phenomena
- Characterizing Granular Materials
- Fluidization Behavior of Different Type Particles
- Hysteresis during Incipient Fluidization
  - *Bubbling*
  - *Channeling*
  - *Solids Handling - Dense phase transport*
- *Diagnostics and Control*



*Richard, P et al (2005) Nature, Slow Relaxation and compaction of granular systems, **4 (Feb)**, 121-128*

What is Fluidization

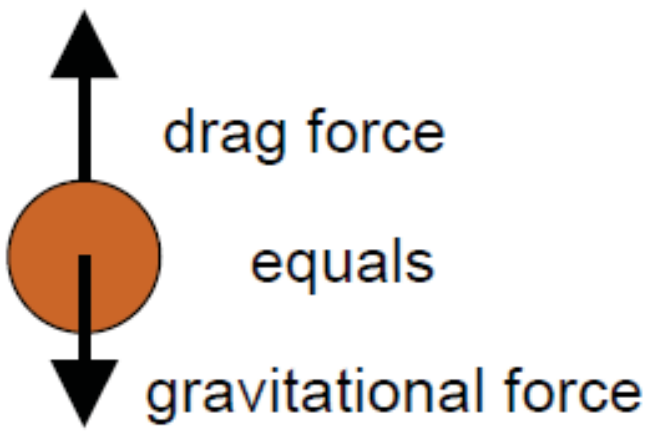
- Fluidization is defined as the operation through which fine solids are transformed into a fluid like state through contact with a gas or liquid.

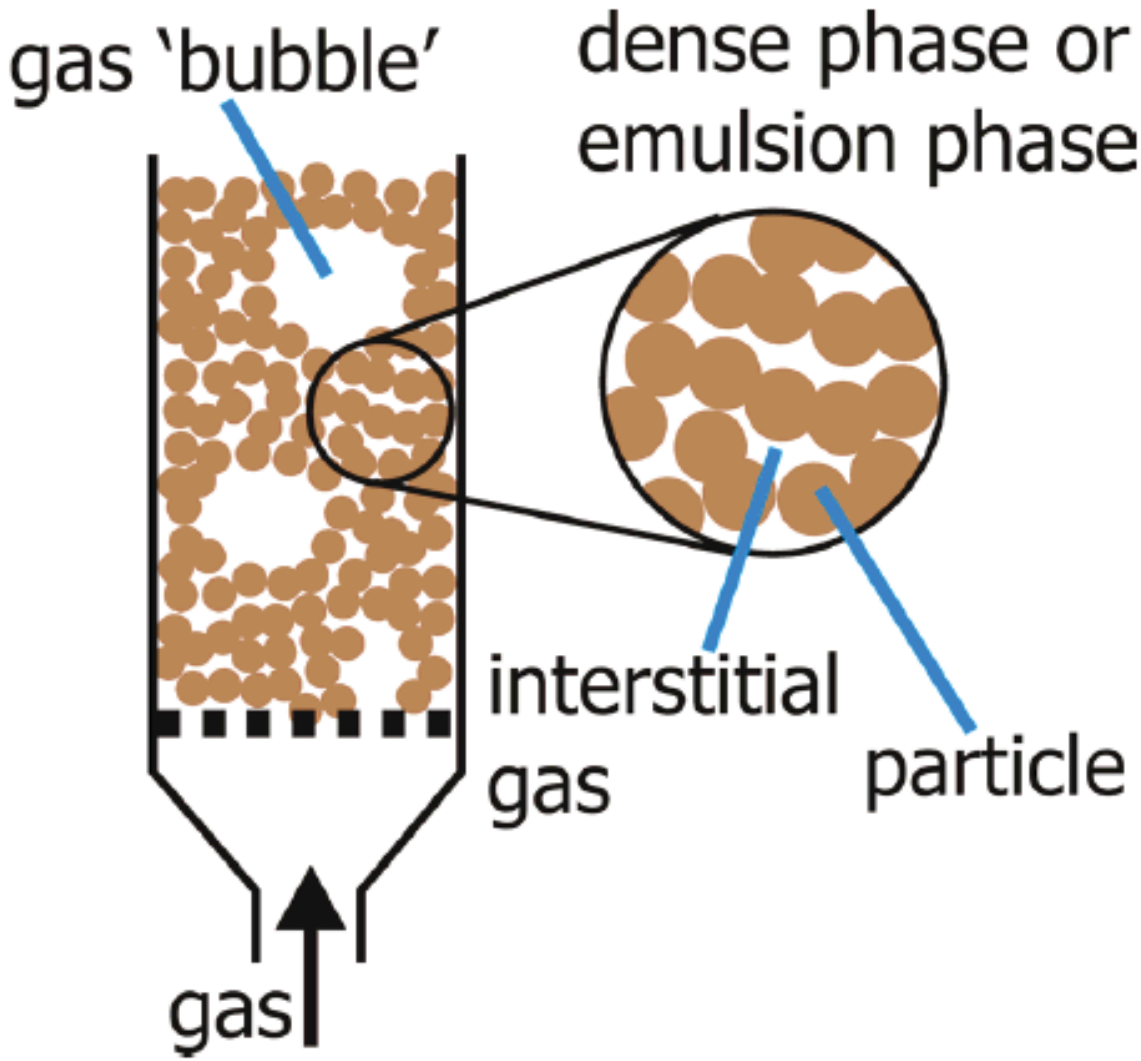
- In fluidization, a gas or liquid is passed through a bed of solid particles which is supported on a perforated or porous plate. In the case of fluidized bed coating, air is passed through a bed of polymer particles.

- When the frictional force acting on the particles, or the pressure drop, of the flowing air through the bed equals or exceeds the weight of the bed, the powder particles become suspended and the bed exhibits liquid-like behavior.

Fluidization Schematics

Fluidized bed: particles suspended in an upward gas stream





Comparison of Principal Gas Solid Contacting Processes

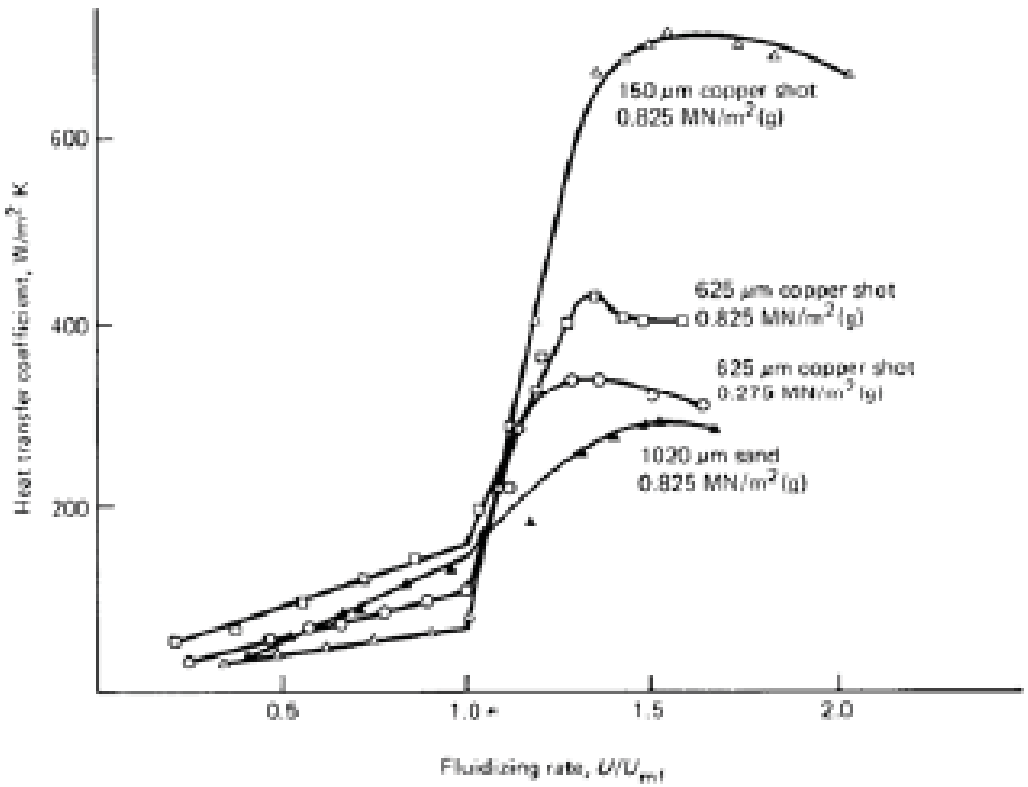
Property	Packed Bed	Fluidized Bed	Fast Bed	Pneumatic Transport
Application in boilers	Stoker fired	Bubbling fluidized	Circulating fluidized	Pulverized coal fired
Mean particle diameter (mm)	<300	0.03–3	0. 05–0.5	0.02–0.08
Gas velocity through combustor zone (m/sec)	1–3	0.5–2.5	4–6	15–30
Typical U/U_t	0.01	0.3	2	40
Gas motion	Up	Up	Up	Up
Gas mixing	Near plug flow	Complex two phases	Dispersed plug flow	Near plug flow
Solids motion	Static	Up and down	Mostly up, some down	Up
Solid–solid mixing	Negligible	Usually near perfect	Near perfect	small
Overall voidage	0.4–0.5	0.5–0.85	0.85–0.99	0.98–0.998
Temperature gradient	Large	Very small	Small	Maybe significant
Typical bed-to-surface. Heat transfer coefficient, (W/m^2 K)	50–150	200–550	100–200	50–100

Advantages of Fluidized Beds

- Liquid like behavior, easy to control and automate,
- Rapid mixing, uniform temperature and concentrations,.
- Resists rapid temperature changes, hence responds slowly to changes in operating conditions and avoids temperature runaway with exothermic reactions.
- Circulate solids between fluidized beds for heat exchange.
- Applicable for large or small scale operations.
- Heat and mass transfer rates are high, requiring smaller surfaces.

Heat Transfer in a Fluidized Bed

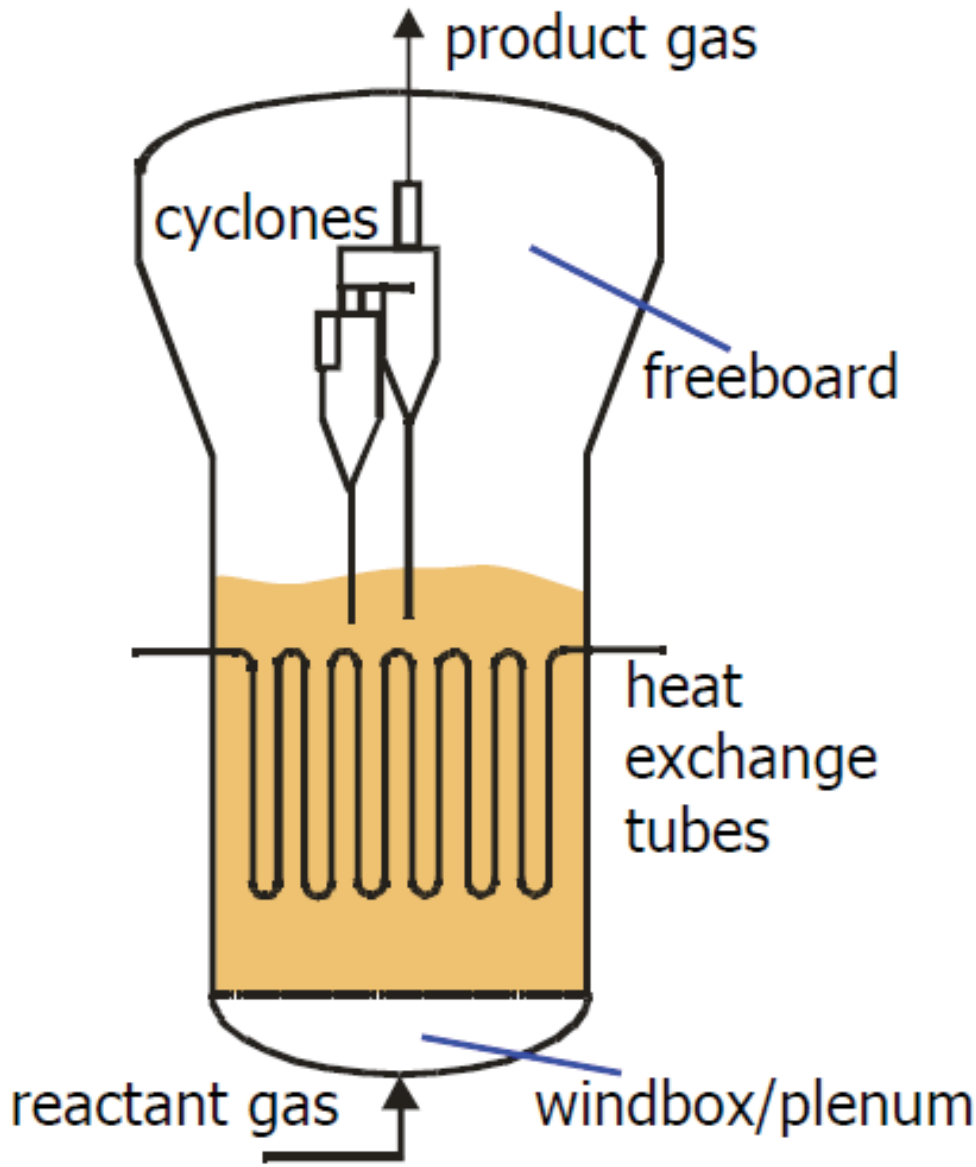
- One of the great advantages of a fluidized bed is the high heat and mass transfer rates that are generated compared to that in a gas only or packed bed.
- In the figure it is demonstrated that the rate of heat transfer can be increased at least 12 times higher than that of a packed bed.
- This is a great advantage for chemical processing as well as heating of fluids.



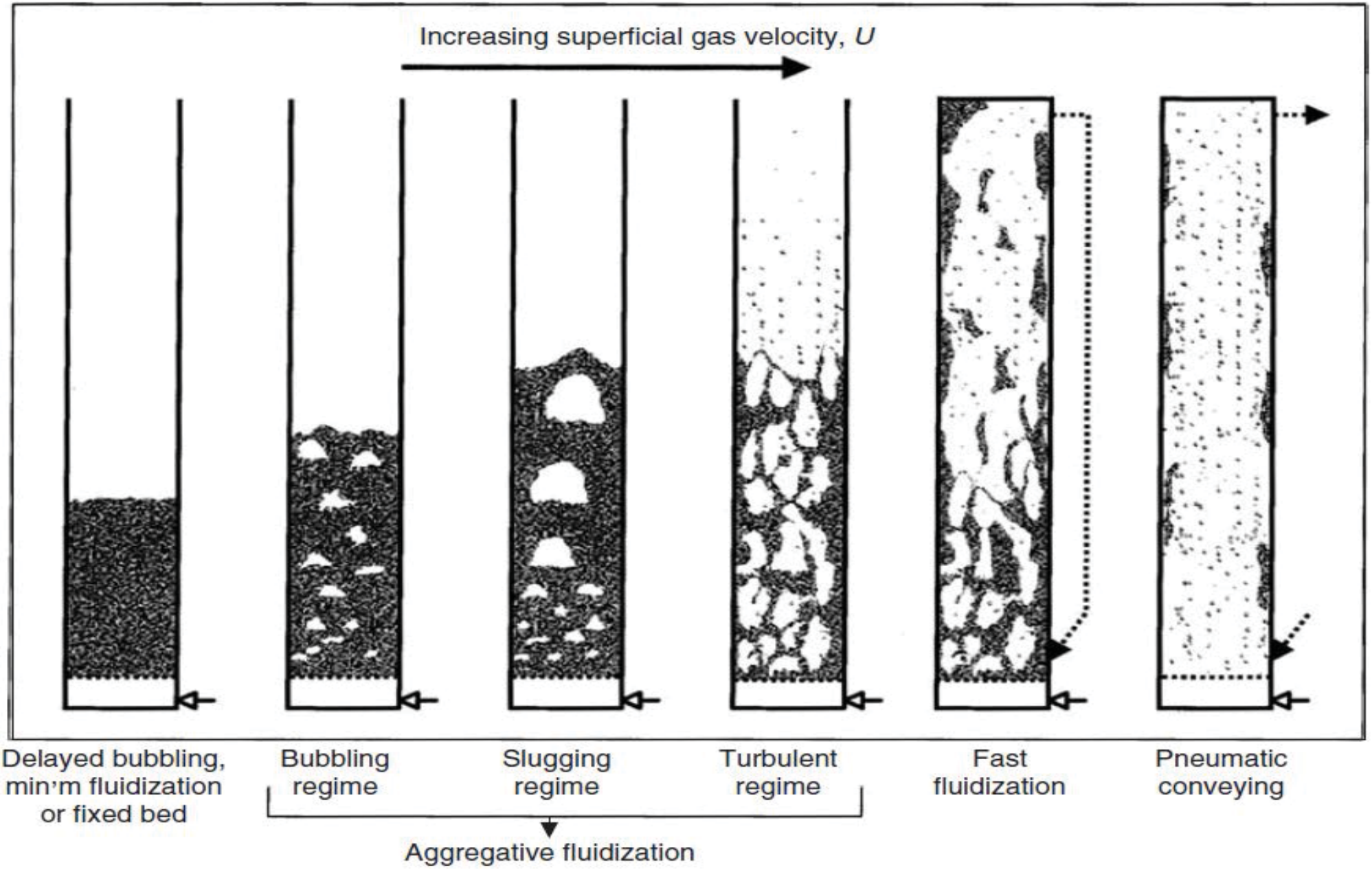
Disadvantages of Fluidized Beds

- **Bubbling beds of fine particles are difficult to predict and are less efficient.**
- **Rapid mixing of solids causes non-uniform residence times for continuous flow reactors.**
- **Particle comminution (breakup) is common.**
- **Pipe and vessel walls erode due to collisions by particles.**

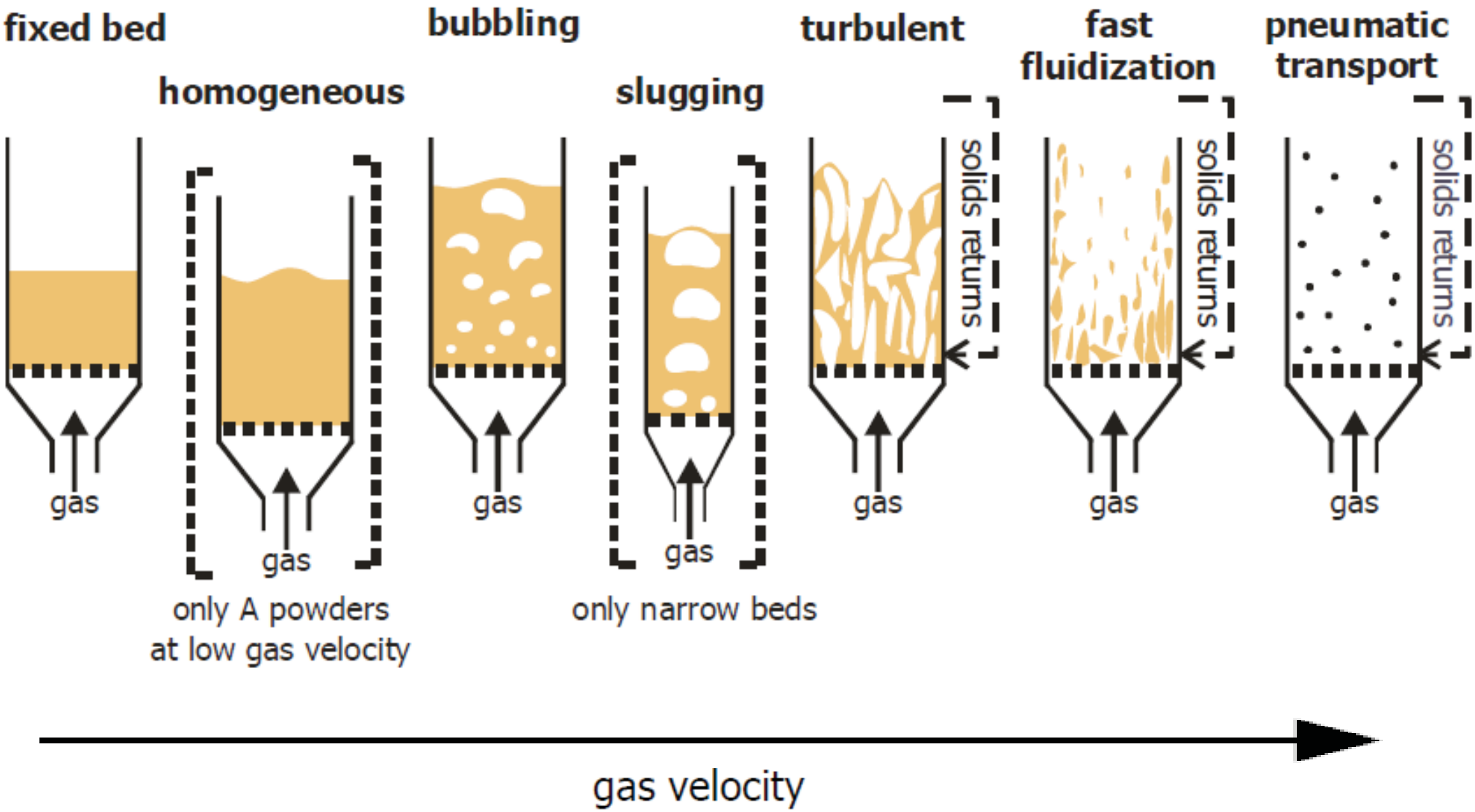
Design of a Fluidized Bed



Regimes of Fluidization Option 2



Regimes of Fluidization



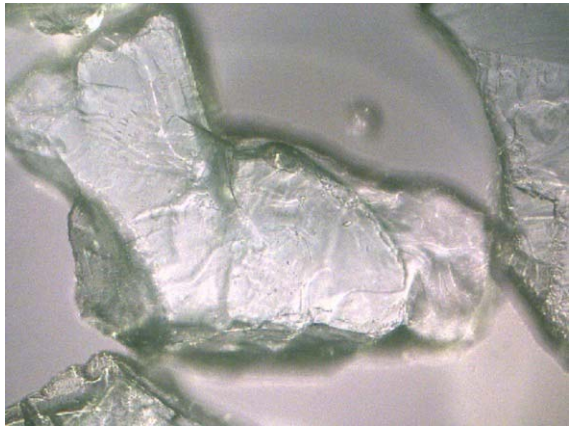
Particle Classification – Physical Properties

- The materials participating in the processes in FBC boilers (sand, coal, limestone, ash) belong to a class of materials called loose (particulate) solids.
- **Bulk density of particulate solids is the mass of particles per unit of bed volume.**
- **The void fraction of a fixed or fluidized bed is expressed as the ratio between the total volume of void space between the particles and the volume of the bed.**
- **Void fraction of a fixed, stagnant bed of loose material depends on the size and shape of the particles, and also their size distribution, state of particle surface and mode of packing.**
- **Rough classification of particulate solids may be accomplished according to their bulk density:**
  - light materials $\rho_b < 600\ kg/m^3$
  - medium heavy materials $600\ kg/m^3 < \rho_b < 2000\ kg/m^3$, *and*
  - heavy materials $\rho_b > 2000\ kg/m^3$

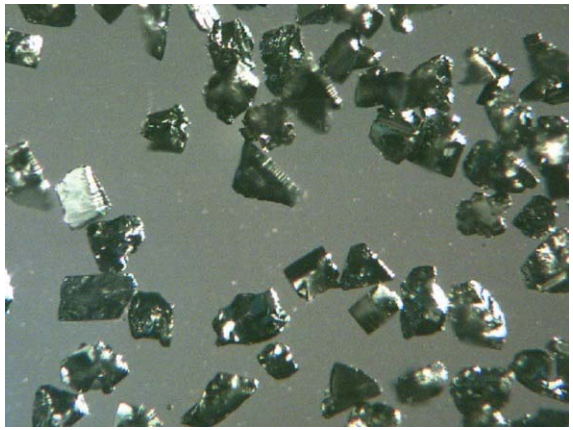
Characterization of Granular Material

- **Free Flowing Granular Powders**
- **Size Ranges: 10 – 6800 Micron**
- **Density: 0.1 – 16 g/cm^3**
- **Sample Required: 500 cm^3**

  (15 cm^3 Archival Sample)
- **Non-Destructive Testing**



Aerogel (1-2 mm)



Tungsten Carbide (100 Micron)

<u>Properties Evaluated in METL's Materials Data Base</u>

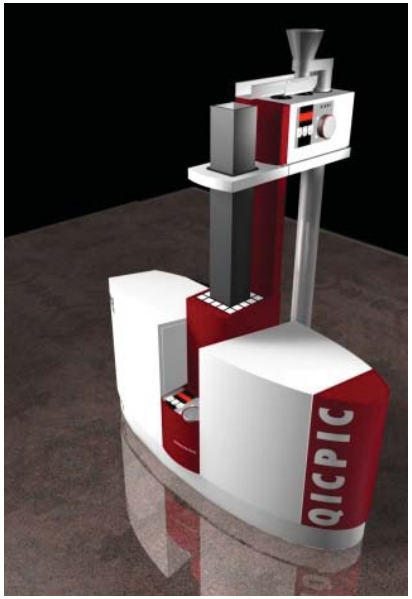
- Diameter [D_p]
- Sphericity [φ]
- Particle Density [ρ_p]
- Skeletal Density [ρ_{skel}]
- Bulk Density (Fluffed) [ρ_{bf}]
- Bulk Density (Packed) [ρ_{bp}]
- Min. Fluidization Velocity [U_{mf}]
- Porosity [ψ]x

Related Standards

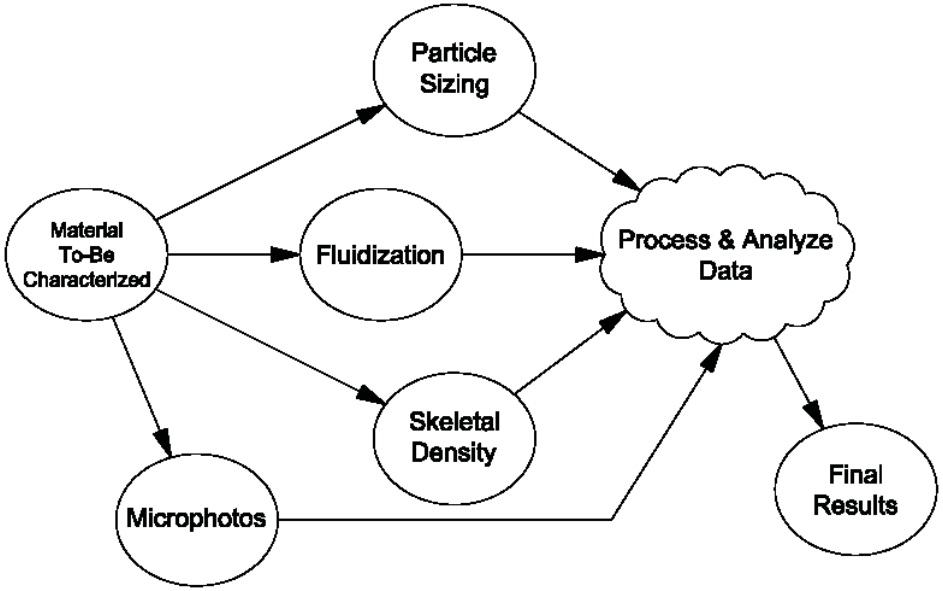
ASTM B822 – Standard Test Method for Particle Size Distribution of Metal Powders and Related Compounds by Light Scattering
ASTM B923 – Standard Test Method for Metal Powder Skeletal Density by Helium or Nitrogen Pycnometry
ASTM D6393 – Standard Test Method for Bulk Solids Characterization
ASTM D6683 – Standard Test Method for Measuring Bulk Density Values of Powders and Other Bulk Solids as a Function of Compressive Stress
ASTM D7481 – Standard Test Method for Determining Loose and Tapped Bulk Densities using a Graduated Cylinder
ASTM D7743 – Standard Test Method for Measuring the Minimum Fluidization Velocities of Free Flowing Powders
ASTM E2578 – Standard Practice for Calculation of Mean Sizes/Diameters and Standard Deviations of Particle Size Distributions
ASTM E2651 – Standard Guide for Powder Particle Analysis
BSI 3406-4 – Methods for Determination of Particle Size Distribution - Guide to Microscope and Image Analysis Methods
DIN 51913 – Testing of Carbon Materials - Determination of Density by Gas Pycnometer Using Helium as the Measuring Gas
DIN 66135-1 – Particle Characterization – Micropore Analysis by Gas Absorption
DS 15103 – Solid Biofuels - Determination of Bulk Density
DS 405.6 – Testing of Sand, Gravel and Stone Materials - Particle Shape
DS 933.4 – Tests for Geometrical Properties of Aggregates - Determination of Particle Shape
ISO 12154 – Determination of Density by Volumetric Displacement - Skeleton Density by Gas Pycnometry
ISO 13322 – Particle Size Analysis - Image Analysis Methods
ISO 14488 – Particulate Materials - Sampling and Sample Splitting for the Determination of Particulate Properties
ISO 8130-5 – Determination of Flow Properties of a Powder / Air Mixute
ISO 9276 – Representation of Results of Particle Size Analysis. Graphical Representation
BSI 812-2 – Testing Aggregates – Methods for Determination of Density
EN 933-4 – Tests for Geometrical Properties of Aggregates – Determination of Particle Shape / Shape Index
ASTM E1617 – Standard Practice for Reporting Particle Size Characterization Data
ISO 26824 – Particle Characterization of Particulate Systems – Vocabulary
ASTM F1877 – Standard Practice for Characterization of Particles
AFNOR X11-364 – Particle Size Analysis – Characterization of the Size and Form of the Elements of a Granular Population

Over 200 Standards were found to be applicable.

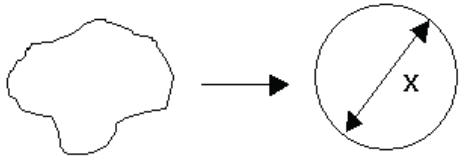
The Methodology Roadmap



Sympatec QICPIC Particle Analyzer

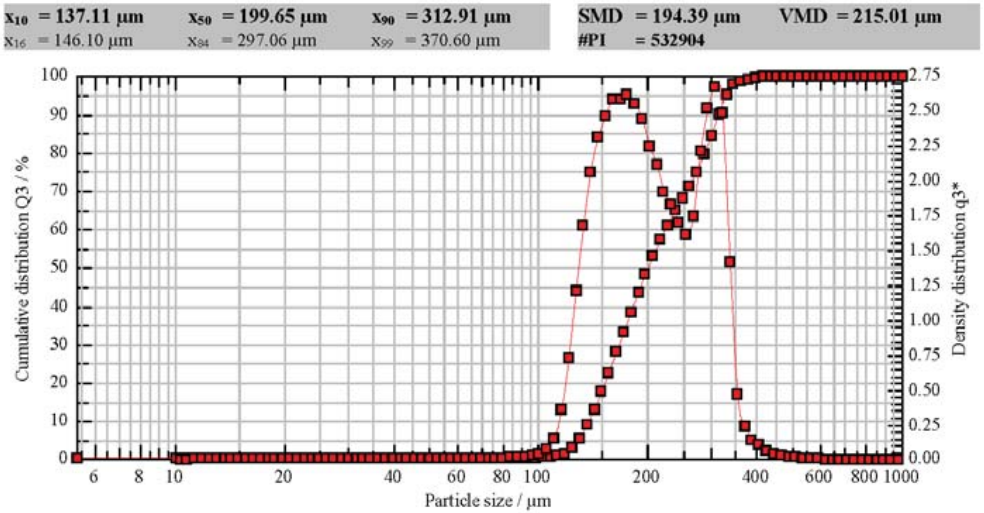


Micromeritics AccuPyc 1330 Helium Pycnometer



Processed using EQPC Analysis
(Diameter of a Circle of Equal Projection Area)

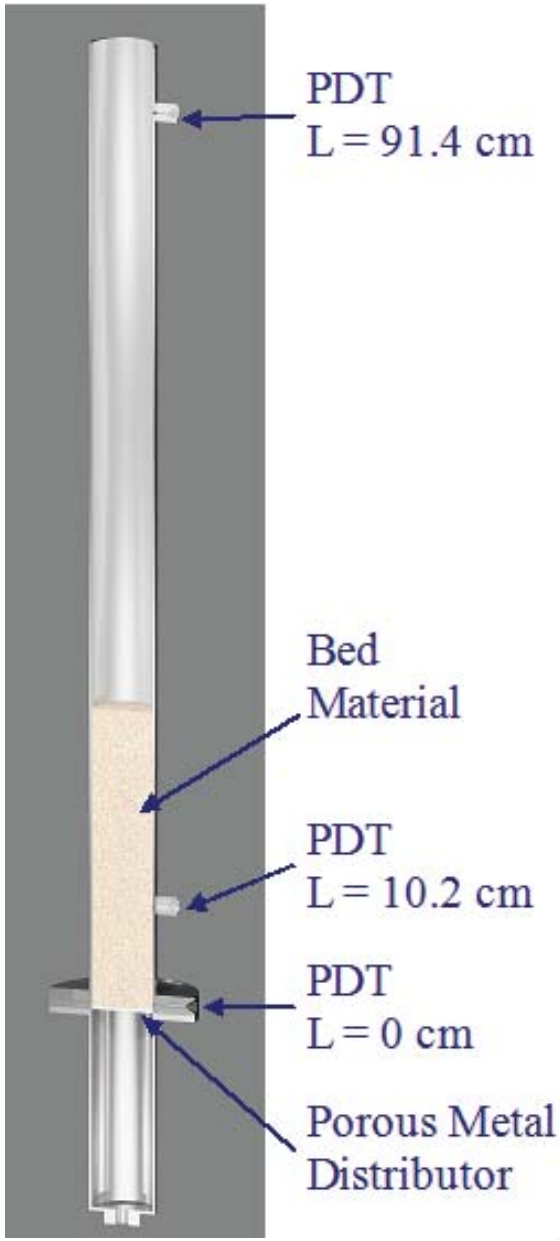
Sauter Mean Diameter (SMD or d_{32})

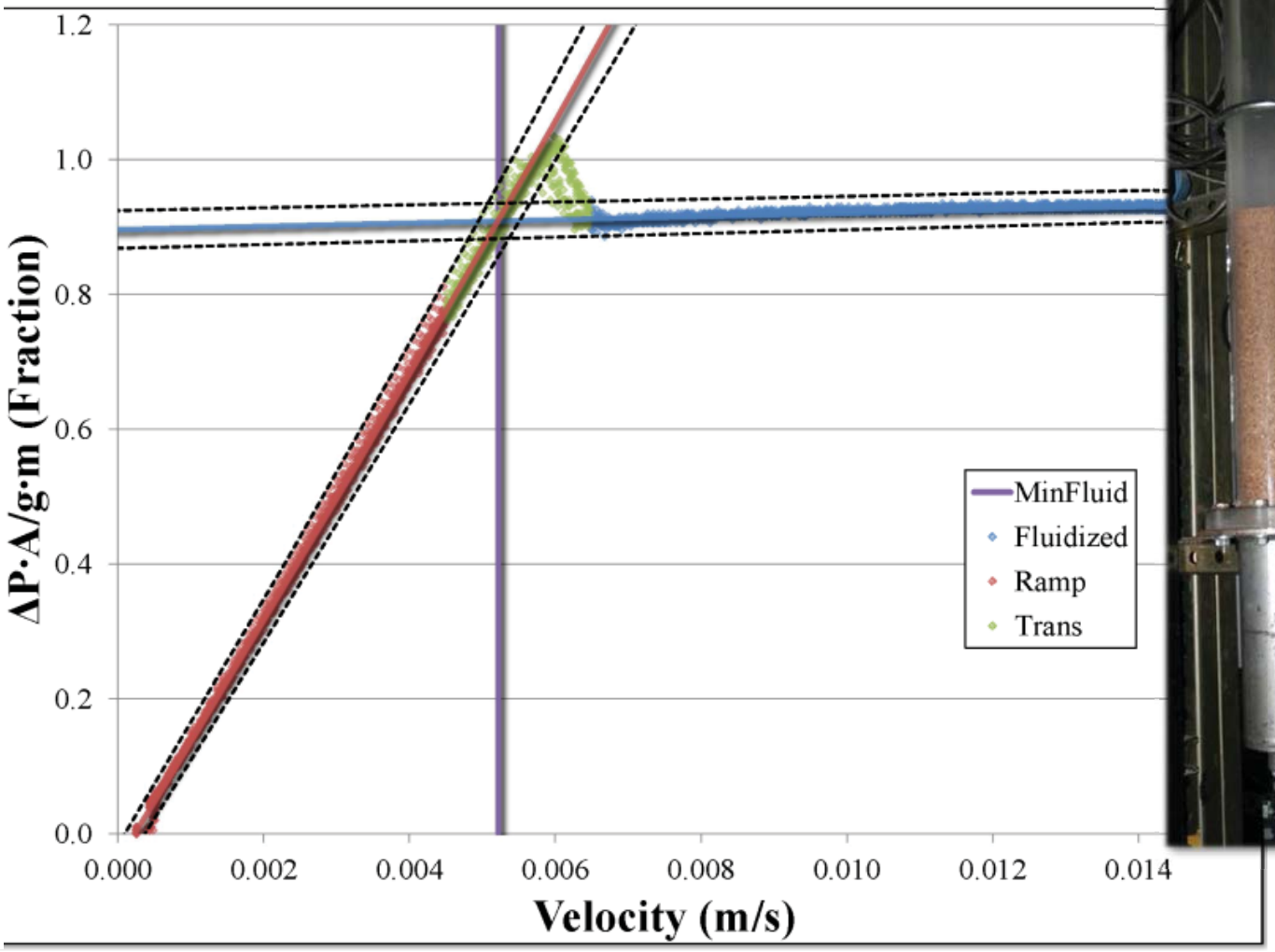


Small Scale Fluid Bed

Minimum Fluidization Velocity

- Normalized w.r.t. to Weight of the Bed
- Packed bed follows Ergun Eq. / Fluidized bed constant ΔP
- U_{mf} found at the Intersection





Geldart Classification

Group C

Cohesive, difficult to fluidize; low bed expansion; exponential bed de-aeration; no bubbles, only channels; very low solids mixing, no spouting.

Group A

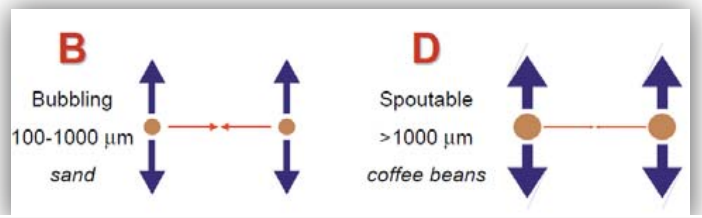
Ideal for fluidization, range of non-bubbling fluidization; high bed expansion, slow linear de-aeration; bubbles split and coalesce with maximum size; high solids mixing, no spouting.

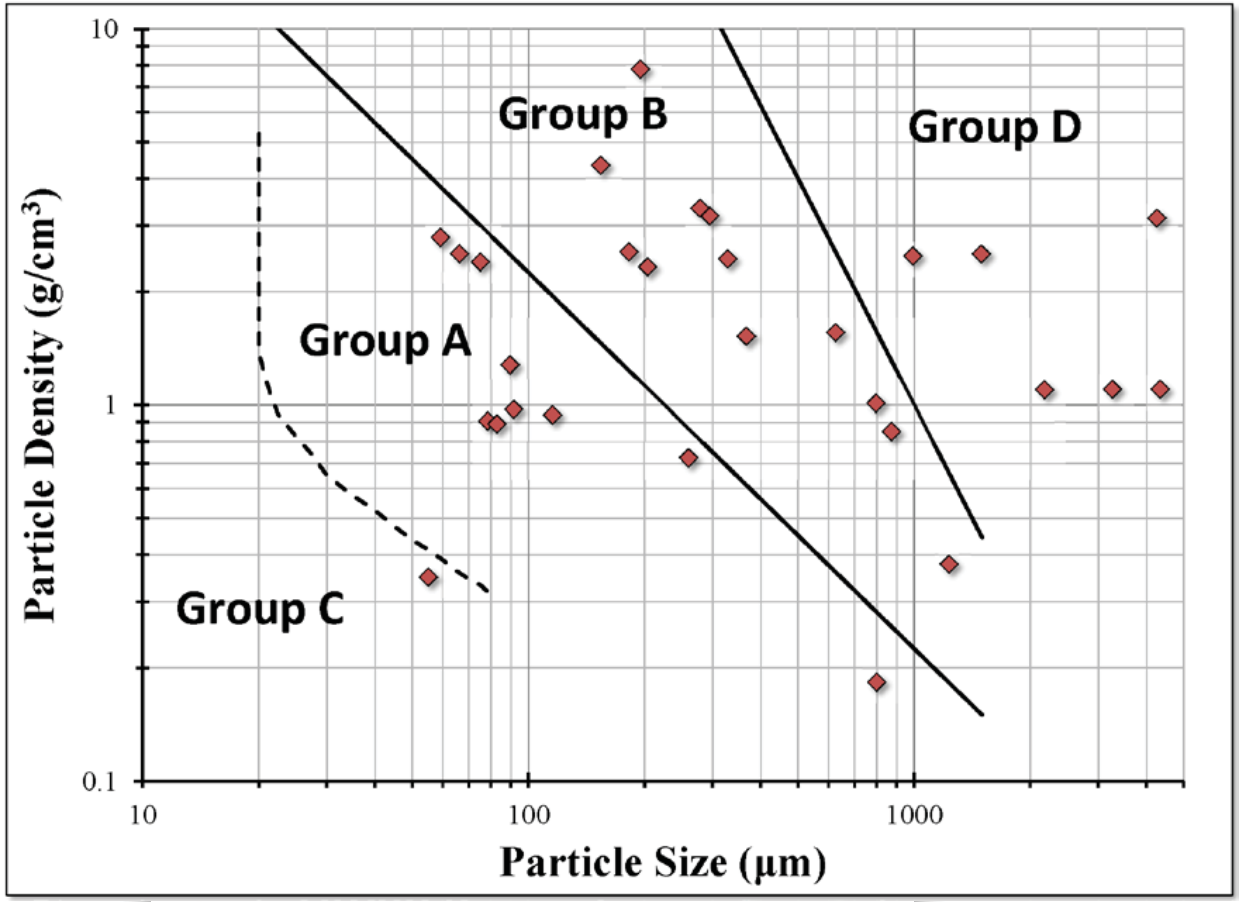
Group B

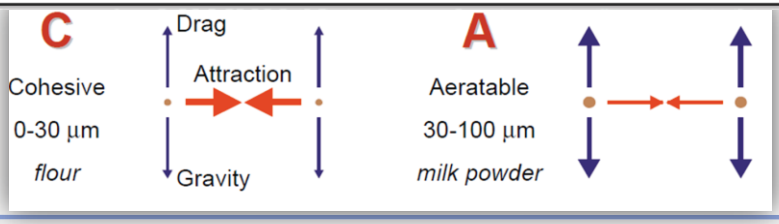
Bubbles at fluidization; moderate bed expansion; fast de-aeration rate; no limit to bubble size; moderate solids mixing; spouting only in shallow beds.

Group D

Coarse solids; low bed expansion; fast de-aeration rate, no limit to bubble size, low solids mixing; spouting even in very deep beds.

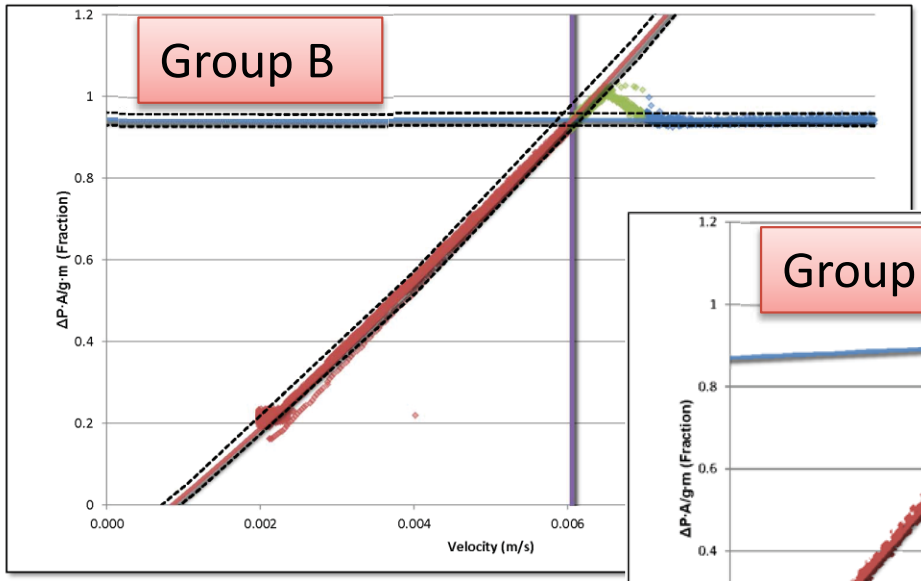




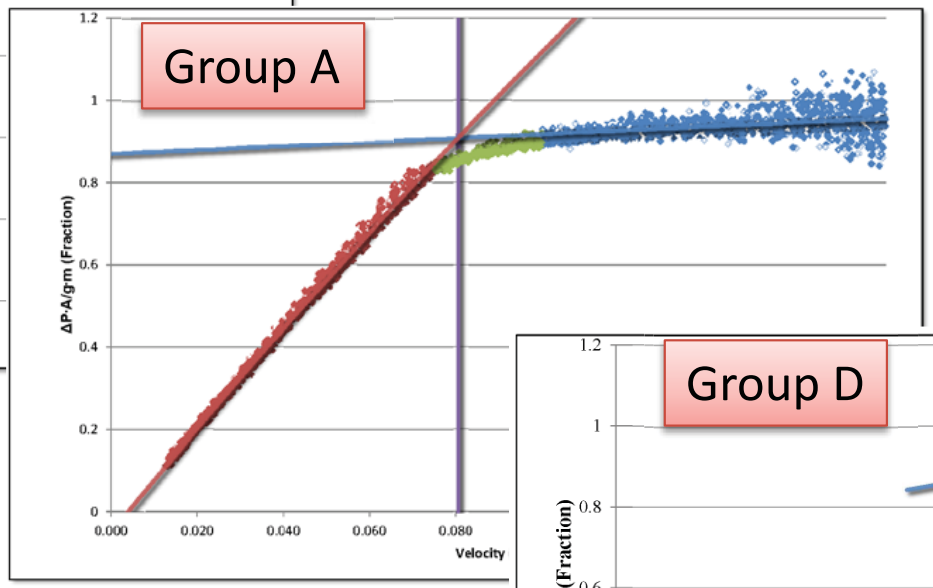


Small Scale Fluid Bed

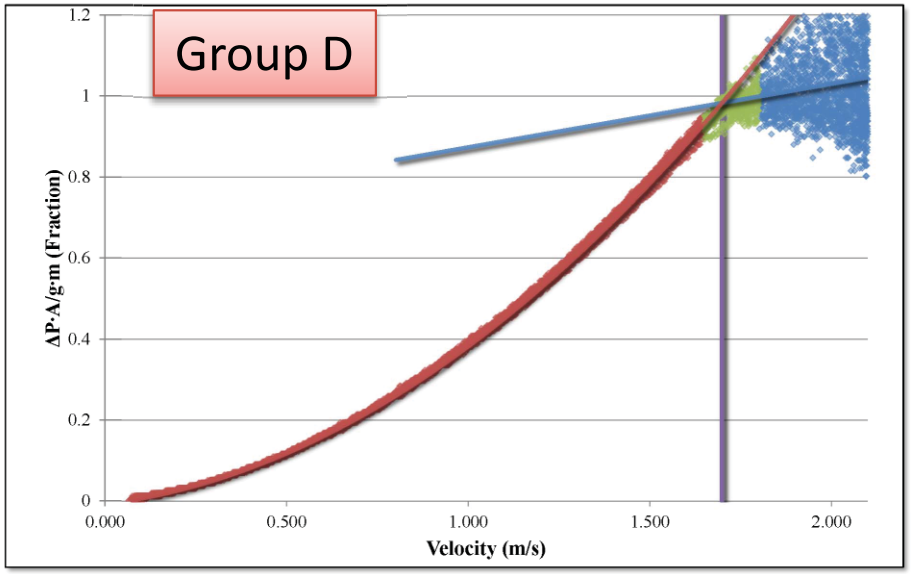
Minimum Fluidization Velocity



Group A are engineered materials – smooth fluidization and less hysteresis

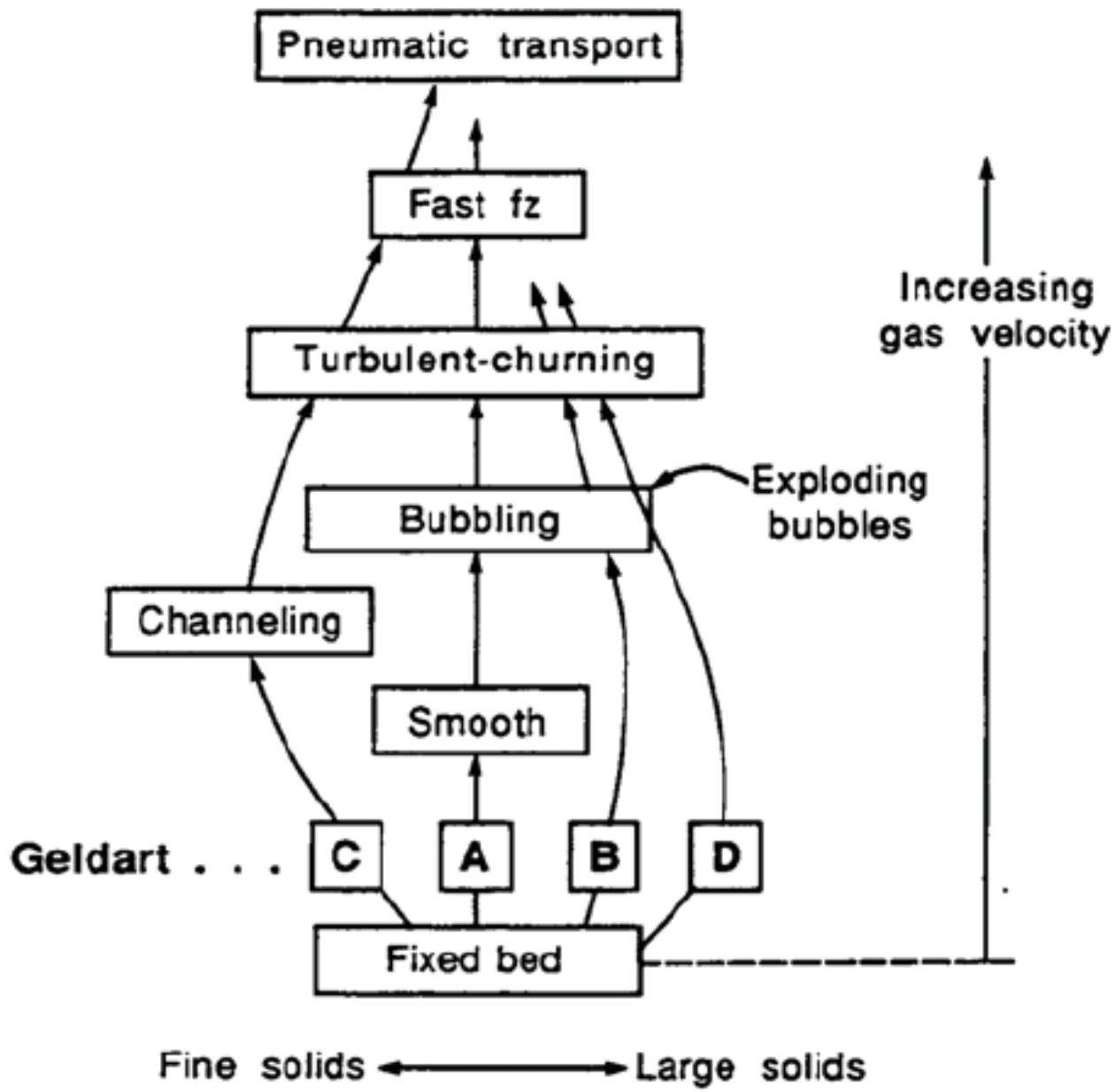


Group B is typical of coal and other natural materials – response with increasing V different than decreasing

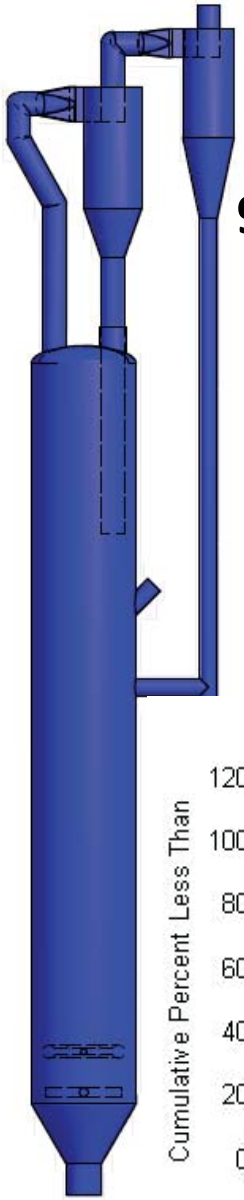


Group D are larger denser particles forming highly permeable beds not readily fluidized, rather spouts and slugs

Progression Between Flow Regimes for Geldart Classification of Particles



Challenge Problem III



PSRI

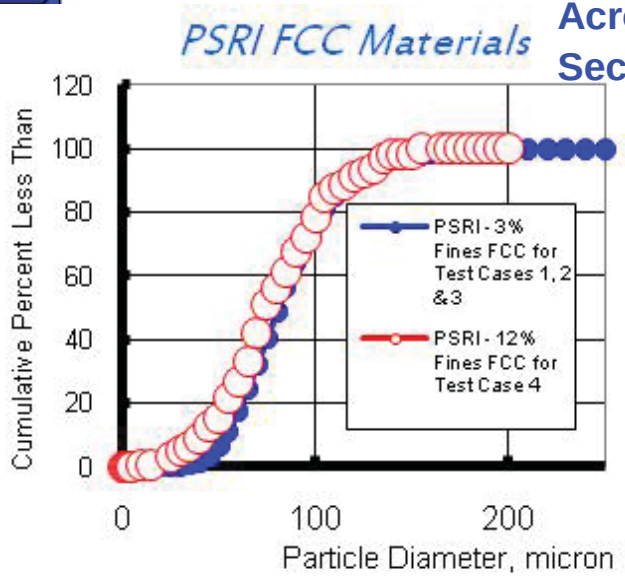
Particulate Solid Research, Inc.

6-m-Long & 92-cm-Diameter Bubbling FB

PSD

$\Delta P/\Delta L$ vs U_g in 15 cm ID FB

FCC

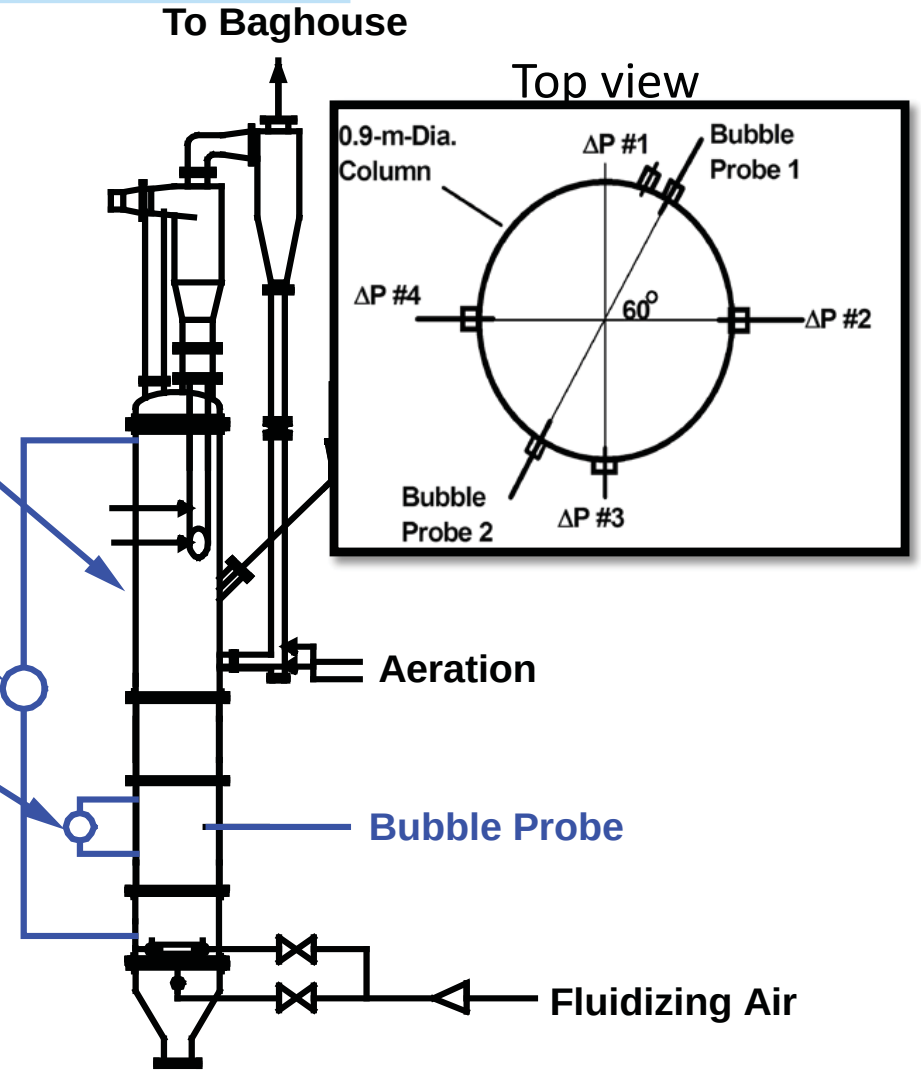


EXPERIMENTAL DATA

Axial DP/L Profile

Overall DP Fluctuations

DP Fluctuations Across 61 cm Section



Column Dia.: 0.9 m, Height: 6.1 m

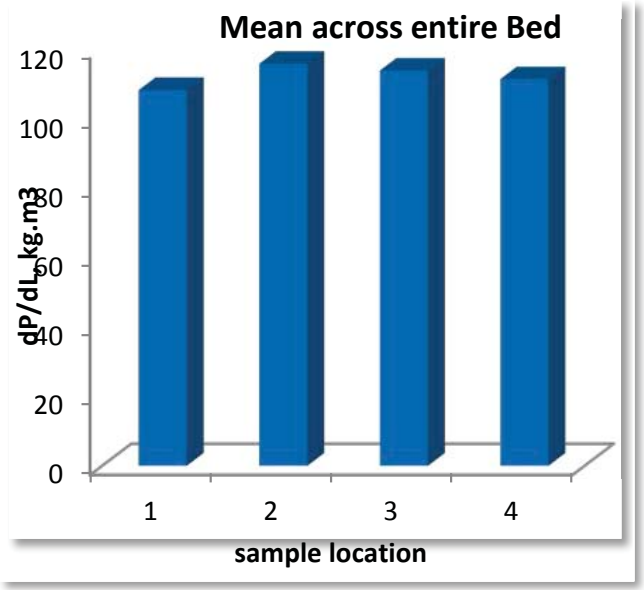
PSRI
Particulate Solid Research, Inc.

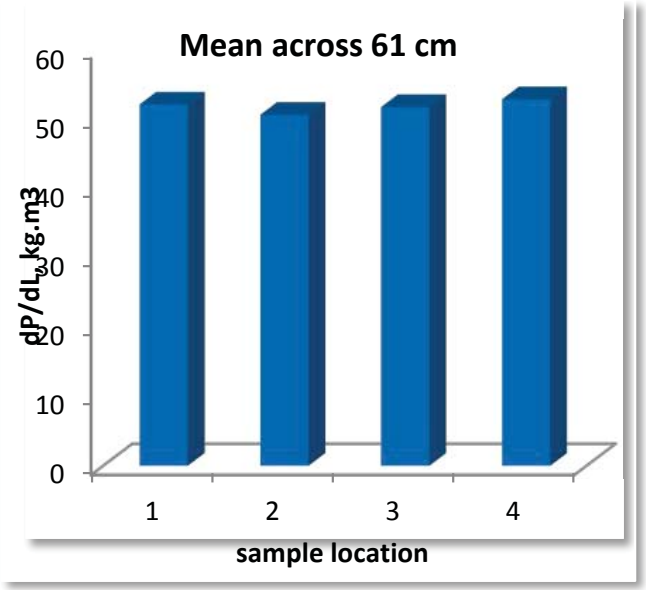
BFB Challenge Problem

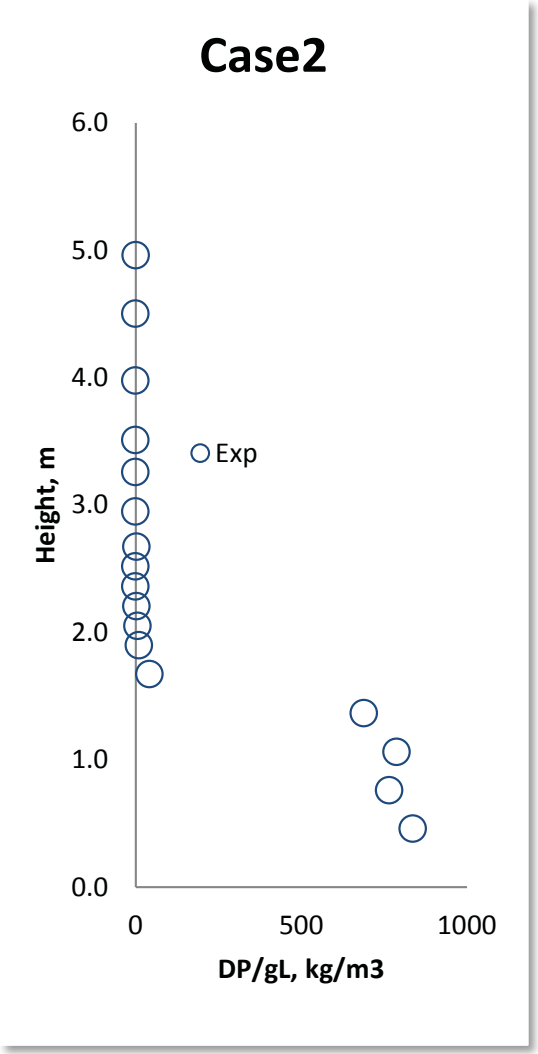
Test Case No.	Static Bed Height, ft (m)	FCC Fines Content % < 44 μm	Ug ft/s (m/s)	Fluidization Behavior
1	12 (3.66)	3	1 (0.3)	Gas bypassing
2	4 (1.22)	3	1 (0.3)	Uniform
3	8 (2.44)	3	2 (0.6)	Gas bypassing
4	8 (2.44)	12	2 (0.6)	Uniform

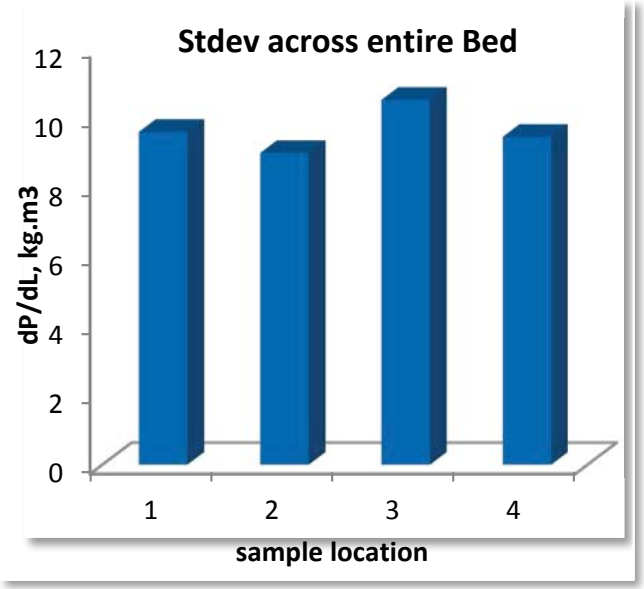
Gas bypassing more likely for tall beds, low fines content and low gas velocity

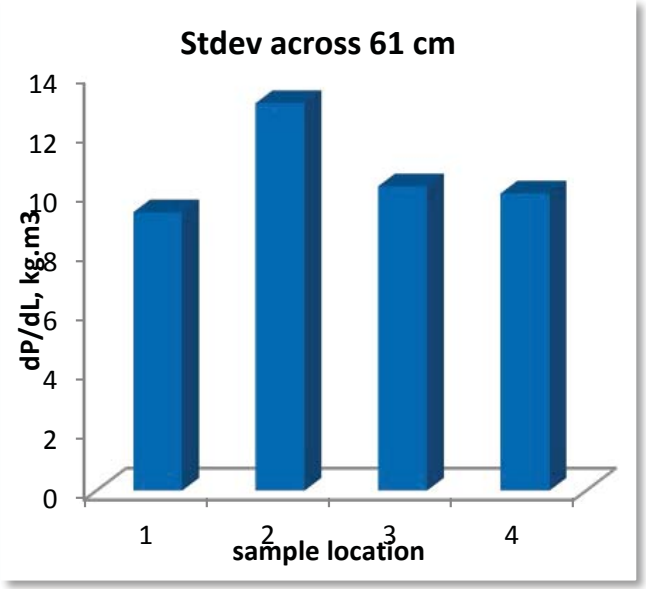
Case 2 Uniform Fluidization



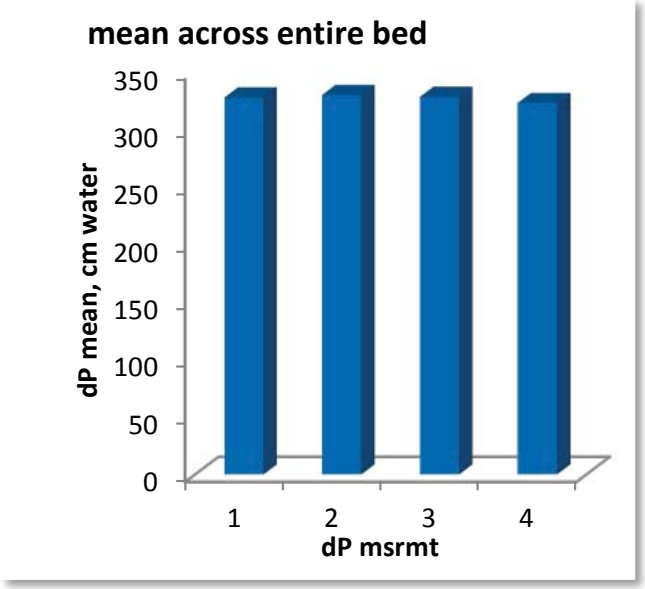


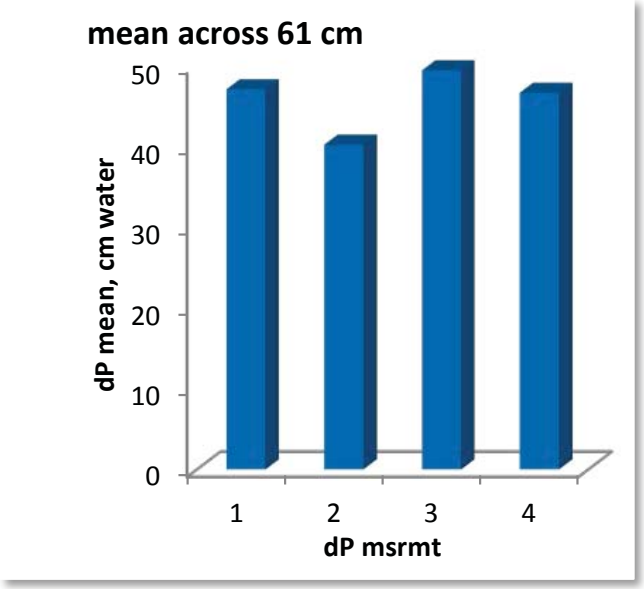


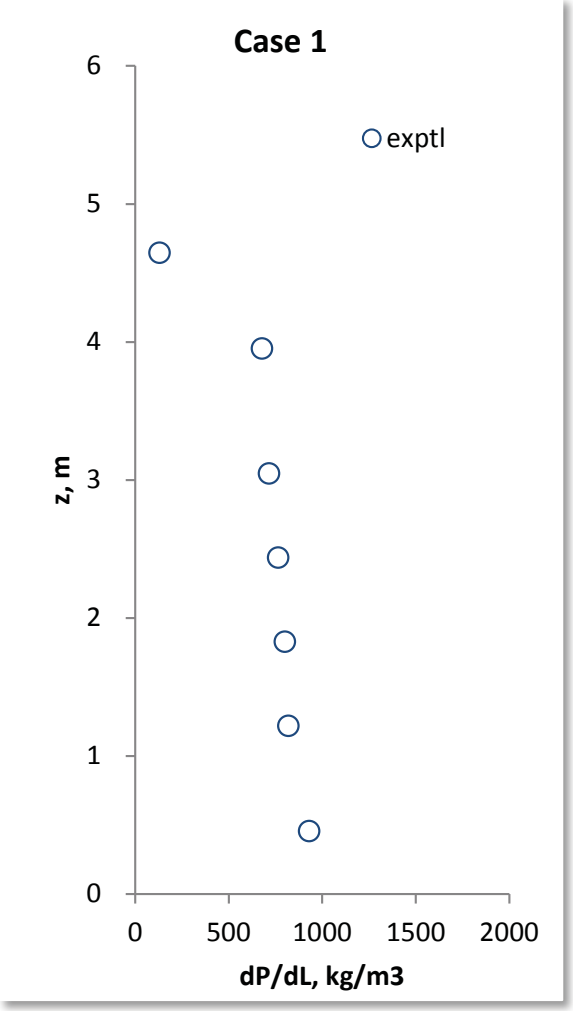


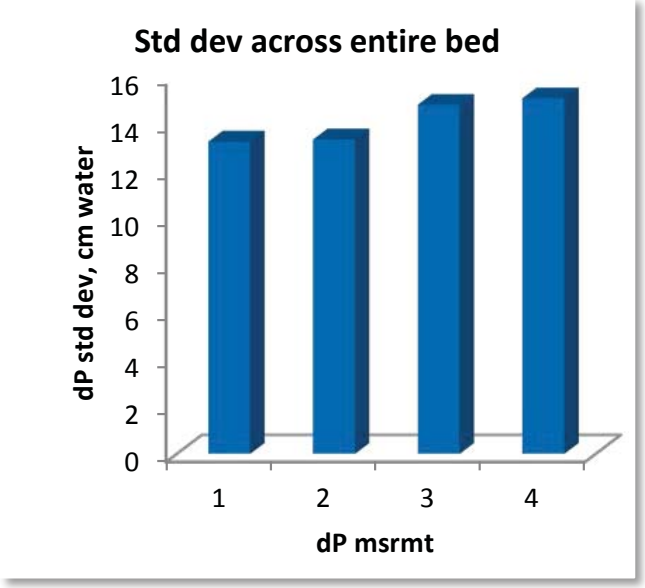


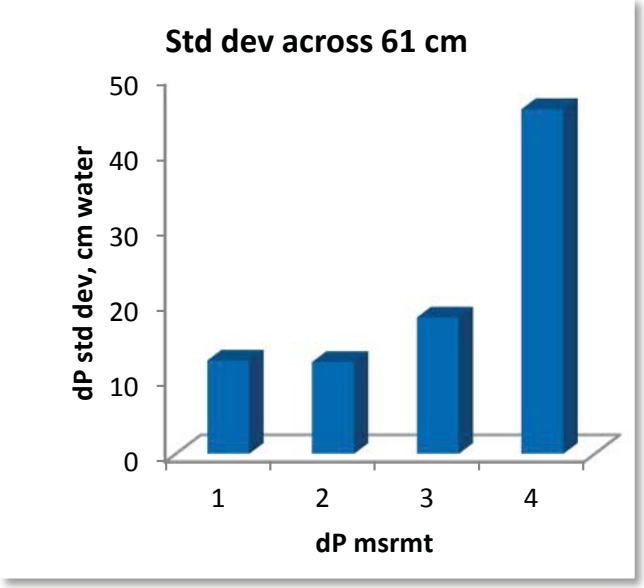
Case 1 Channeling in Deep Bed



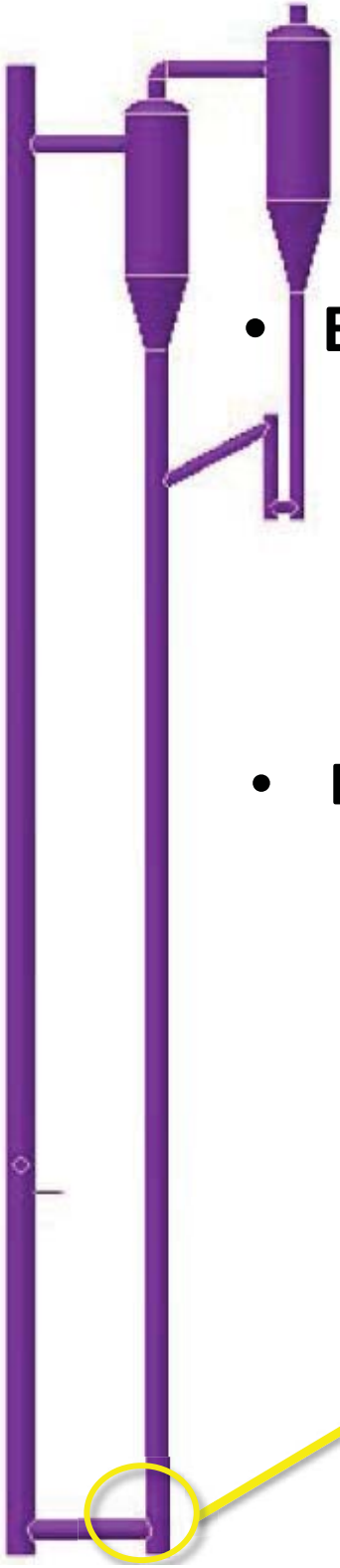






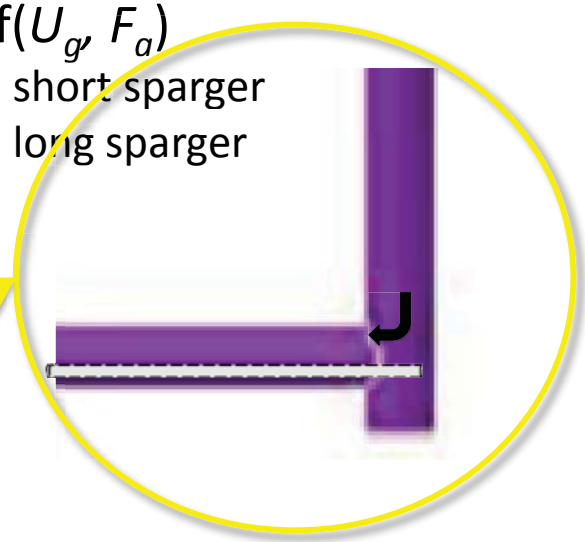


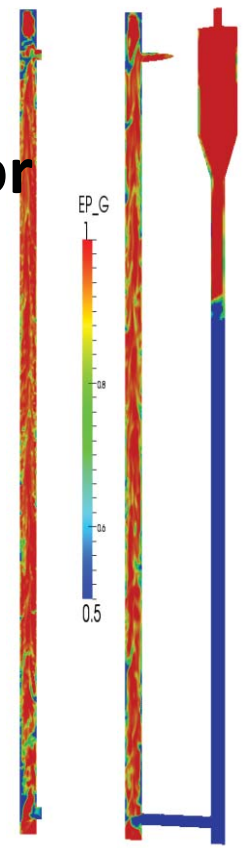
Solids Flow

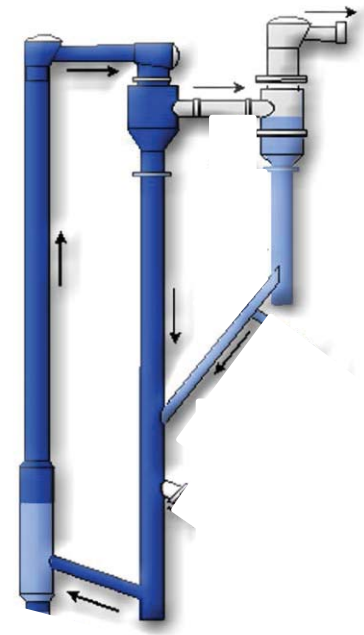


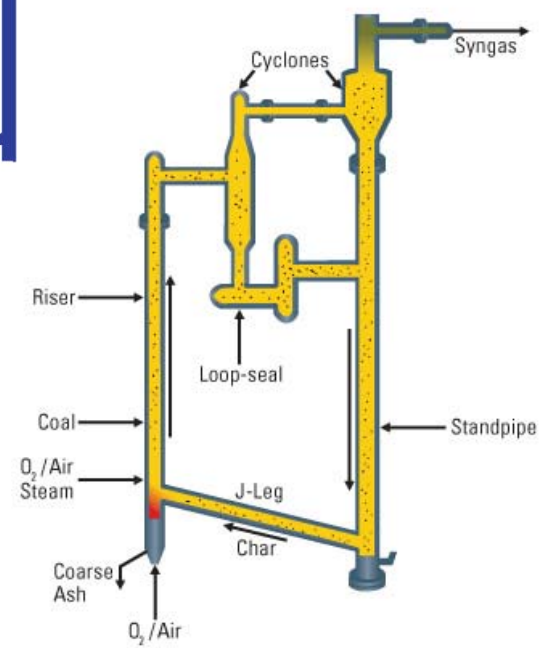
- **Evolution of the Transport Reactor**
  - Fines Carryover Events
  - Maximize Solids Recycle Rates
  - Flow of Fines in the Recycle leg
  - Transport flow in the Riser

- **Experience in 1-ft ID 55ft tall CFB**
  - Solids flow control (Riser)
  - Aeration control (Full Loop)
    for $M_s = f(U_g, F_a)$
    - R^2=88% short sparger
    - R^2=99% long sparger

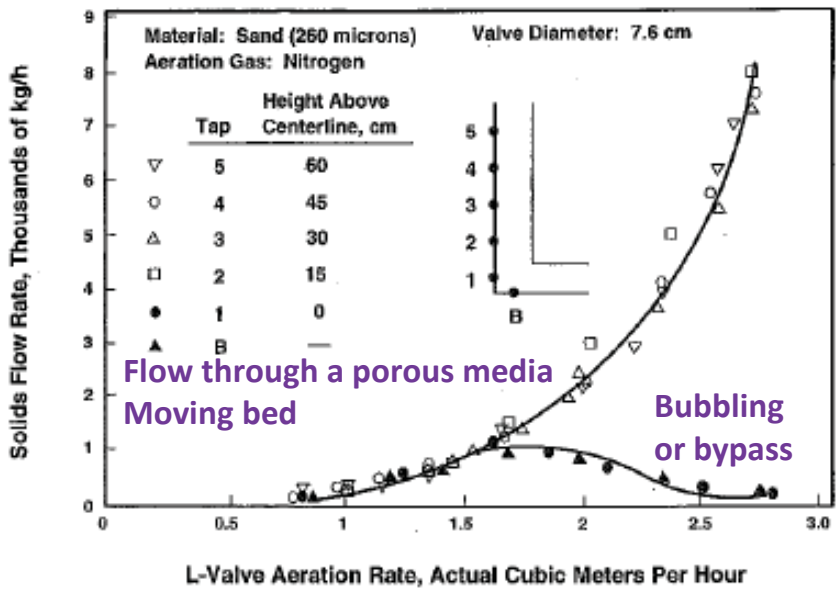


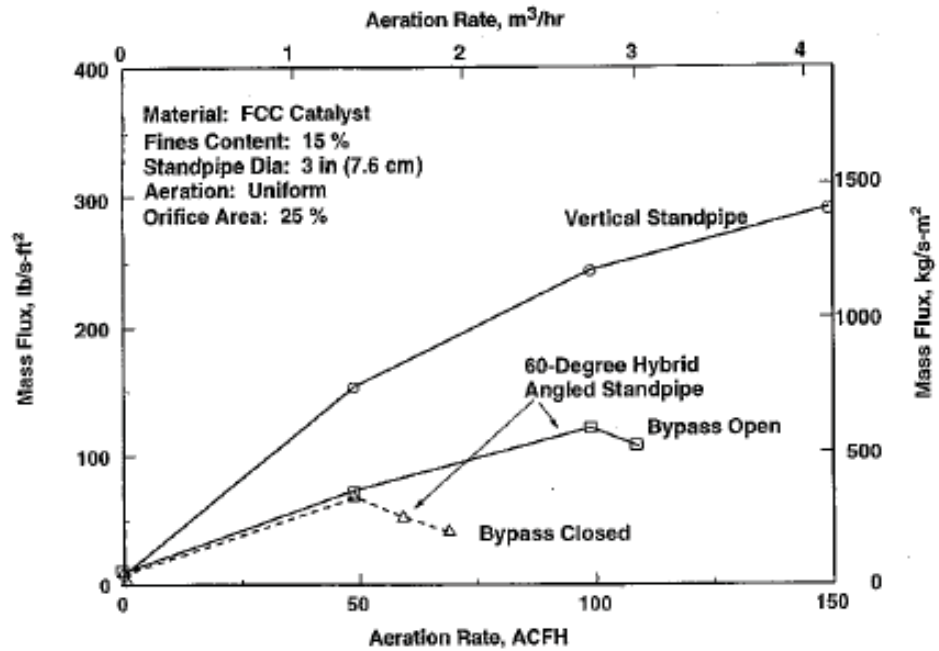


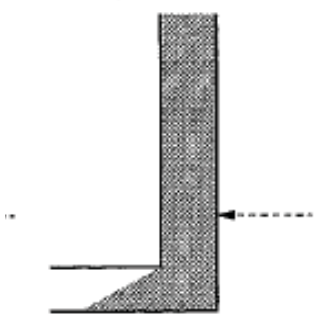


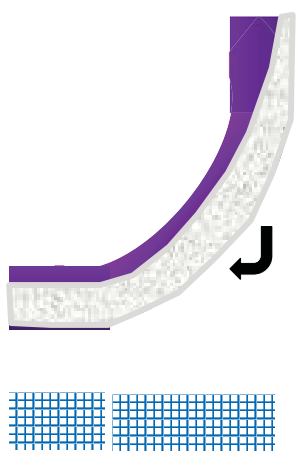


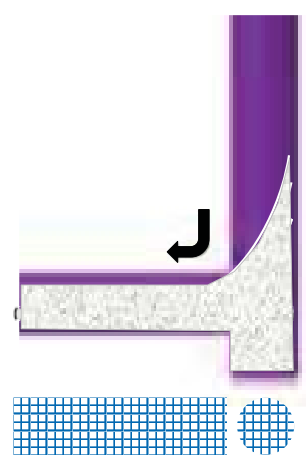
Solids Flow in an L-Valve

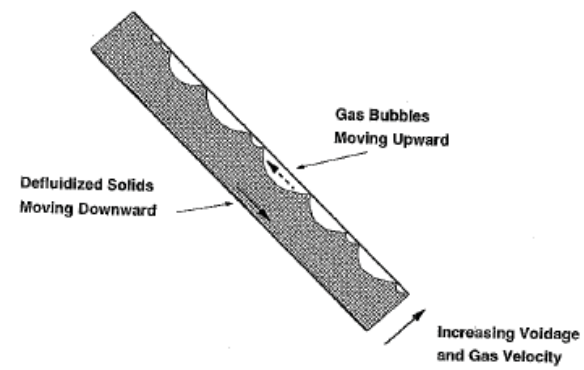






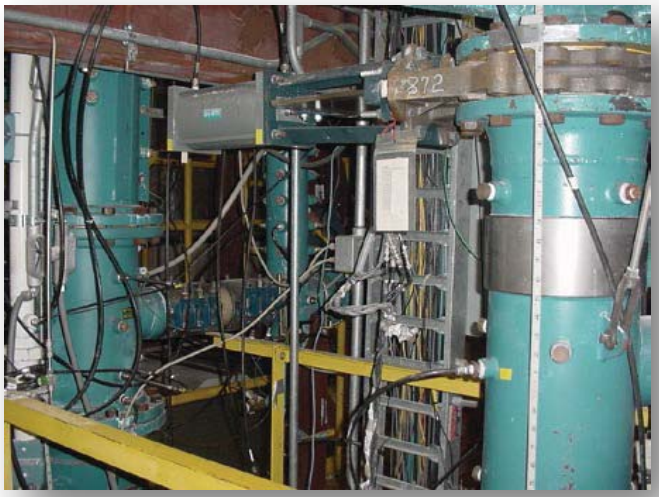




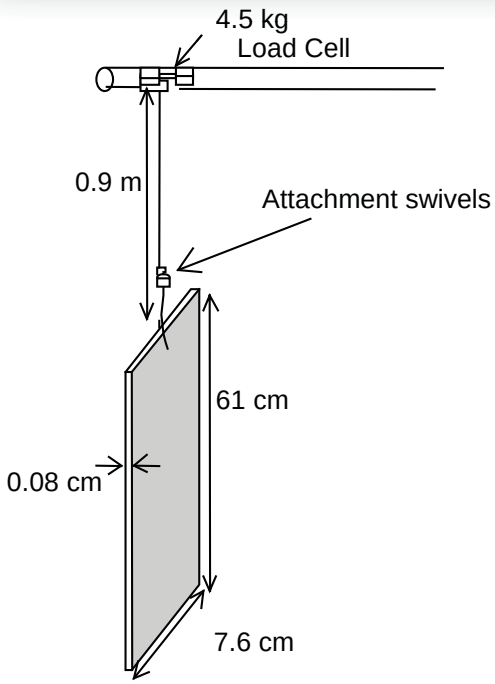


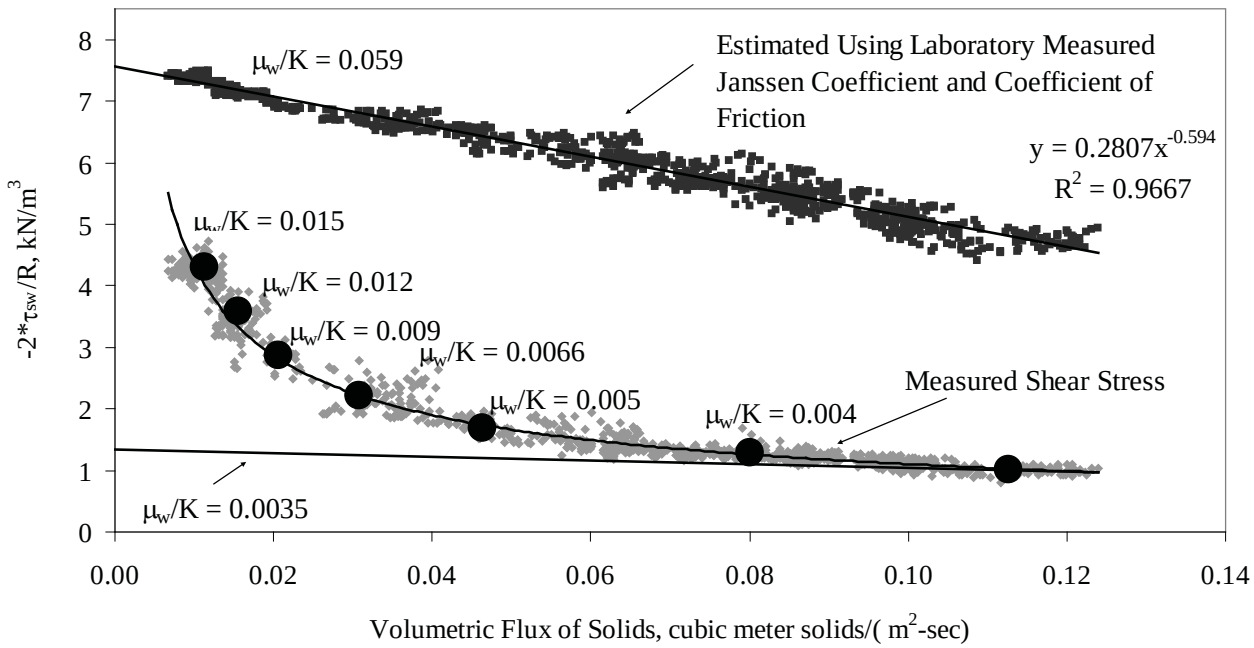
U_g=Flow*Area

Wall Shear Measurements



- Gas-solids viscosity from wall shear and shear rate
- Standpipe wall shear vane

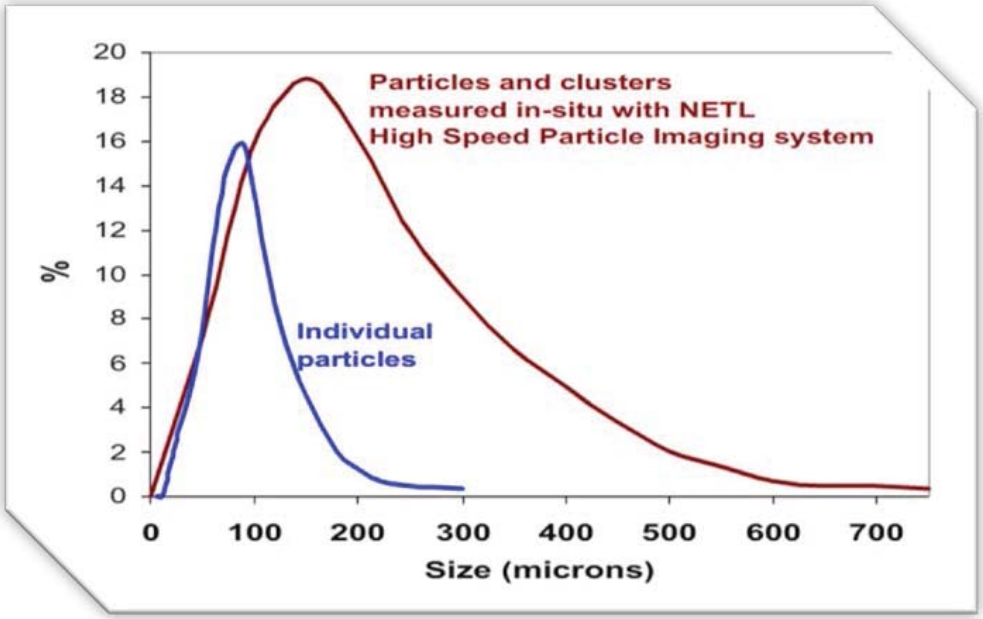


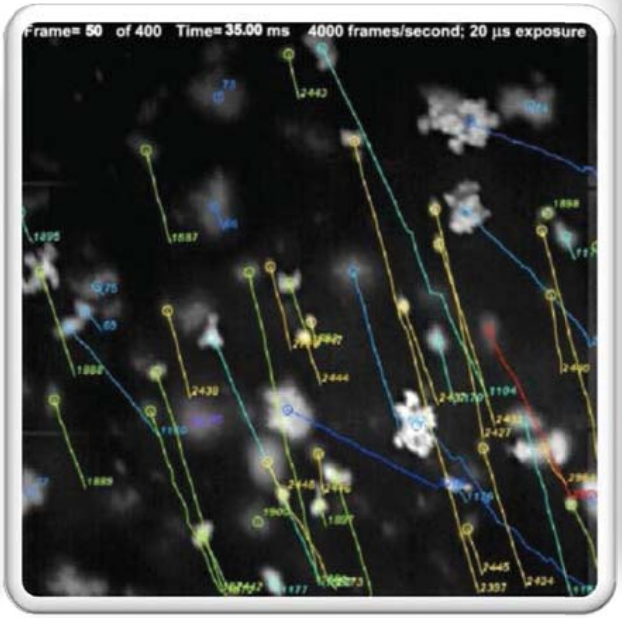


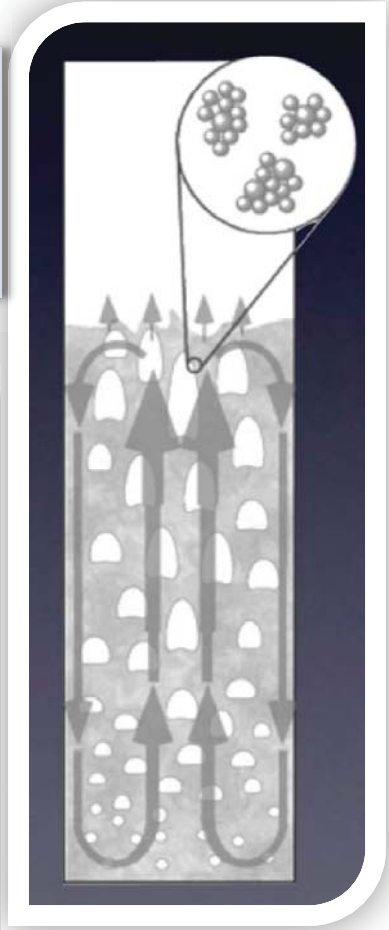
Observations of Particle Clustering in Fluidized Beds

- **NETL applied our unique high speed particle imaging system in the labs of Chicago based PSRI, an industry R&D organization representing 30 companies in the chemical and energy industries.**
- **NETL-PSRI collaboration led to the first direct measurements of particle clustering in fluidized beds.**

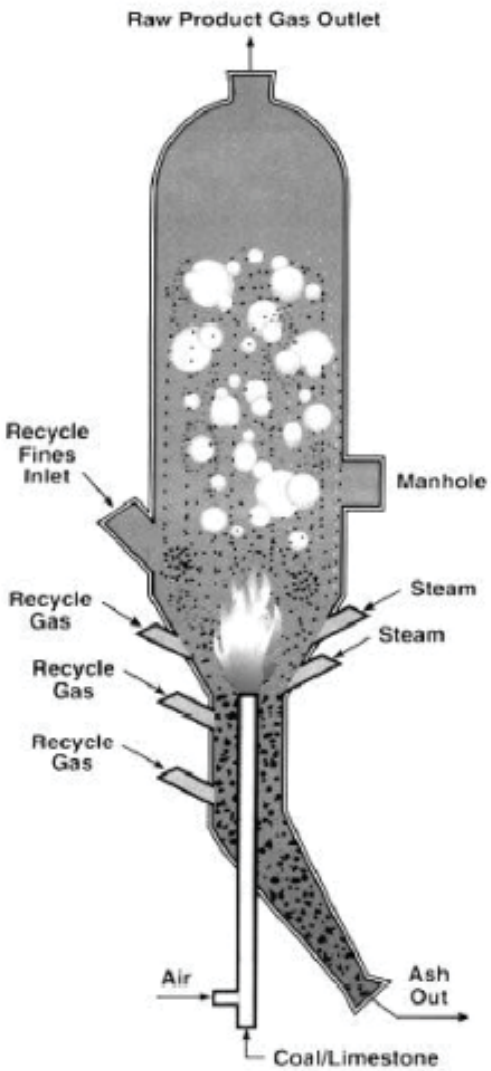
Industry plants are designed using benchtop measurements of <u>individual</u> particle sizes, but once particles are in a plant, they form clusters that behave as much larger particles, thereby dramatically changing system design and performance.

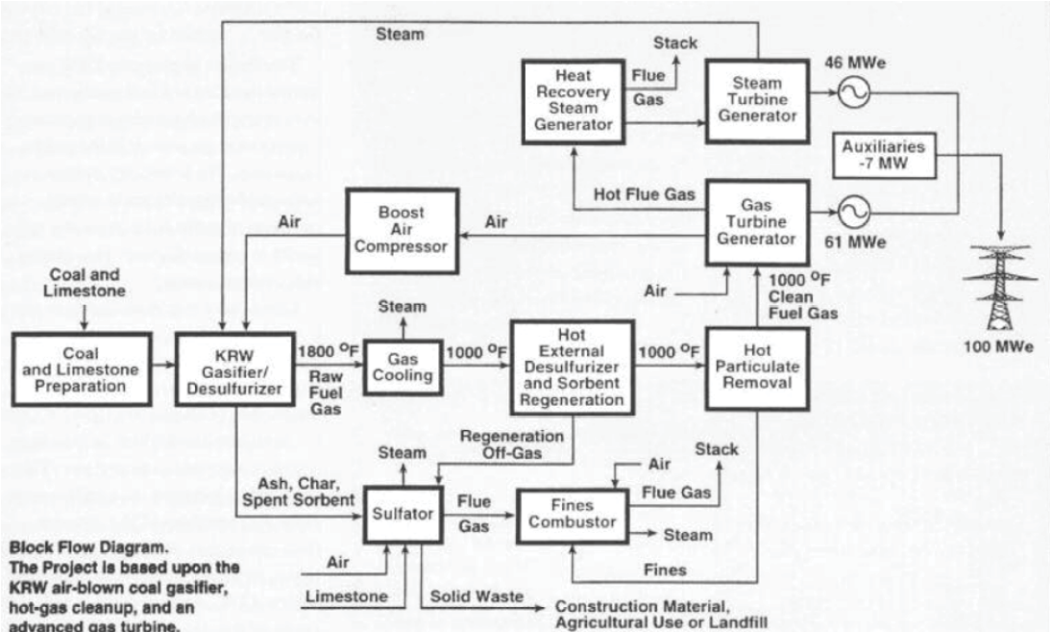




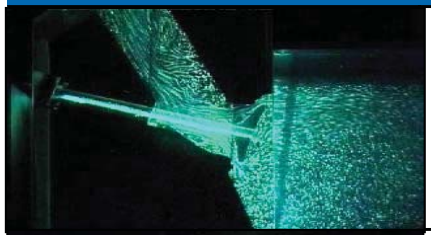
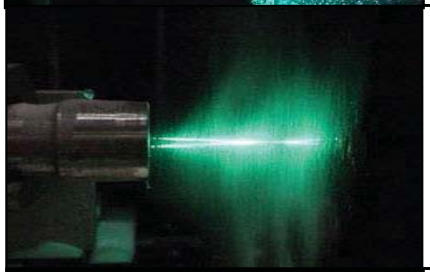
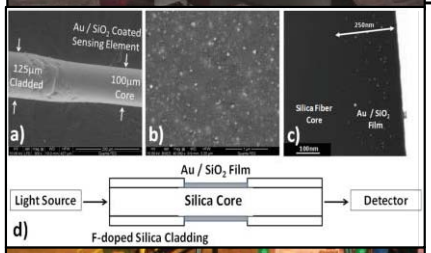


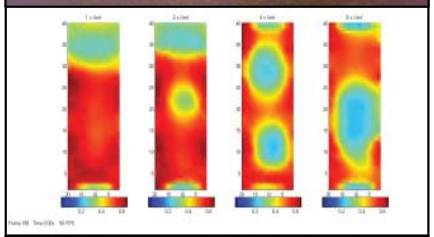
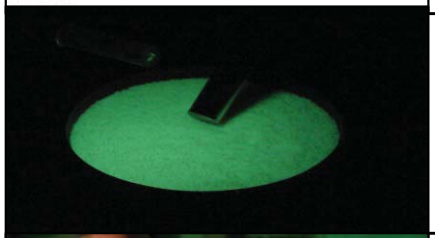
Agglomerating Gasifier





- **Installed at Pinon Pine 100 MW IGCC facility**
- **~50:1 scale up operated using utility operations crew**
- **Plagued with solids handling issues:**
  - Fines carryover
  - Ash underflow solids removal

Equipment		Capabilities	Limitations
	**Particle Image Velocimetry (PIV)**	• Images particles in a system • Calculates velocity and direction for those particles • Measures all particles on a 2D plane at rapid speeds	• Requires optical access to fluidized bed • Can only map particles at low densities • Requires small particles
	**Laser Doppler Velocimetry (LDV)**	• Measures velocity and direction of particles in a fluidized system. • Measures velocity in transparent or semi-transparent fluid flows, or the linear or vibratory motion of opaque or reflecting surfaces	• Requires optical access to fluidized bed • Can only map small particles at low densities • Only performs point measurements
	Particle Size Analyzer	• Measures particle size and shape distribution • Capable of counting 10^7 particles in under 10 minutes • High fidelity/ high repeatability	• Particles must be bigger than 5 micron or smaller than 6000 micron • Performs off-line measurements only
	**Evanescent Wave Absorption**	• Single point measurement or distributed interrogation of temperature, pressure, chemical species (hydrogen, CO, CO2, etc), pH, gas flow, and other features. • Immune to electrical interference. • Small sensor form factor.	• Optical interrogation systems are expensive. • Operating temperature range is limited • In development
	Microwave Doppler	• Measures gas flow of solid/gas flow • Works up to 1,000 °C • Measures quantity and velocity of particles	• Experimental • In development • Solid/gas flow must be dilute

Equipment		Capabilities	Limitations
	Pressure Sensors	• Calculates density of particles in fluidized bed systems • Measures bed height • Detects state of bed	• Must keep solids out • Limited capabilities
	Fiber Optics	• Measures particle velocities • Works in-situ • Measures bubble rise/flow rates	• Intrusive • Only work at room temperature
	**Electrical Capacitance Volume Tomography (ECVT)**	• Measures bubbles, clusters and jets • Measures solids concentrations • Provides validation for CFD	• Static electricity sensitive • Geometry specific • Only works at room temperature
	**Jet Tracer**	• Shows penetration of riser or fluid bed • Useful for mapping	• Only works with phosfluorescent materials • Coarse measurement
	Raman Sensor	• Measures N2, O, CO2, CO, H2O in gas-phase species from the exhaust. • Permits measurements of homonuclear diatomics such as hydrogen, nitrogen and oxygen.	• Only measures majority gases • Particles must be kept separate from gas stream

End

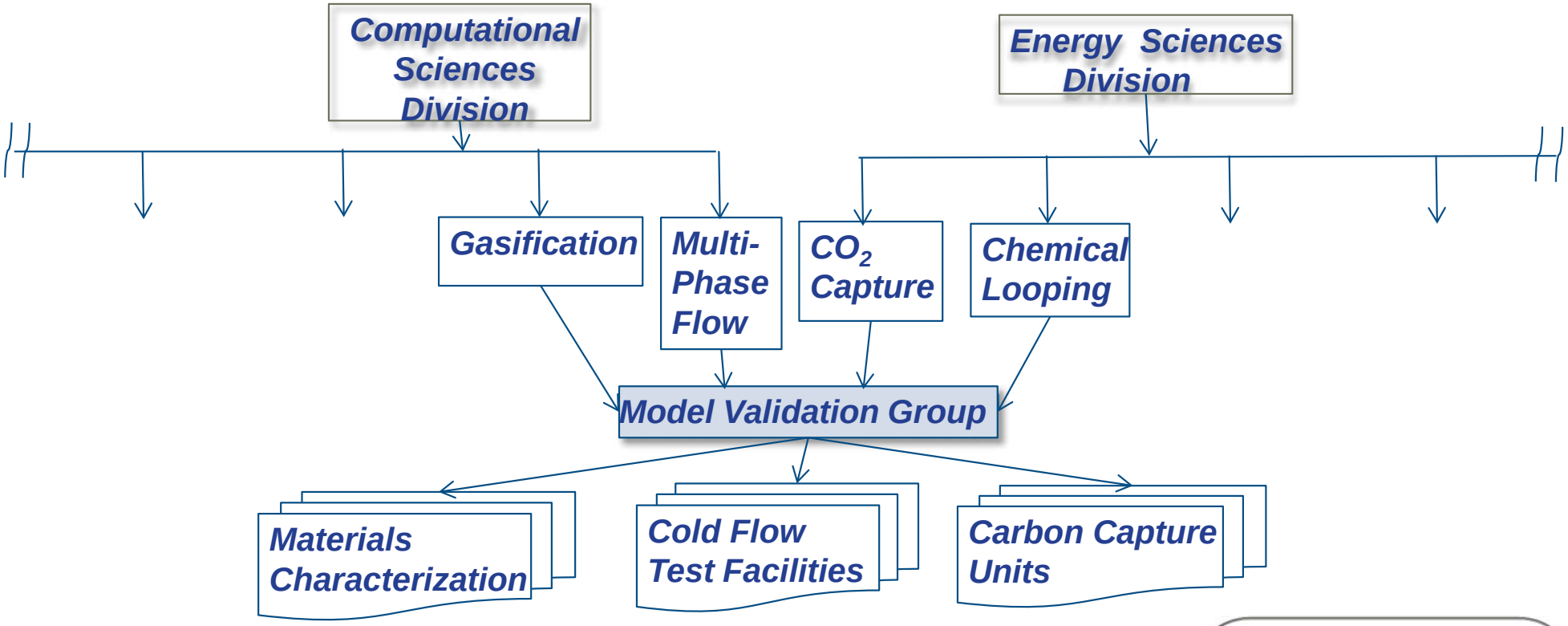
Questions/Comments

Next

Mike Buric – Raman Gas Analyzer

BACKUP SLIDES

Research Activities



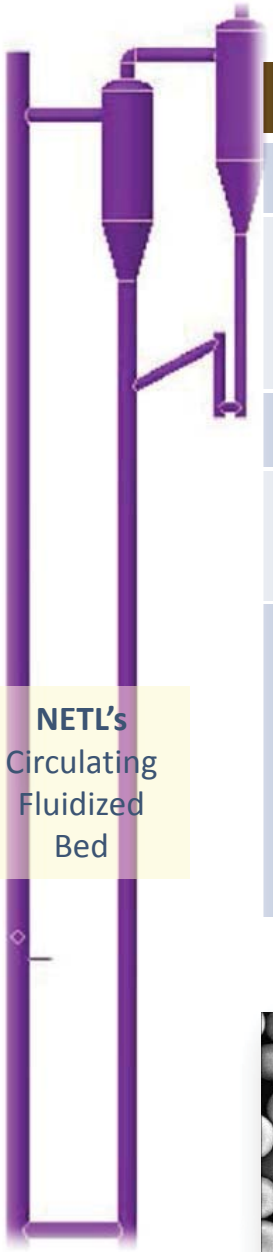
Flow Analysis
- Granular Temp.
- Dispersion
- Particle Wall Collisions
- Cluster Formation
- Temporal Variations

Diagnostics
- Circulation Rates
- Gas and Solids Tracers
- Flux and Velocity Profiles
- Tomography
- Transients
- Data Quality/Uncertainty

Fluidization
- Regimes
- Non mechanical valves
- Inlet and outlet effects
- Separations
- Attrition
- Frictional Flow

Reaction Analysis
- Kinetics
- Heat Transfer
- Mass Transfer
- Thermodynamics
- Reaction Conversion
- Gas production and consumption

Fluidization Challenge Problems

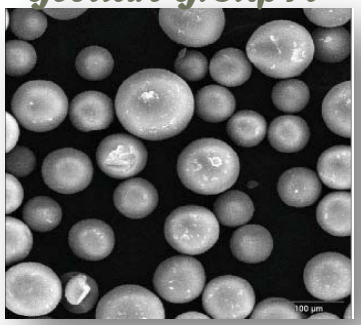


NETL's Circulating Fluidized Bed

	I (1995)[1]	II (2001)[2]	III (2011)[3]
Organizer	PSRI	PSRI	NETL/PSRI
System modeled	CFB: 20cm & 40cm-Dia FCC and Sand	CFB: 20 cm-Dia, blind tee & elbow at exit FCC and Sand	CFB: 16m x 30.5cm-Dia BFB: 6-m x 92-cm-Dia Group A & B solids
Response	10	13	5 (CFB), 3 (BFB)
Predictivity, % diff.		77 to 334%	CFB: 5 to 80% BFB: 20 to 30%
Summary Comment	***"Models were not sophisticated enough to be used to predict all of the hydrodynamics in a CFB".***	***"Models still needed substantial development to be able to predict CFB hydrodynamics".***	***"CFD codes are in their infancy… and given the resources and time, can simulate industrial scale multiphase processes."***

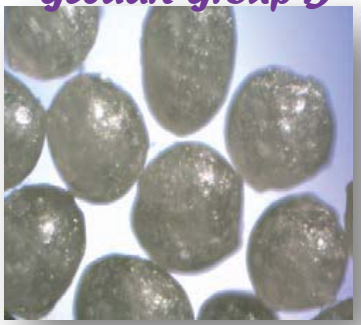
PSRI's Bubbling Fluidized Bed

Geldart Group A

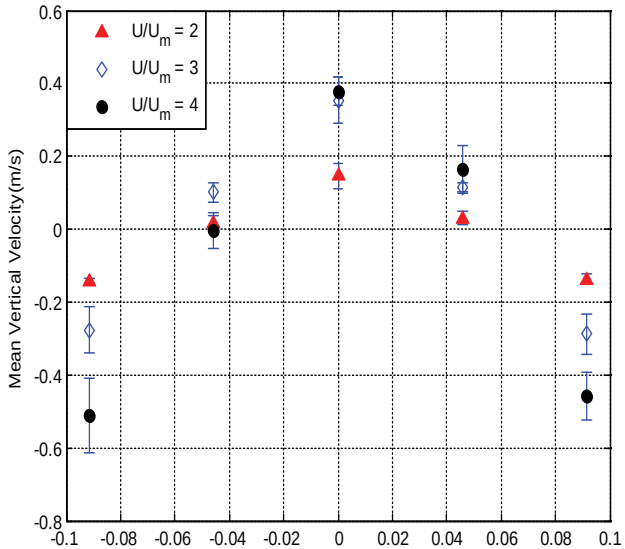


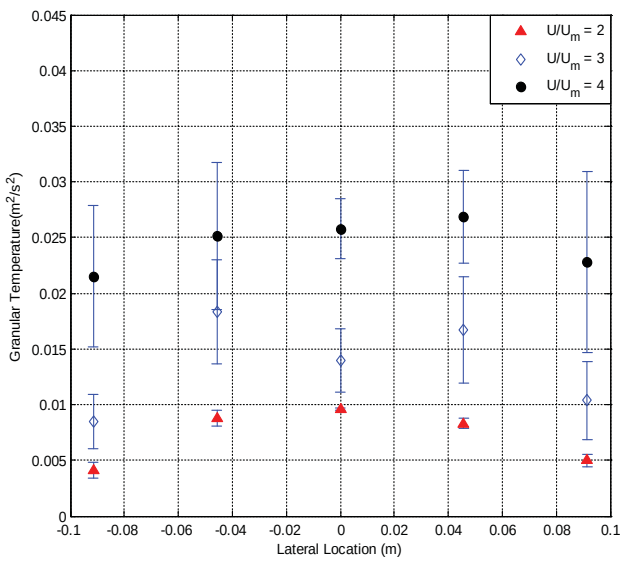
[1]Laguerie & Large, Fluidization VIII Workshop, 1995.
[2]Kwauk and Yang, Fluidization X Workshop, 2001.
[3]Shadle et al., CFB X Workshop, 2011.
https:\\mfix.netl.doe.gov

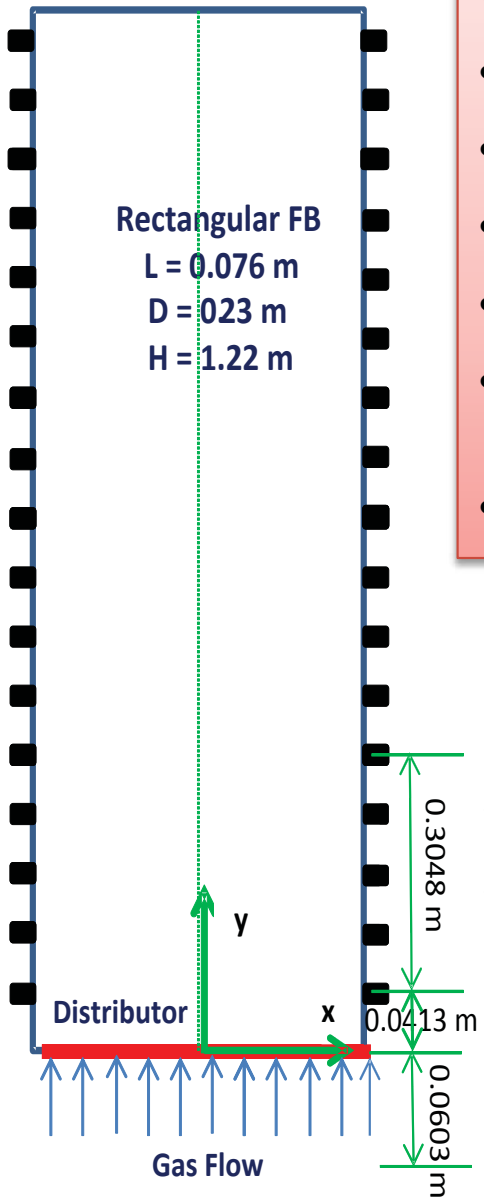
Geldart Group B



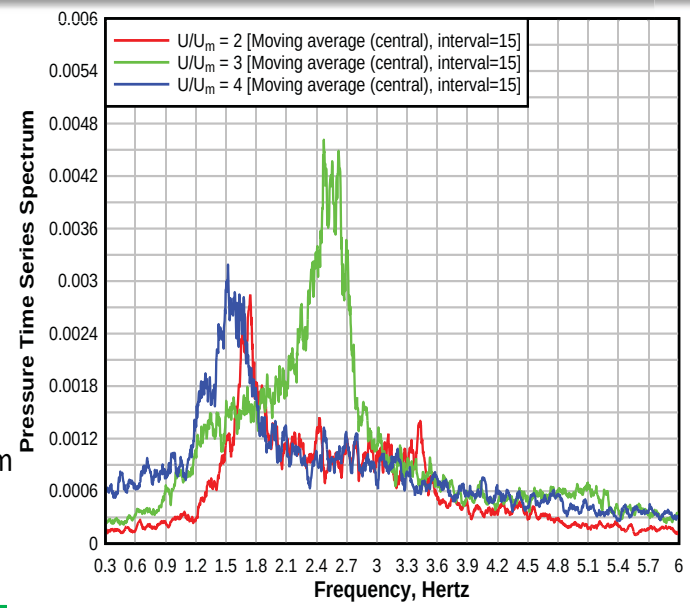
Small Scale Challenge Problem





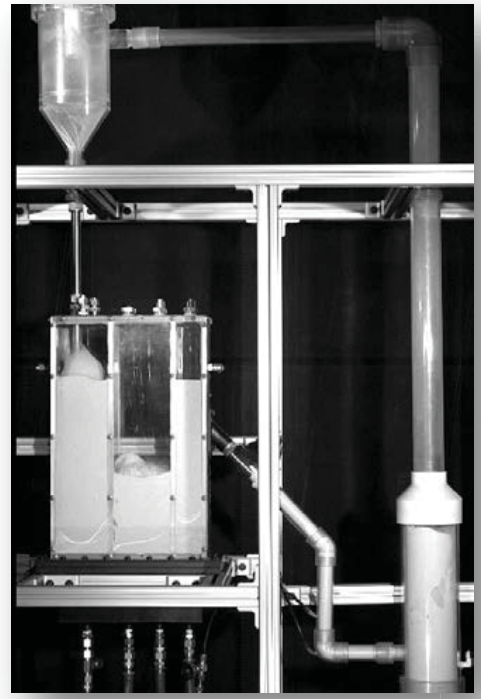


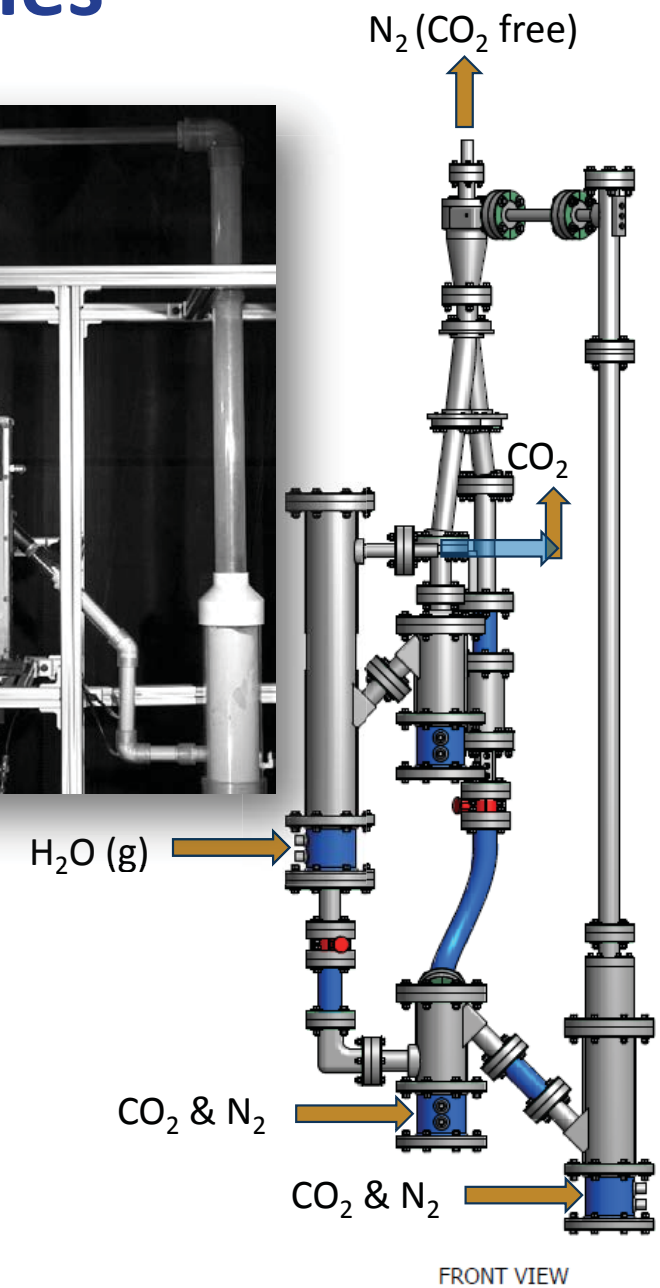
- 22 Inquiries (9 Countries)
- Submissions : 11
- 5 USA; 4 Asia; 2 Europe
- 8 University; 3 Industry
- DEM – 7; E-E – 4
- Submissions anonymous results published
- Already cited



Fluidization Test Facilities

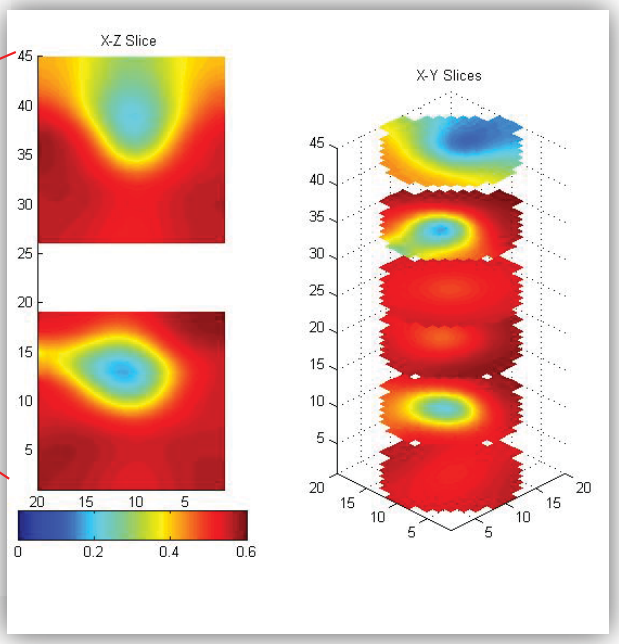
- **Non-Reacting Flows**
  - 12-inch ID Circulating Fluidized Bed
  - 3D Rectangular Fluid Bed
  - Integrated CLR Demo Unit
  - 4-inch ID Bubbling Fluid Bed
  - 2.5-inch ID Minimum Fluidization Unit
- **Reacting Flows**
  - Carbon Capture Unit (C2U)
  - Electro Dynamic Balance

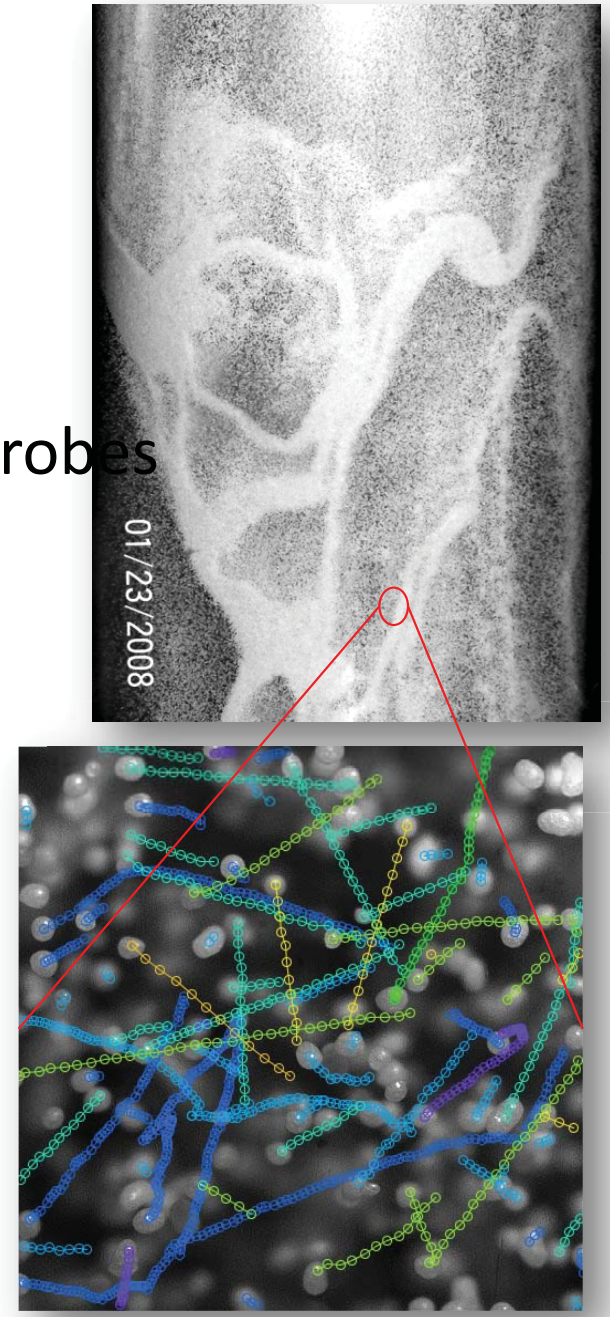




Diagnostics

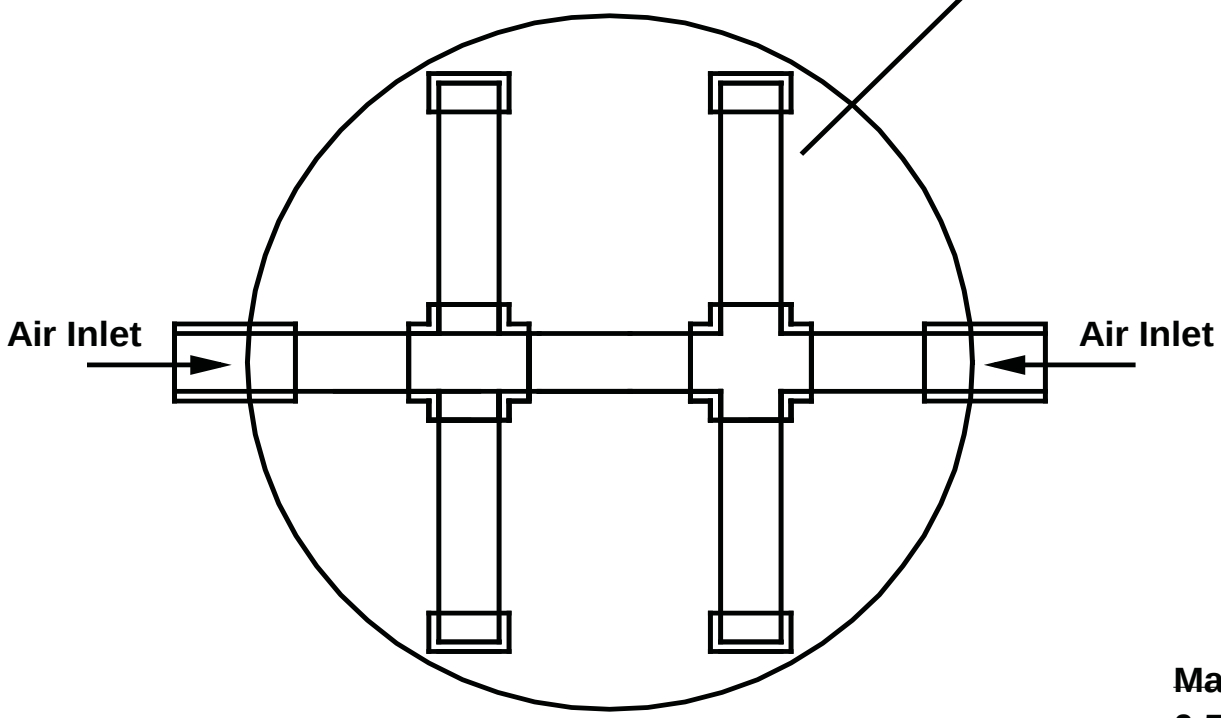
- Electro Capacitance Volumetric Tomography (ECVT)
- High Speed Imaging (HS-PIV)
- Fiber Optic and Piezo-electric probes
- Laser Doppler Velocimetry.
- Spiral solids flow meter

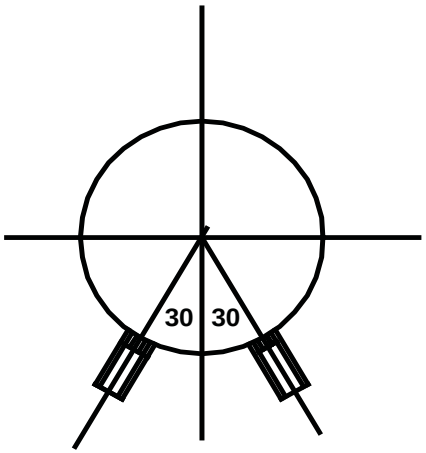




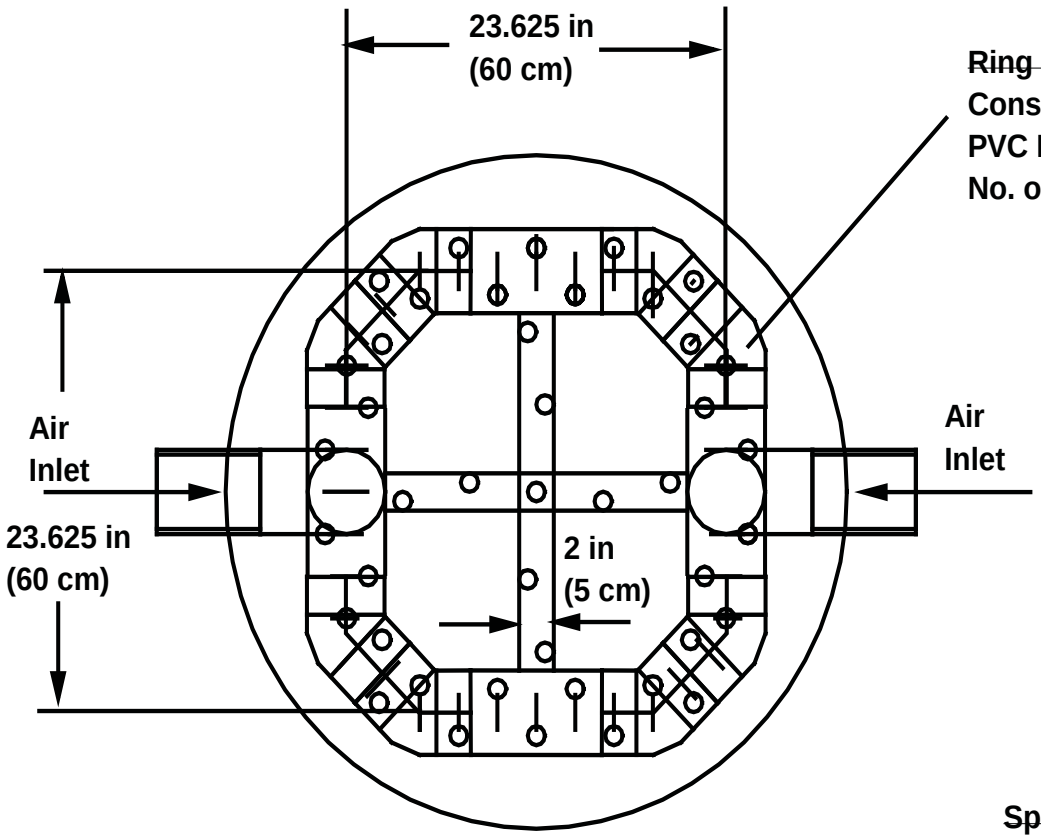
Pipe Manifold Air Distributor (For Tests at U_g < 0.5 m/s)

~~Pipe Manifold Sparger:~~
Constructed From 3 in (7.6 cm) PVC Pipe and Pipe Fittings
No. of Nozzles = 50

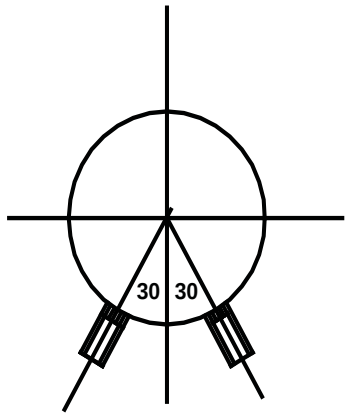




~~Manifold Nozzles:~~
0.5 - in (1.3 - cm)-Dia. PVC Nipples, 2 in (5 cm) Long
Orifice Dia. = 15/64 in (0.6 cm)



~~Ring Sparger:~~
Constructed From 4 in (10.2 cm) PVC Pipe and Pipe Fittings
No. of Nozzles = 36



~~Sparger Nozzles:~~
1- in (2.5-cm)-Dia. PVC Nipples, 3.25 in (8.3 cm) Long
Orifice Dia. = 0.5 in (1.3 cm),
Pitch = 2.125 in (5.4 cm), Staggered and Facing Downwards 30 Degrees From Vertical

Ring Sparger (For Tests at U_g > 0. 5 m/s)

Void Fractions

$$\left(\frac{\Delta P D_p \varphi}{L \rho v_s^2}\right)\left(\frac{\varepsilon^3}{1-\varepsilon}\right) = \frac{150\mu}{D_p \varphi v_s \rho} + 1.7555$$

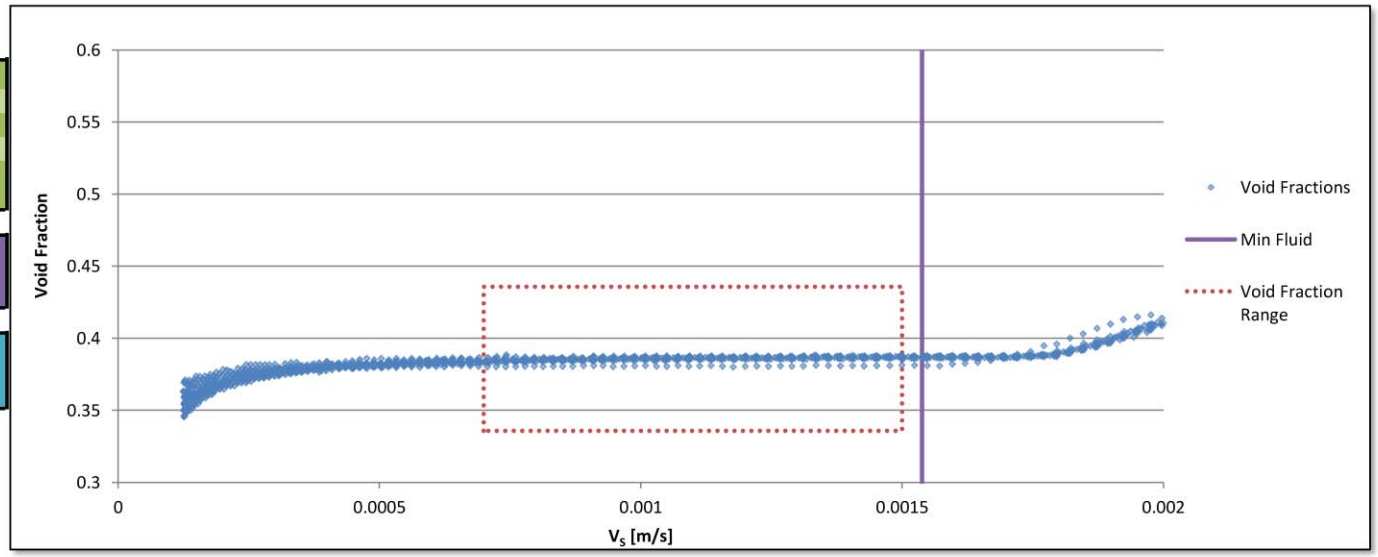
$$\alpha\varepsilon^3 - \beta\varepsilon^2 + (2\beta + \gamma)\varepsilon - (\beta + \gamma) = 0$$

$$\alpha = \frac{\Delta P D_p \varphi}{L \rho v_s^2} \qquad \beta = \frac{150\mu}{D_p \varphi v_s \rho} \qquad \gamma = 1.7555$$

	V_S (m/s)
Define Start of Stable Void Fraction I	0.0007
Define End of Stable Void Fraction L	0.0015
Minimum Fluidization Velocity:	0.001538

Cell Range Used for Void Fraction
Start: 1027
End: 1606

Void Fraction Average (Ramp)
0.3857



Flowrate (SCFH)	ΔP (PSID)	V_s (m/s)	ΔP (Pa)	α	β	γ	A Coef	B Coef	C Coef	D Coef	ε
0.050217	-0.007326	0.00012505	71.563205	2349503.247	277113.4337	1.7555	2349503.247	277113.4337	554228.6229	277115.1892	0.363049437
0.050217	-0.007326	0.00012505	71.563205	2349503.247	277113.4337	1.7555	2349503.247	277113.4337	554228.6229	277115.1892	0.363049437
0.050217	-0.007326	0.00012505	71.563205	2349503.247	277113.4337	1.7555	2349503.247	277113.4337	554228.6229	277115.1892	0.363049437
0.050735	-0.005495	0.00012634	84.18795	2707836.265	274284.1293	1.7555	2707836.265	274284.1293	548570.0141	274285.8848	0.349842896
0.050735	-0.005495	0.00012634	84.18795	2707836.265	274284.1293	1.7555	2707836.265	274284.1293	548570.0141	274285.8848	0.349842896
0.050735	-0.005495	0.00012634	84.18795	2707836.265	274284.1293	1.7555	2707836.265	274284.1293	548570.0141	274285.8848	0.349842896
0.050735	-0.006105	0.00012634	79.982	2572555.338	274284.1293	1.7555	2572555.338	274284.1293	548570.0141	274285.8848	0.354257866
0.050735	-0.005495	0.00012634	84.18795	2707836.265	274284.1293	1.7555	2707836.265	274284.1293	548570.0141	274285.8848	0.349842896
0.050735	-0.005495	0.00012634	84.18795	2707836.265	274284.1293	1.7555	2707836.265	274284.1293	548570.0141	274285.8848	0.349842896
0.050735	-0.005495	0.00012634	84.18795	2707836.265	274284.1293	1.7555	2707836.265	274284.1293	548570.0141	274285.8848	0.349842896
0.050735	-0.005495	0.00012634	84.18795	2707836.265	274284.1293	1.7555	2707836.265	274284.1293	548570.0141	274285.8848	0.349842896
0.050735	-0.006105	0.00012634	79.982	2572555.338	274284.1293	1.7555	2572555.338	274284.1293	548570.0141	274285.8848	0.354257866