INVESTIGATION OF GAS-SOLID FLUIDIZED BED DYNAMICS WITH NON-SPHERICAL PARTICLES

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Presented by: **Norman Love**

THE UNIVERSITY OF TEXAS AT EL PASO
CENTER FOR SPACE EXPLORATION TECHNOLOGY RESEARCH

Project Participants

- PI: Ahsan Choudhuri
- Co-PI: Norman Love

- Masters: MD Rashedul Sarker
- Undergrad: ASM Chowdhury

<u>Graduates</u>

Mario Ruvalcaba (Now at Federal Mogul)

MD Mahamudur Rahman (Now at Drexel Univ)

Publications and Presentations

JOURNAL PAPER

Ruvalcaba, M., Sarker, M., Love, N., and Choudhuri, A., "Experimental and Numerical Study on the Effect of Particle Geometry on Drag and Flow Behaviors in a Packed Fluidized Bed," 2012 (In Preparation).

CONFERENCE PAPERS

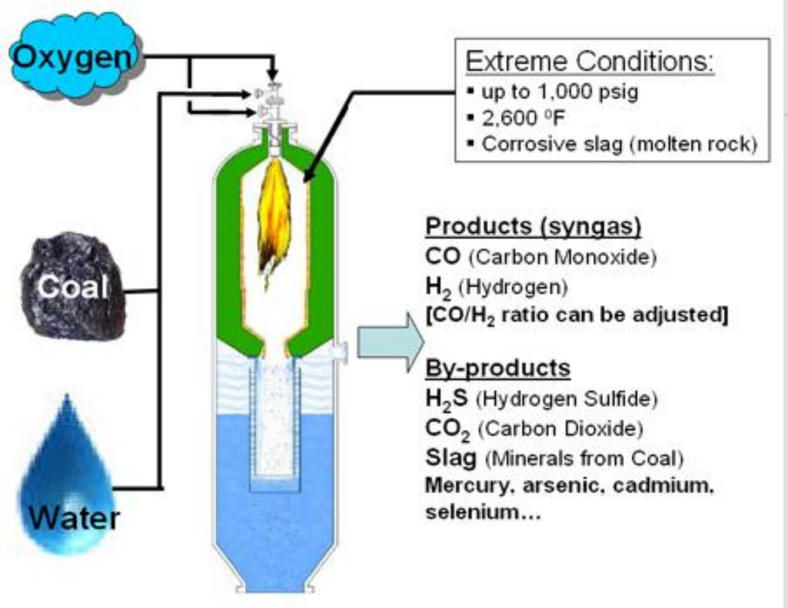
Ruvalcaba, M., Rahman, M., Love, N., and Choudhuri, A., "Numerical Study of Gas- Solid Fluidized Bed Dynamics," AIAA-2012-0643, *50th Aerospace Sciences Meeting*, AIAA, Nashville, TN, January 6-9, 2012.

Sarker, M., Rahman, M., Love, N., and Choudhuri, A., "Effect of Bed Height, Bed Diameter, and Particle Shape on Minimum Fluidization in a Gas-Solid Fluidized Bed," AIAA-2012-0644, *50th Aerospace Sciences Meeting and Exhibit*, AIAA, Nashville, TN, January 6 – 9, 2012.

Ruvalcaba, M., Rahman, M., Love, N., and Choudhuri, A., "Analysis of Drag on Non-Spherical Particles in a Fluidized Bed," AIAA-2011-5746, *9th International Energy Conversion Engineering Conference and Exhibit*, AIAA, San Diego, CA, July 31-August 3, 2011.

Rahman, M., Ruvalcaba, M., Love, N., and Choudhuri, A., "Investigation of Gas-Solid Fluidized Bed Dynamics with Spherical and Non-Spherical Particles," AIAA-2011-0131, *49th Aerospace Sciences Meeting and Exhibit*, AIAA, Orlando, FL, January 4 – 7, 2011.

Gasification



U.S. Department of Energy, Clean Coal & Natural Gas Power Systems, www.fossil.energy.gov/programs /powersystems/gasification/index.html, May 25, 2010

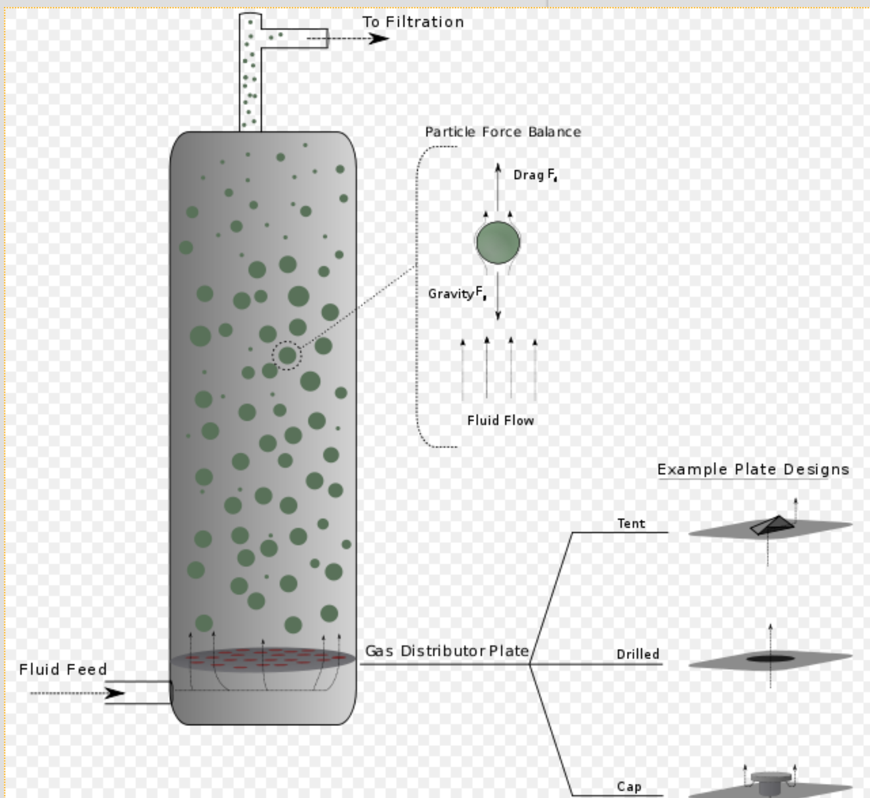
$$\text{Feedstock} \xrightarrow{\text{Heat, Pressure, Steam}} CO + H_2 \text{ (Syngas)}$$

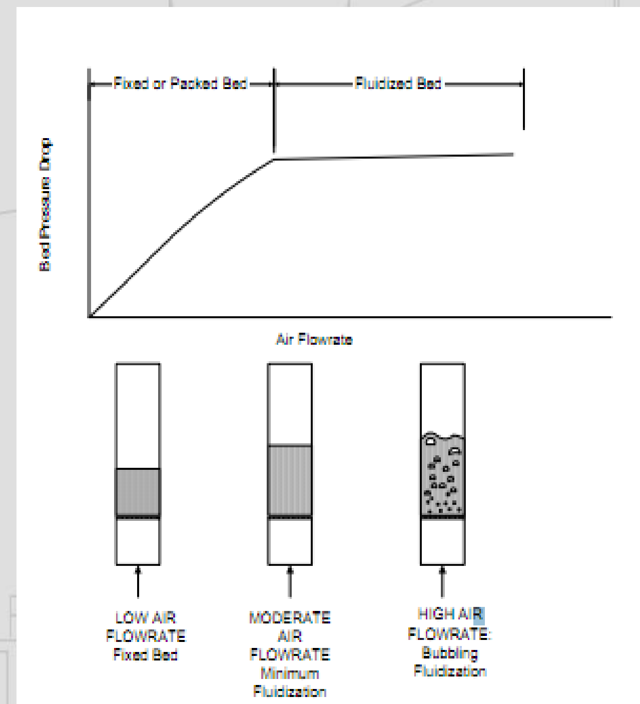
- **<u>Gasifier:</u>**
  - Types of gasifiers used commercially:

Counter-current fixed bed	Fluidized bed
Co-current fixed bed	Entrained flow

Fluidized Bed

- **<u>Fluidized Bed Reactor:</u>**
  - Solid particles
    - Become suspended
    - Behave as though they were a fluid





http://en.wikipedia.org/wiki/Fluidized_bed

Background

- **2006 Multiphase Workshop-** postulated a set of near-midterm, mid-term, and long-term research needs to attain a significant development in the design, operation, and troubleshooting of multiphase flow devices in fossil fuel processing plants by the year 2015.

- Despite previous efforts on gas-solid flows in a fluidized bed, bed dynamics and particle scale motions are still poorly understood

- A majority of past experimental and computational efforts have been focused on the behavior fluidized bed with spherical particles whereas in most fossil-fuel processes the particles are often non-spherical

Project Objectives

Objective 1: To Evaluate Drag Force on Non-Spherical Particles

Objective 2: To Incorporate Experimental Data for Non-Spherical Particles in MFIX and FLUENT

Objective 3: To Obtain Full-Field Visualization of Motions of Non-Spherical Particles

Tasks- Overview

Year 1:

- Task 1: Design of the Experimental Setup: Production and Categorization of Non-Spherical Particles
- Task 2: Map fluidization velocities in bed
- Task 3: Terminal Velocity Determination of Free Falling Non-Spherical Particles

Year 2:

- Task 4: Obtain Drag relations for Non-Spherical Particles
- Task 5: Modeling of Pressure Drop and Terminal Velocities in Fluidized Bed for Non-Spherical Particles
- Task 6: Implement Experimental Drag Relations Using Numerical Model

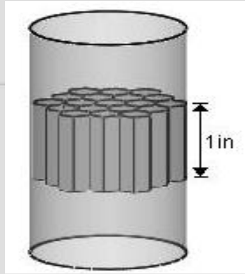
Year 3:

- Task 6 Continued: Implement Experimental Drag Relations Using Numerical Model
- Task 7: Integration of the Imaging Instrumentation and Diagnostics with the Experimental Setup
- Task 8: Development of Algorithm for Detection of Non-Spherical Geometries, Particle Pair Identification, Trajectory, and Velocity Components

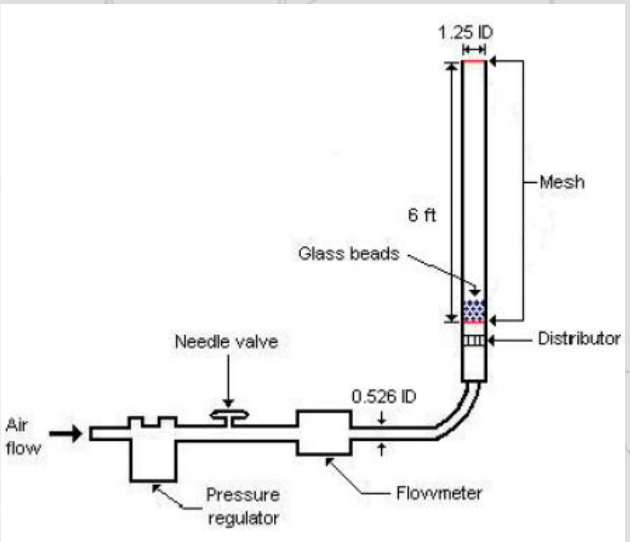
Outline

- Experimental Benchmarking – Spherical Particles
  - 1^{st} Generation Bed
  - 2^{nd} Generation Bed
- Measure the effect of:
  - Bed Height
  - Particle Shape
- Development of numerical models
  - Benchmarking with experimental data
  - Drag model development
  - Implementation into FLUENT
- Qualitative comparisons with Computational Data
  - High-speed camera Images

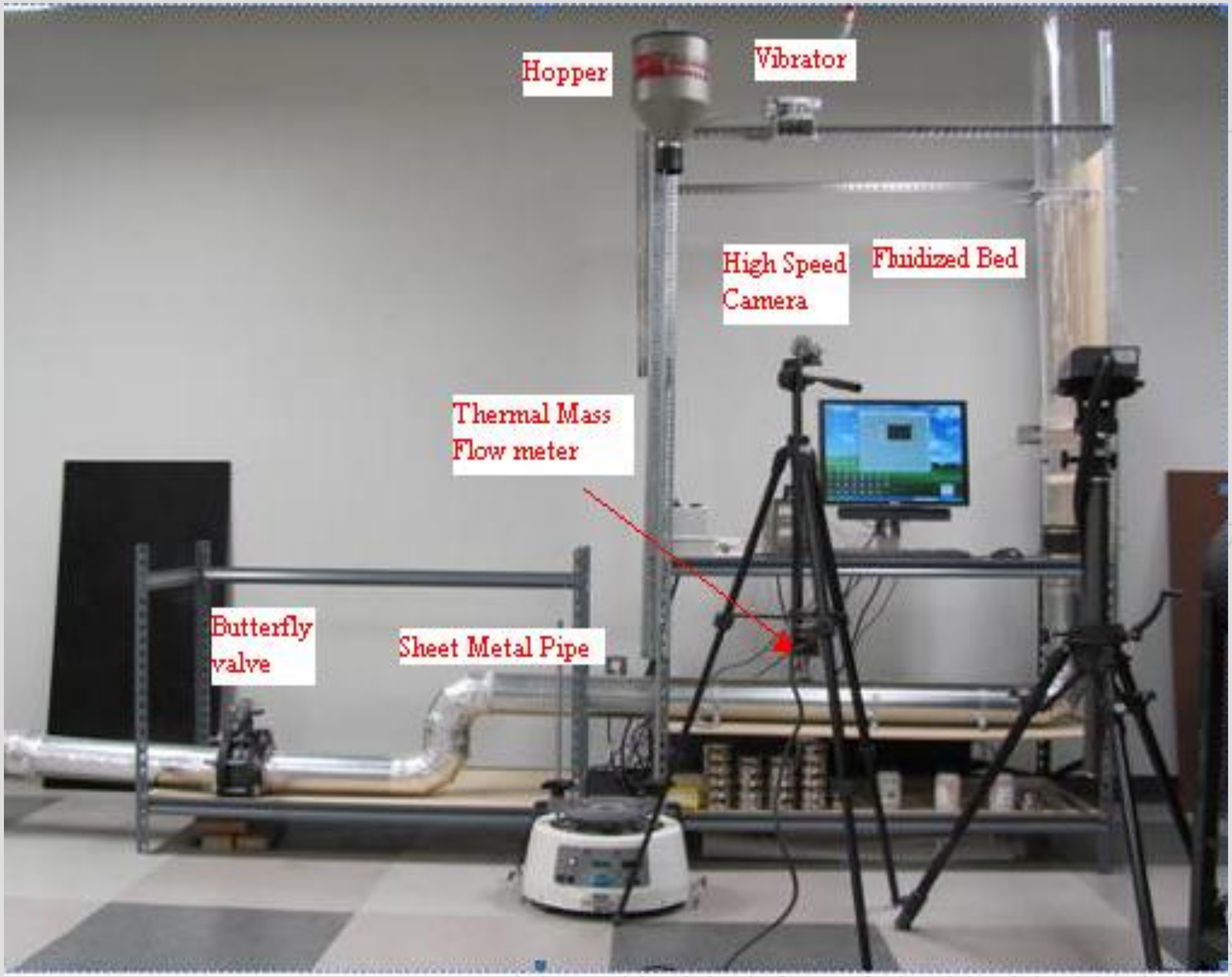
Experimental Setup 1st Gen



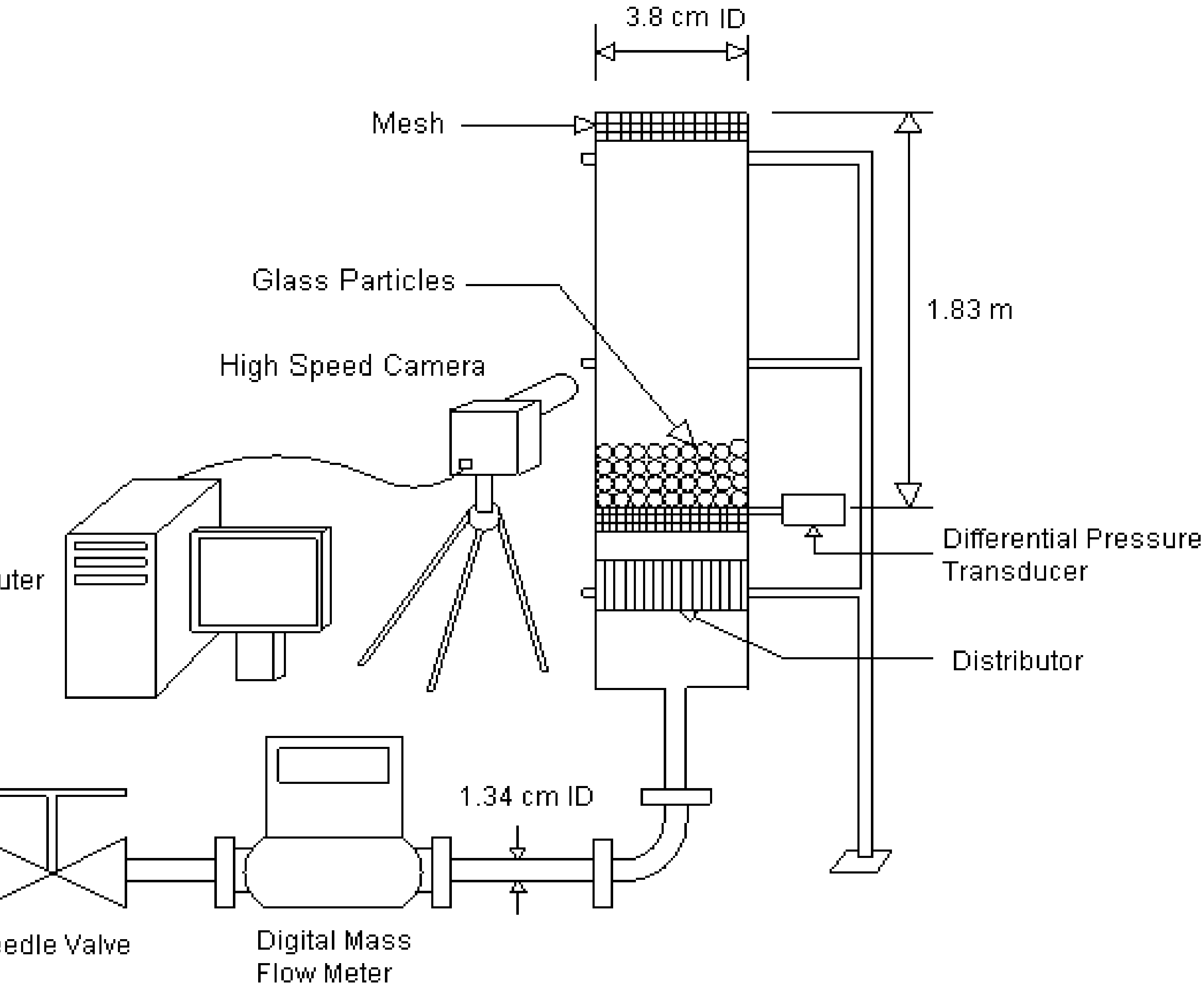
1	Pressure Transducer
2	High-Speed Camera
3	LDV



Experimental Setup 2nd Gen

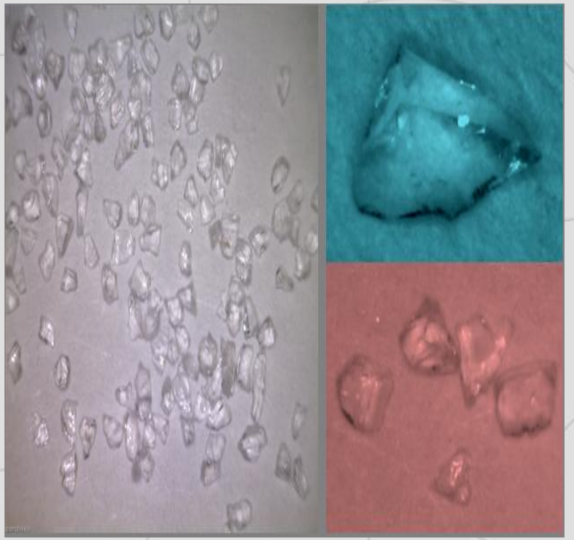


Experimental Setup



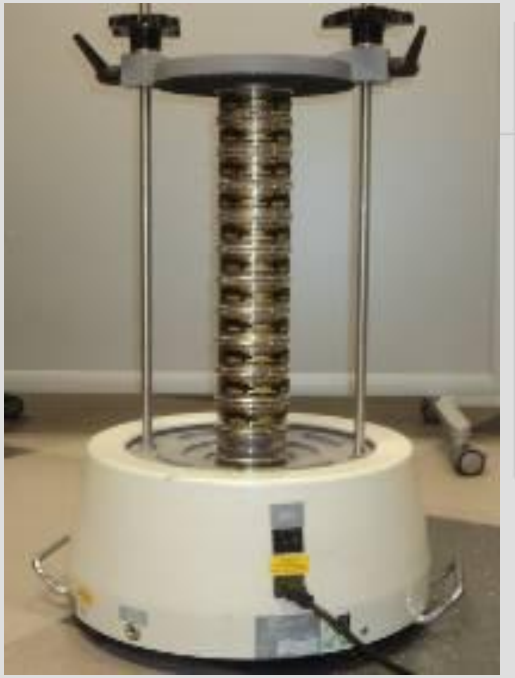
Test Particles

Spherical
Mean Diameter = 1 mm



Non-spherical
Mean Diameter = 0.9-1 mm

Particle Production



Sieve Shaker and Sieves

Hydraulic Compressor

Particle Size

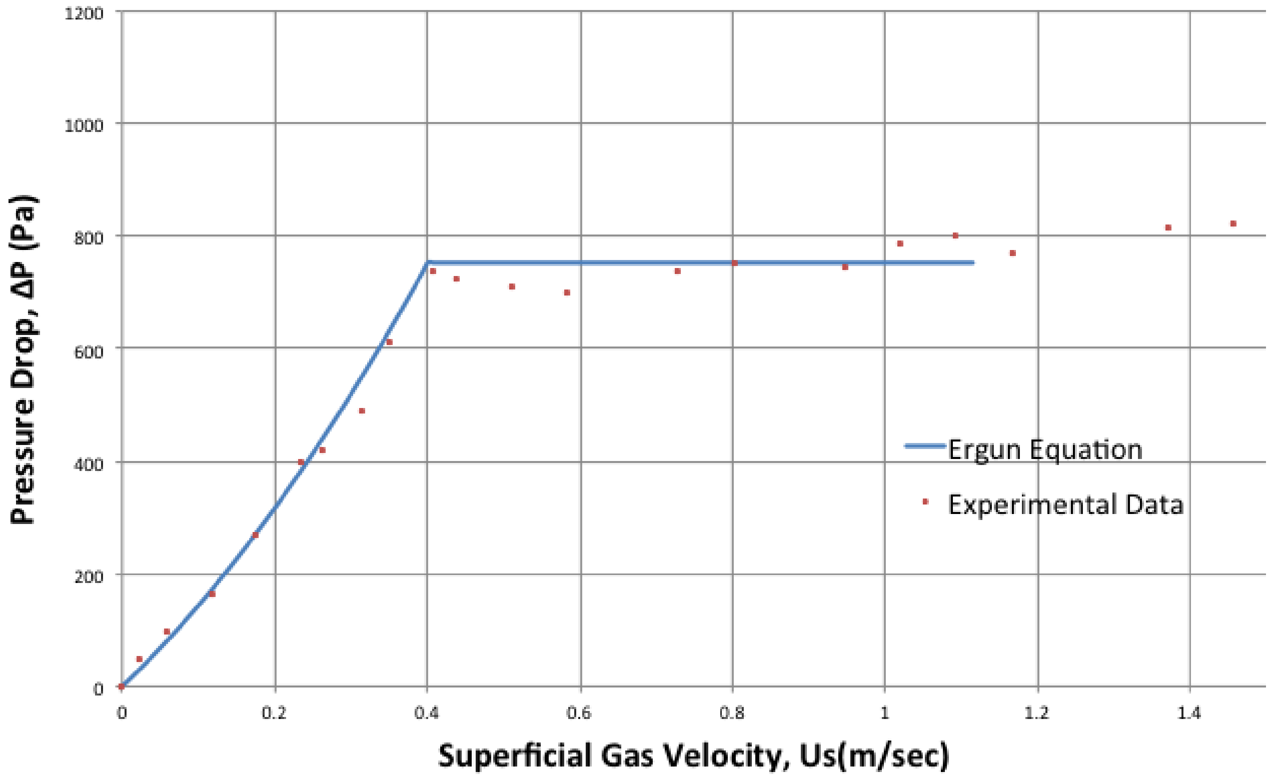
- **Spherical Particles**
  - 1 mm borosilicate glass beads with a density of 2230 kg/m^3

- **Non-Spherical Particles:**
  - Sieve was used to get the particle size distribution
  - Mean particle size is 0.9 – 1 mm

Physical Properties	
SiO_2 = 80.6%	Coefficient of expansion (20°C–300°C) 3.3 x 10^{-6} K^{-1}
$B2O_3$ = 13.0%	Density 2.23g/cm^3
Na_2 O = 4.0%	Refractive index (Sodium D line) 1.474
$Al2O_3$ = 2.3%	Dielectric constant (1MHz, 20°C) 4.6
Optical Information	Specific heat (20°C) 750J/kg°C
Refractive index (Sodium D line) = 1.474	Thermal conductivity (20°C) 1.14W/m°C
Visible light transmission, 2mm thick glass = 92%	Poisson's Ratio (25°C – 400°C) 0.2
Visible light transmission, 5mm thick glass = 91%	Young's Modulus (25°C) 6400 kg/mm2

Experimental Benchmarking

$$\frac{\Delta P_b}{L} = 150 \; \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu_f U}{(\varphi \, d_m)^2} + 1.75 \; \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho_f U^2}{\varphi \, d_m}$$



Void Fraction

- Spherical Particles
  - Fluidized beds are made densely packed by shaking.
  - Voidage ranged from 0.37 to 0.39 for dense packed bed of monosized spherical particles
- Non-Spherical Particles
  - Packing void fraction depends on particles sphericity

	Voidage	
Sphericity	Loose Packing	Dense Packing
0.25	0.85	0.8
0.3	0.8	0.75
0.35	0.75	0.7
0.4	0.72	0.67
0.45	0.68	0.63
0.5	0.64	0.59
0.55	0.61	0.55
0.6	0.58	0.51
0.65	0.55	0.48
0.7	0.53	0.45
0.75	0.51	0.42
0.8	0.49	0.4
0.85	0.47	0.38
0.9	0.45	0.36
0.95	0.43	0.34
1	0.41	0.32

Yang W.C., "Handbook of Fluidization and Fluid-Particle Systems",Marcel Dekker Inc, Madison Aveneu, New York 2003

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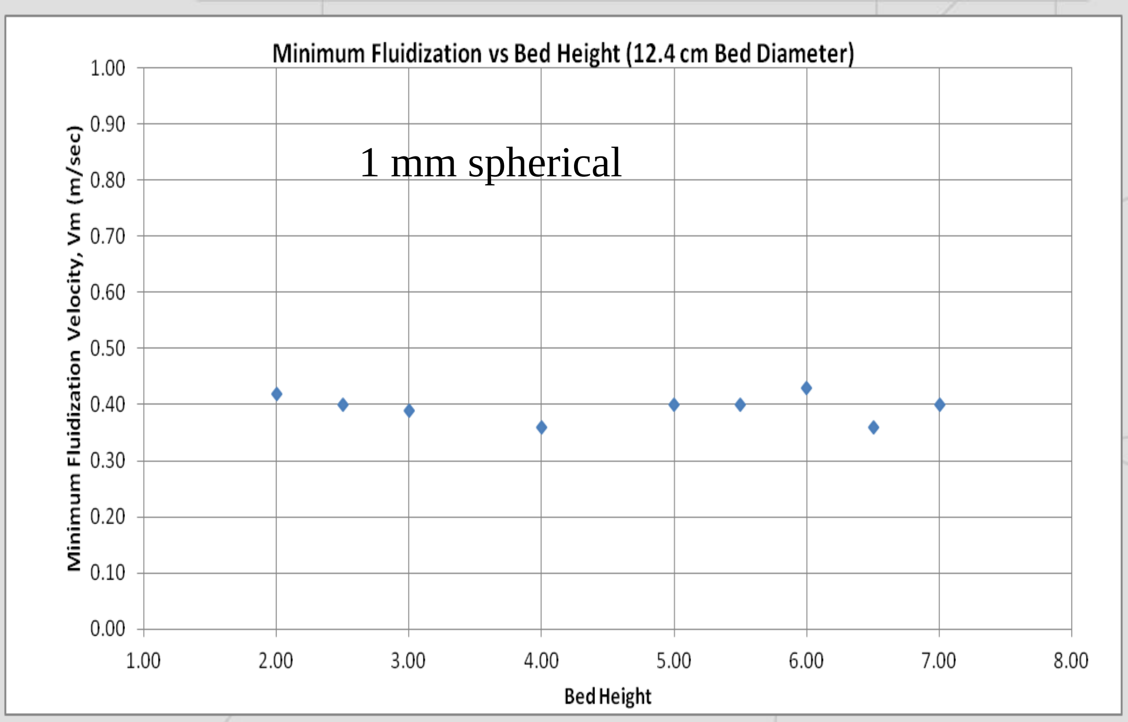
  - High-speed camera Images

Effect of Bed Height

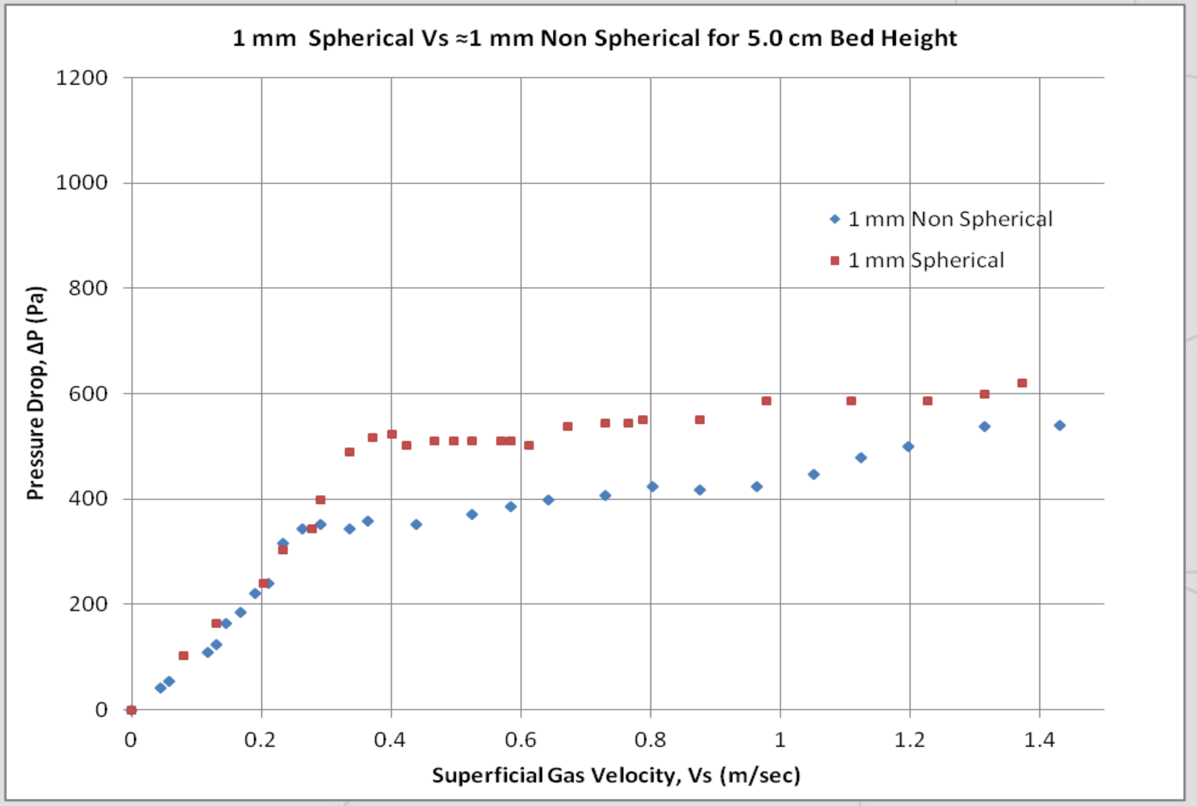
❑ Spherical Particles:



$$\Delta P = 150 \frac{(1-\varepsilon)^2 \mu}{D_P^2 \varepsilon^3} H V_s + 1.75 \frac{(1-\varepsilon)\rho_f}{D_P \varepsilon^3} H V_s^2$$

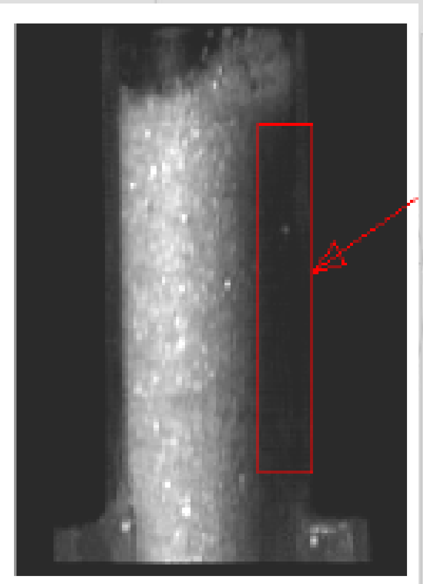
$$\Delta P = g\,(1-\varepsilon)\,(\rho_P - \rho_f)\,H$$

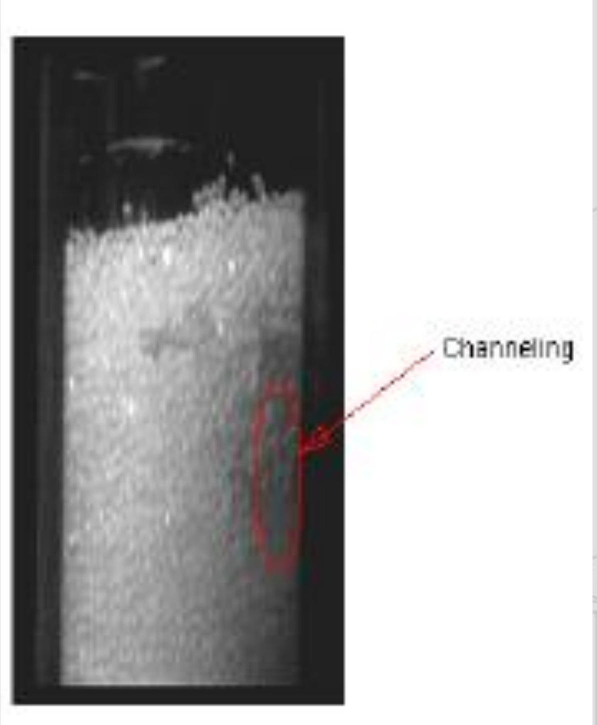
Effect of Particle Shape



- Non-spherical particles had higher voidage fractions (ε)
- Particle bed weights were measured: spherical particles with the same bed heights contained higher mass then the non spherical particles.

- Higher channeling for non-spherical particles
- Pressure drop due to high velocities





- Channeling caused non-uniform distribution of fluid and solid inside of bed

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  - High-speed camera Images

Objective

- To develop and validate a computational model that can predict the pressure drop across a packed bed operating with spherical or non-spherical particles

- Use both FLUENT and MFIX to develop the model and compare results
  - FLUENT, a general-purpose CFD code based on the finite volume method on a collocated grid.

  - MFIX (Multiphase Flow with Interphase eXchanges), a solver developed at the Department of Energy's National Energy Technology Laboratory (NETL) for multiphase flows

Theory

Governing Equations:

- Volume Fraction

$$\varepsilon_g + \varepsilon_s = 1$$

- Continuity Eqn.

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

- Momentum Eqns.

$$\frac{\partial}{\partial t}(\varepsilon_g \, \rho_g \overrightarrow{v_g}) + \nabla \cdot (\varepsilon_g \, \rho_g \overrightarrow{v_g} \, \overrightarrow{v_g}) = \nabla \cdot \overline{\overline{S_g}} + \varepsilon_g \, \rho_g \vec{g} + \overrightarrow{I_{gs}}$$

the rate of momentum transfer between the gas and solid phase per unit volume

$$\overrightarrow{I_{gs}} = -\varepsilon_s \nabla P_g - F_{gs}(\overrightarrow{v_s} - \overrightarrow{v_g})$$

Drag Force

Theory

- **Spherical Particles**
- Two popular drag models were tested:
  - Gidaspow et al. (1992)
    - Gidaspow, D., Bezburuah, R., and Ding, J., “ Hydrodynamics of Circulating Fluidized Beds, Kinetic Theory Approach,” *Proceedings of the 7th Engineering Foundation Conference on Fluidization*, Engnieerign Foundation, Brisbane, Australia, 1992, pp. 75-82.
  - Syamlal and O’brien (1989)
    - Syamlal, M., and O’Brien, T., “Computer Simulation of Bubbles in a Fluidized Bed,” AIChE Symposium Series, Vol. 85, 1989, pp.22–31.

Theory

- Gidaspow et al. (1992)

$$F_{gs} = \begin{cases} \frac{3}{4} C_{D-sphere} \frac{\rho_g \varepsilon_g \varepsilon_s |\vec{v_s} - \vec{v_g}|}{d_p} \varepsilon_g^{-2.65} & \varepsilon_g \geq 0.8 \\ \frac{150 \varepsilon_s (1-\varepsilon_g) \mu_g}{\varepsilon_g d_p^2} + \frac{1.75 \rho_g \varepsilon_s |\vec{v_s} - \vec{v_g}|}{d_p} & \varepsilon_g < 0.8 \end{cases}$$

$$C_{D-sphere} = \begin{cases} 24/Re(1 + 0.15 Re^{0.687}) & Re \leq 1000 \\ 0.44 & Re > 1000 \end{cases}$$

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

v_s	=	solids velocity	ε_s	=	solids volume fraction
v_g	=	gas velocity	ε_g	=	gas volume fraction

Theory

- Syamlal and O'brien (1989)

$$F_{gs} = \frac{3\varepsilon_s \varepsilon_g \rho_g}{4{v_t}^2 d_p} C_{D-sphere} \left| \overrightarrow{v_s} - \overrightarrow{v_g} \right|$$

$$C_{D-sphere} = \left(0.63 + 4.8\sqrt{\frac{v_t}{Re}} \right)^2$$

$$v_t = 0.5\left(A - 0.06Re + \sqrt{(0.06Re)^2 + 0.12Re(2B - A) + A^2} \right)$$

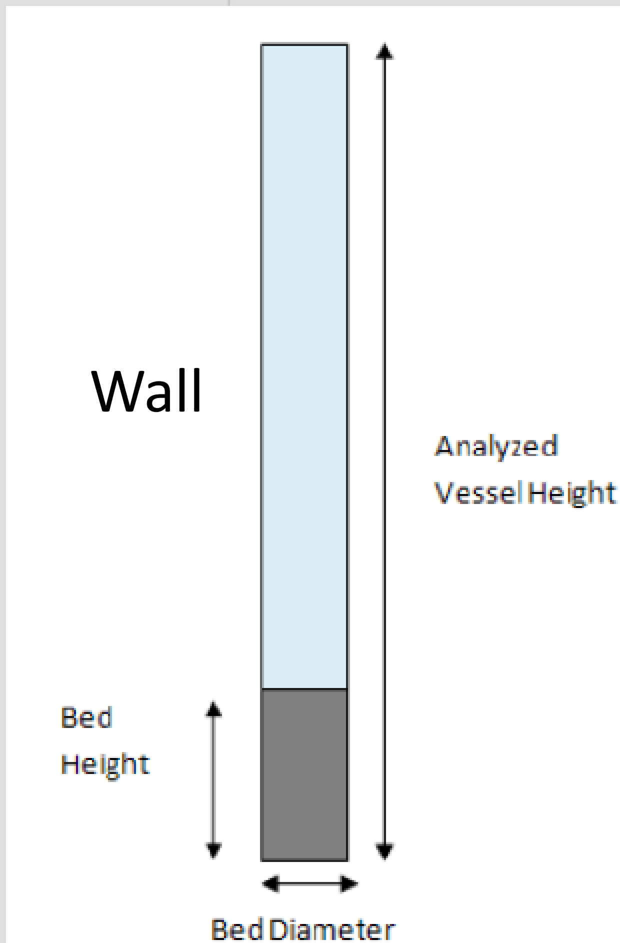
$$A = {\varepsilon_g}^{4.14}$$

$$B = \begin{cases} 0.8{\varepsilon_g}^{1.28} & \varepsilon_g \leq 0.85 \\ {\varepsilon_g}^{2.65} & \varepsilon_g > 0.85 \end{cases}$$

$$Re = \frac{d_p \left| \overrightarrow{v_s} - \overrightarrow{v_g} \right| \rho_g}{\mu_g}$$

Numerical Model

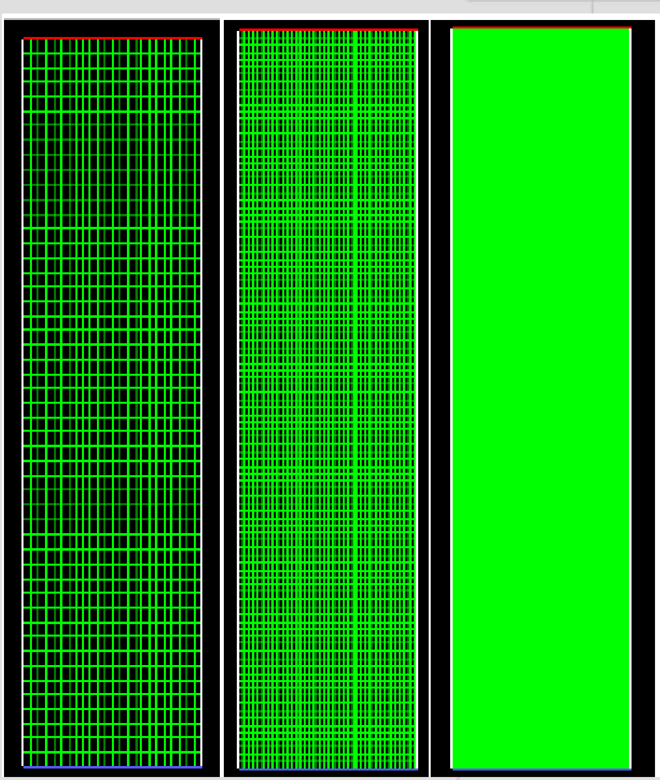
Pressure Outlet

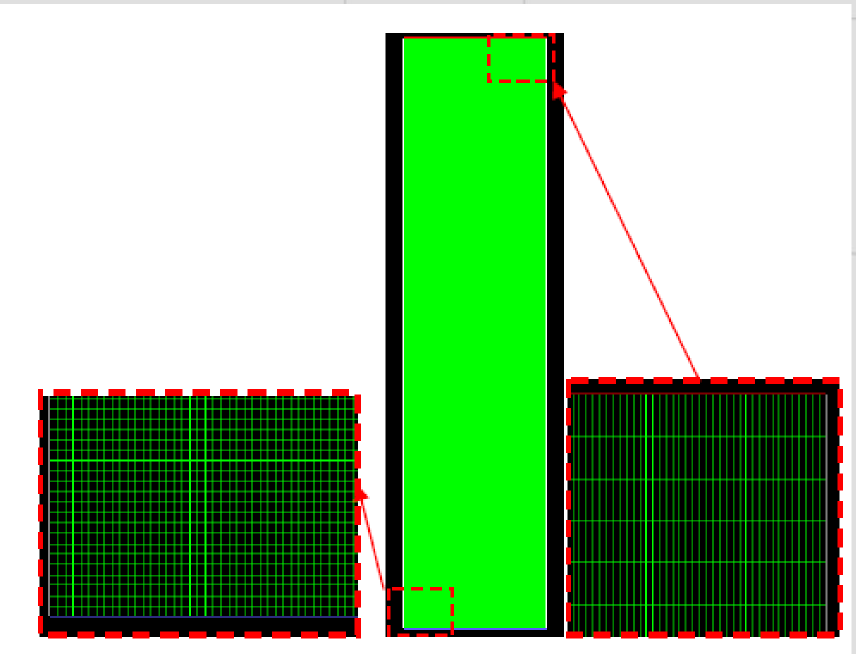


Velocity Inlet

Bed Section	
Gas Void Fraction (ε_g)	0.37
Gas Velocity (v_g)	5 cm/s

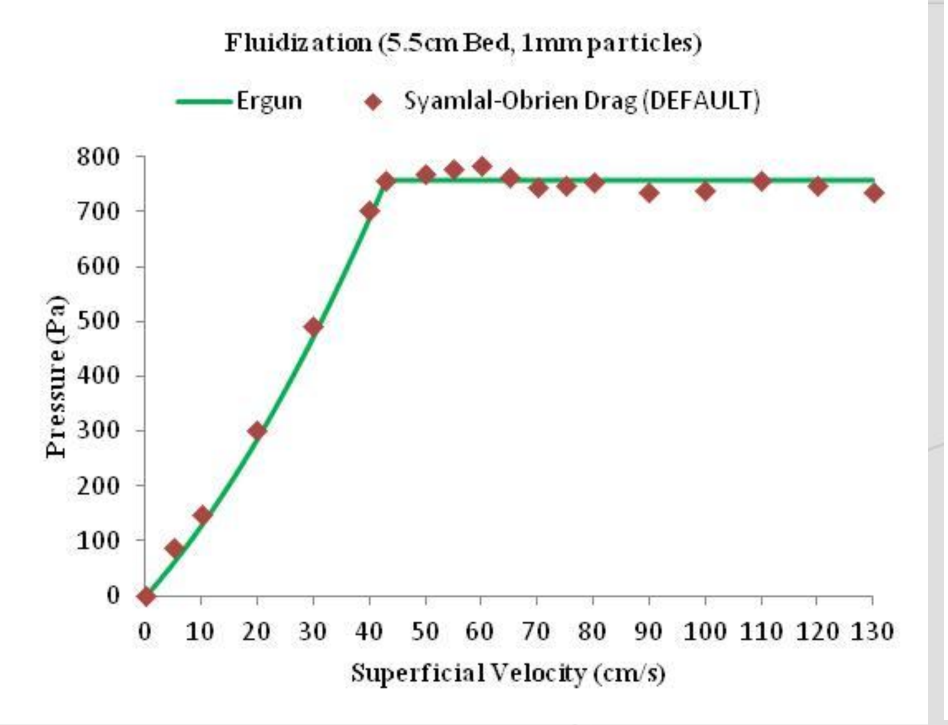
Numerical Model

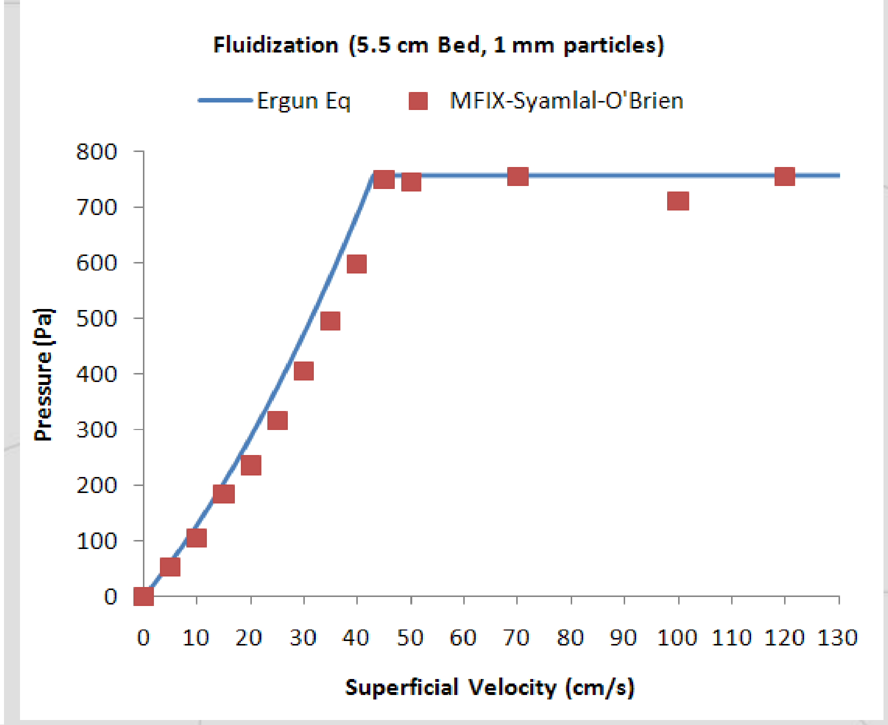




Grid	Cells
1	4800
2	24200
3	64400
4	100625
5	35420 (Adaptive)

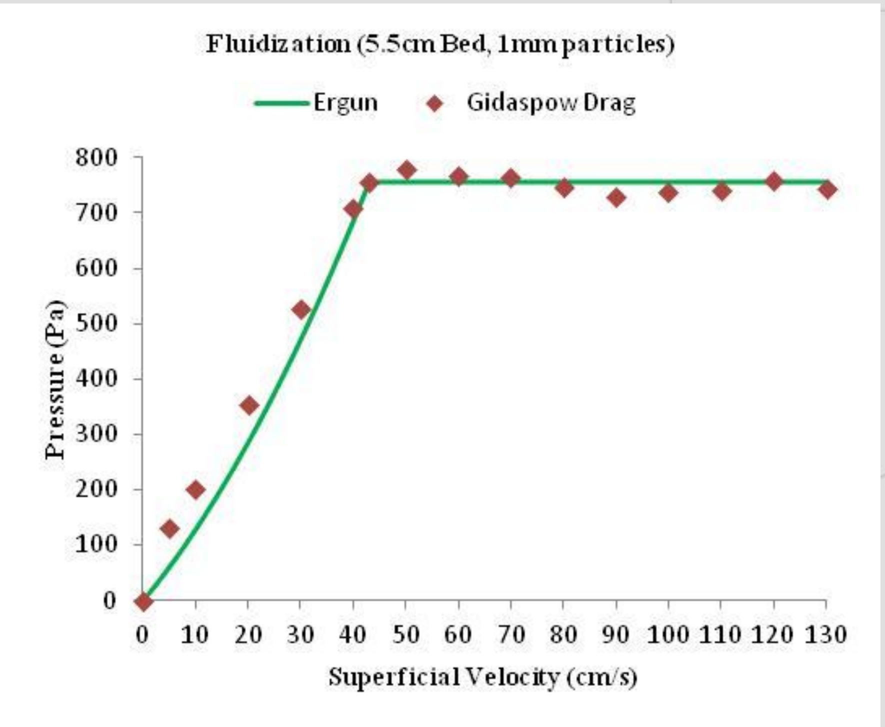
Results

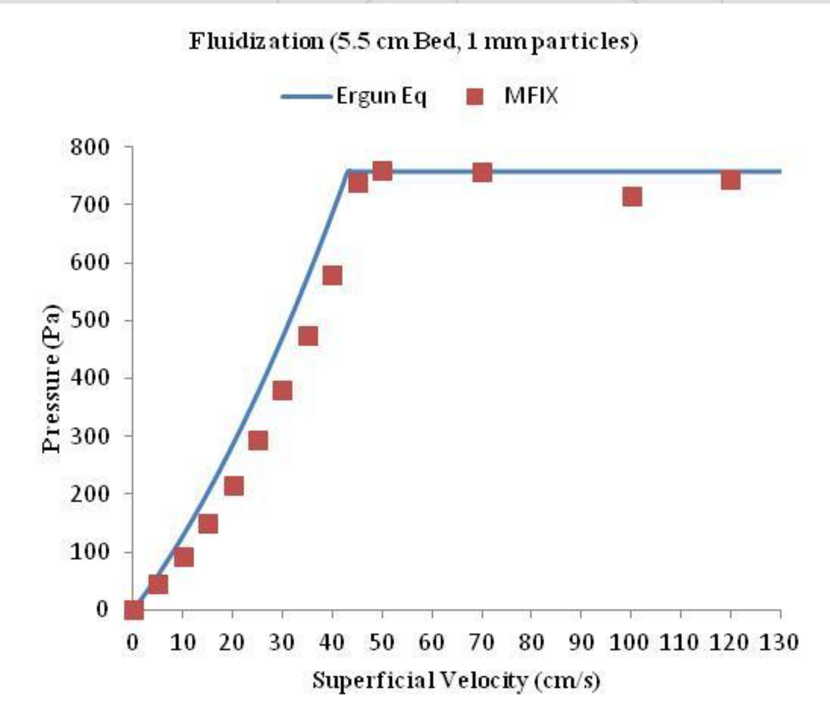




Spherical

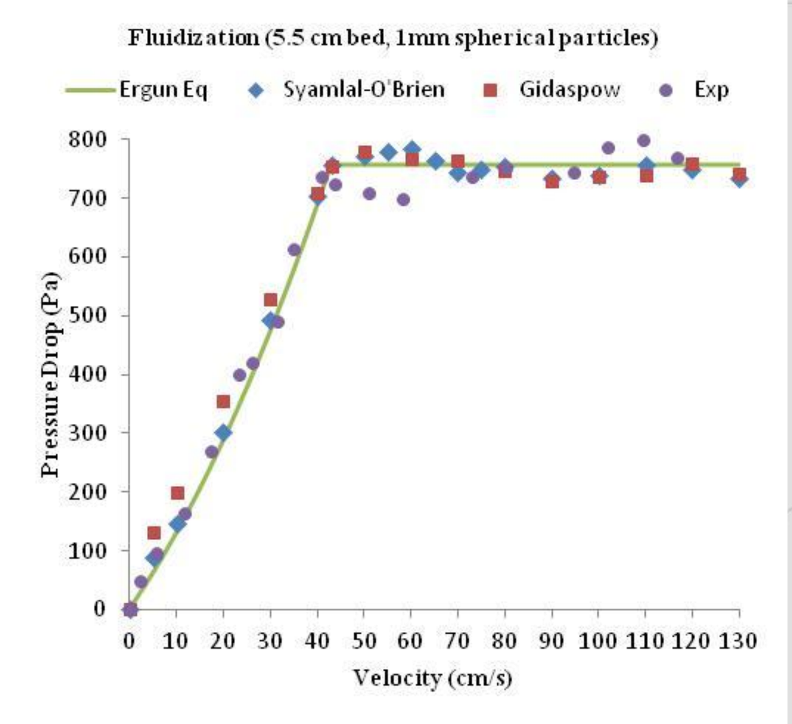
Results

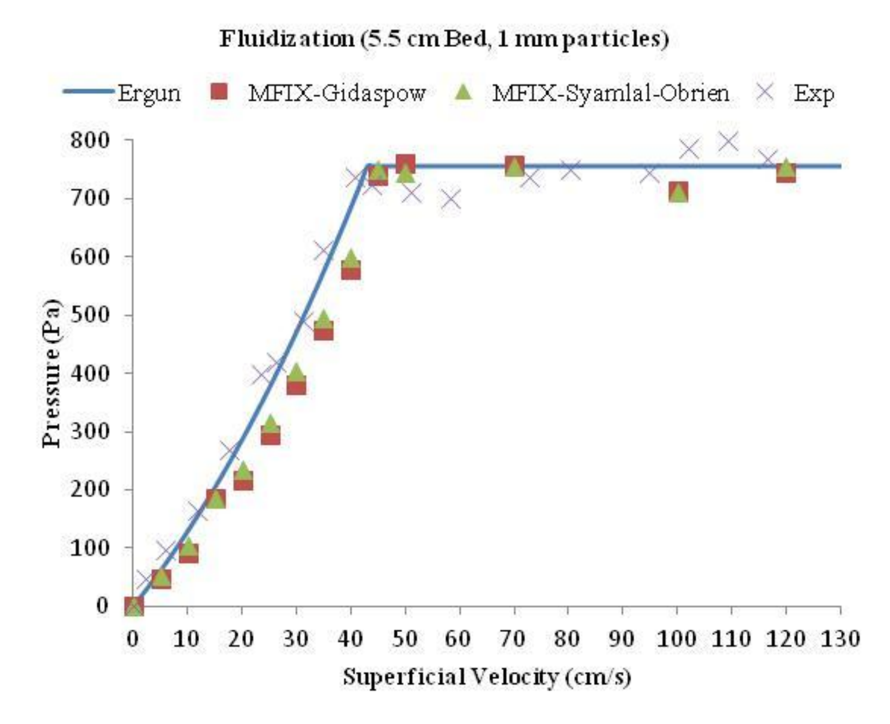




Spherical

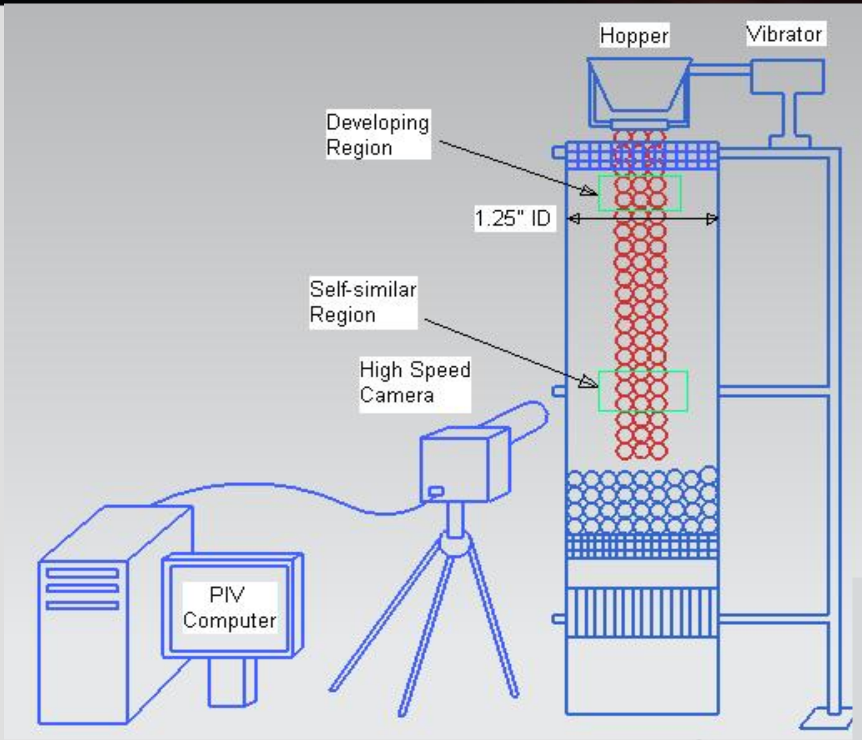
Benchmarking with Experiments

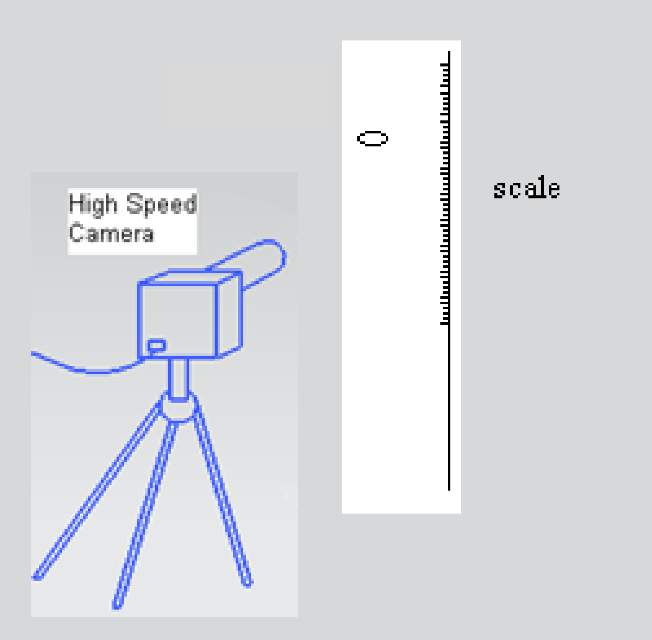


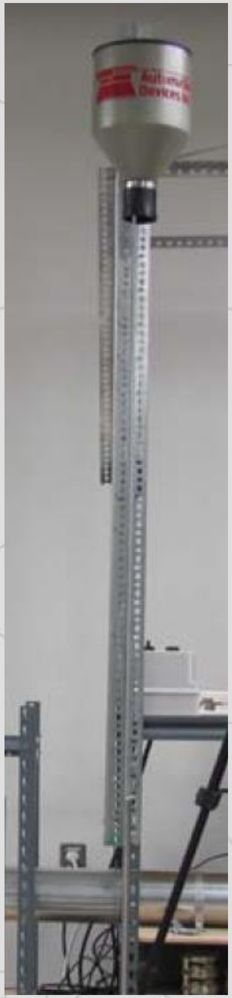


Spherical

Drag Model Development



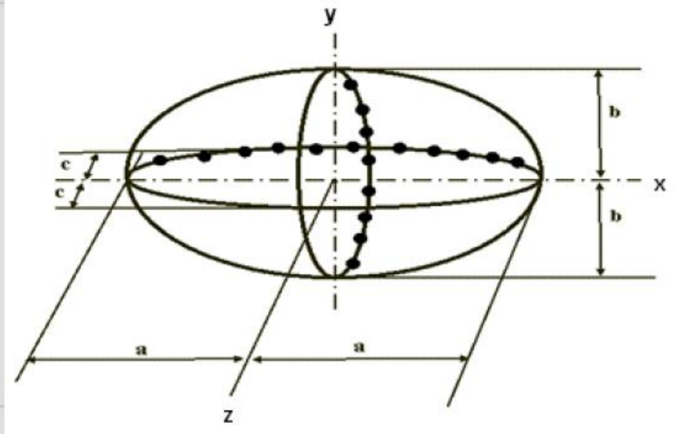




Drag Model Development

- The rice grains were assumed to ellipsoid in shape
- The Eqn. used to determine the initial terminal velocity :

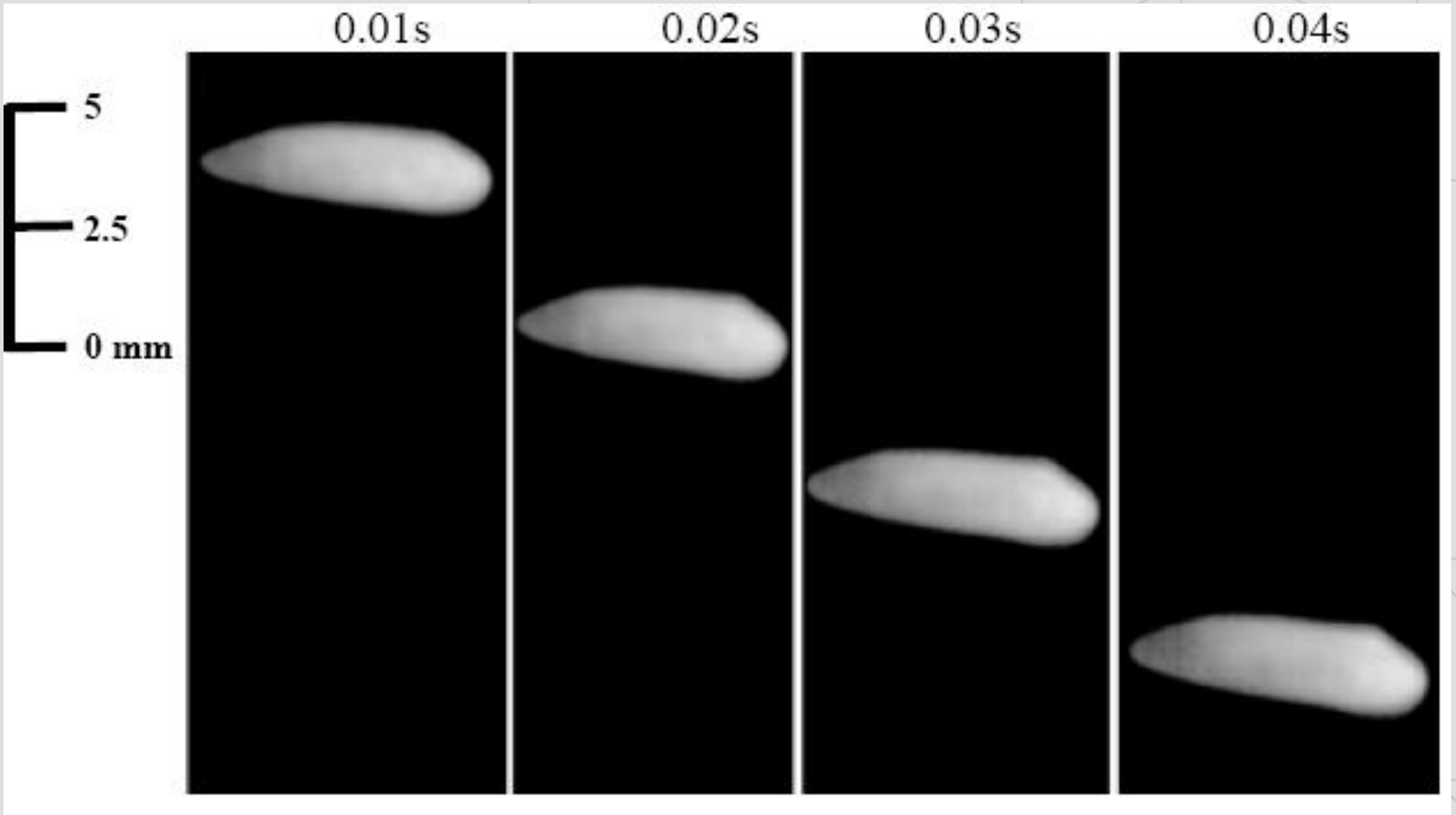
$$v_t = \sqrt{\frac{8\,bg}{3\,C_D}\frac{(\rho_s - \rho_f)}{\rho_f}}$$



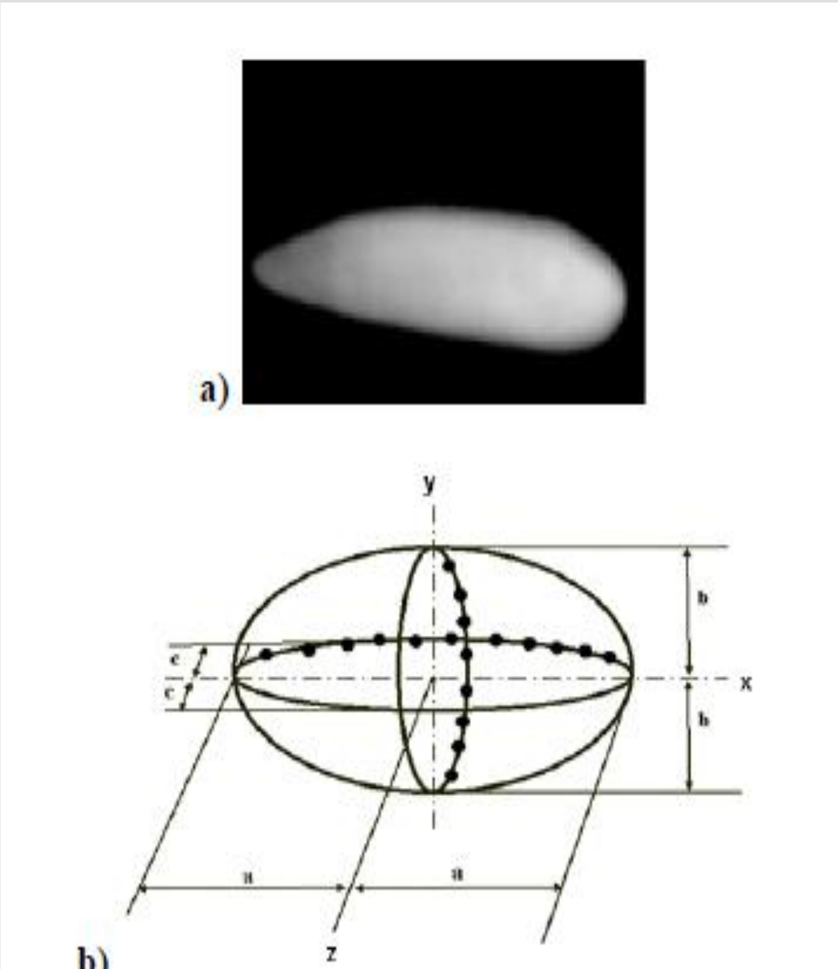
where V_t is the terminal velocity, b is the mean polar diameter along the y-axis, ρ_s is the density of rice grain, ρ_f is the density of air, and C_D is the drag coefficient initially assumed to be 0.6.

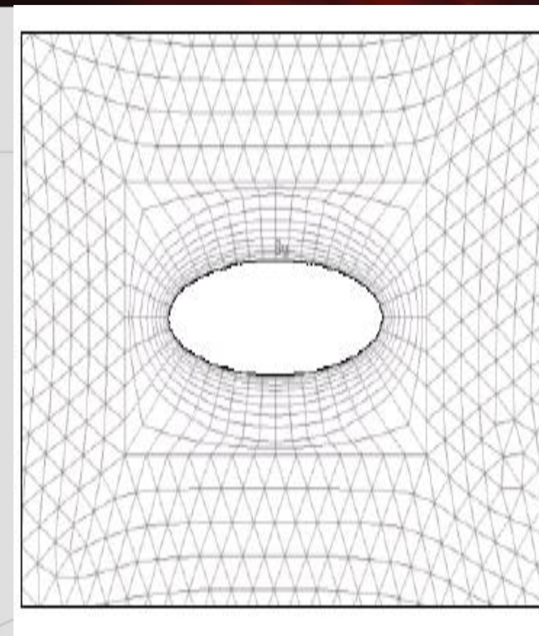
- Rice density 577 kg/m^3
- Air density as 1.2 kg/m^3
- 3100 frames per second

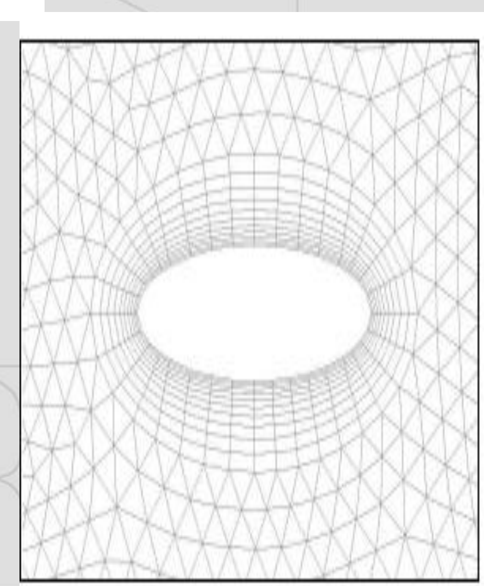
Drag Model Development



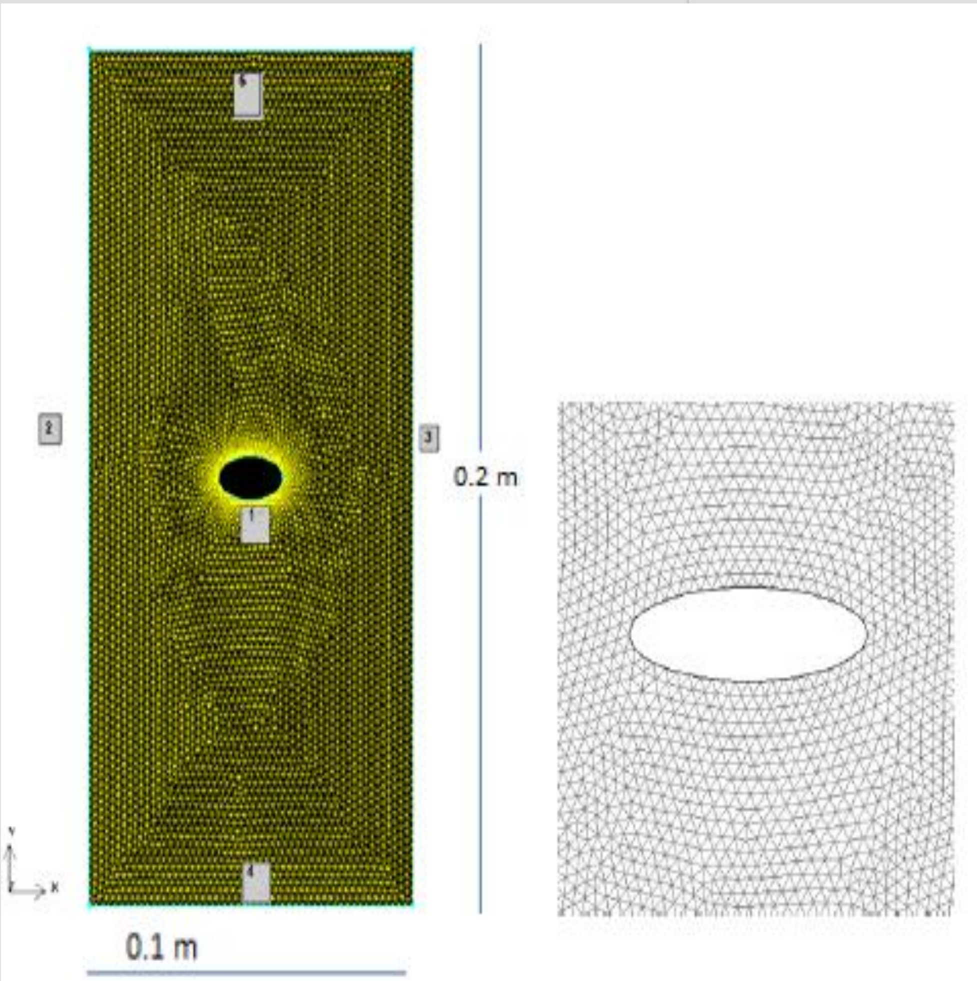
Drag Model Development





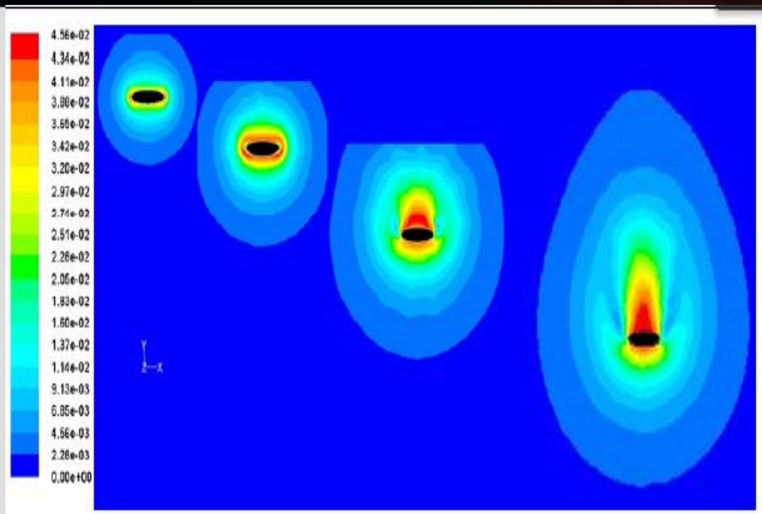


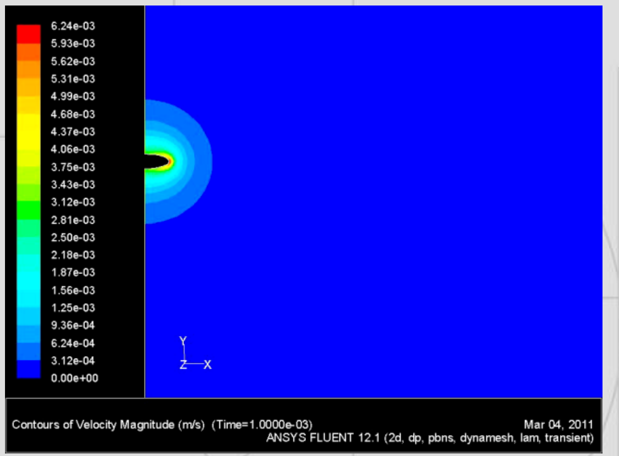
Drag Model Development



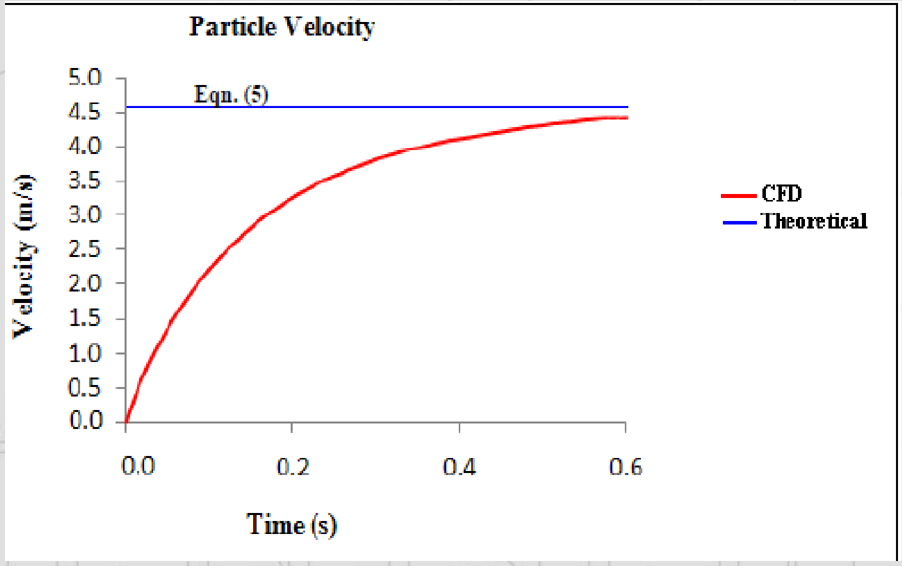
Boundary No.	Boundary Condition
1	Moving Wall
2	Pressure Outlet
3	Pressure Outlet
4	No-Slip Wall

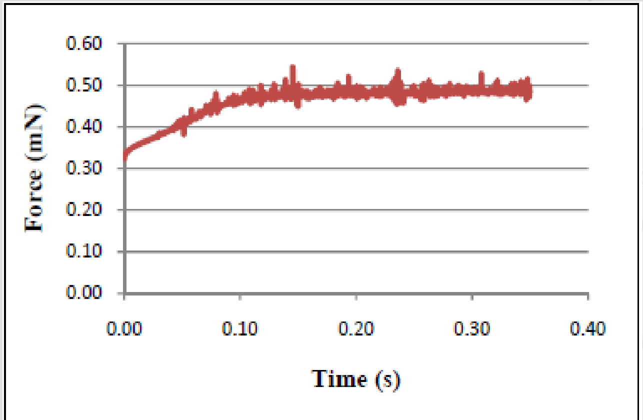
Drag Model Development



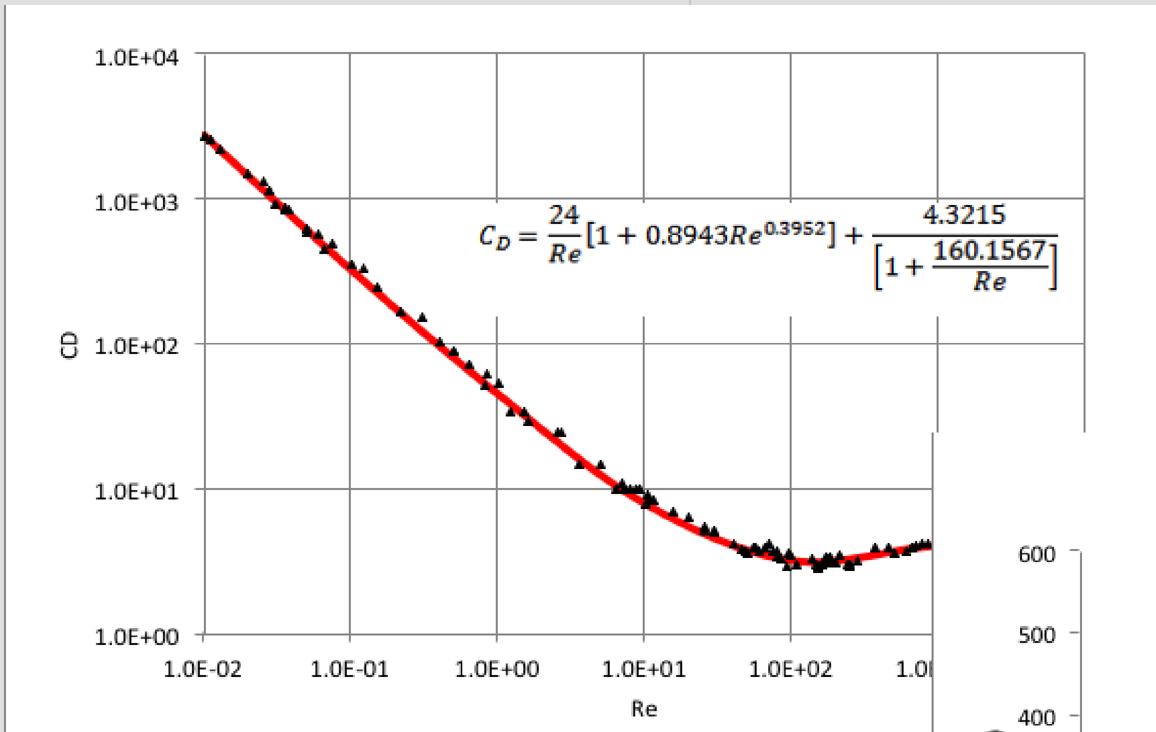


Results	Numerical	Experimental
Re	1058	1081
C_D	0.55	0.58

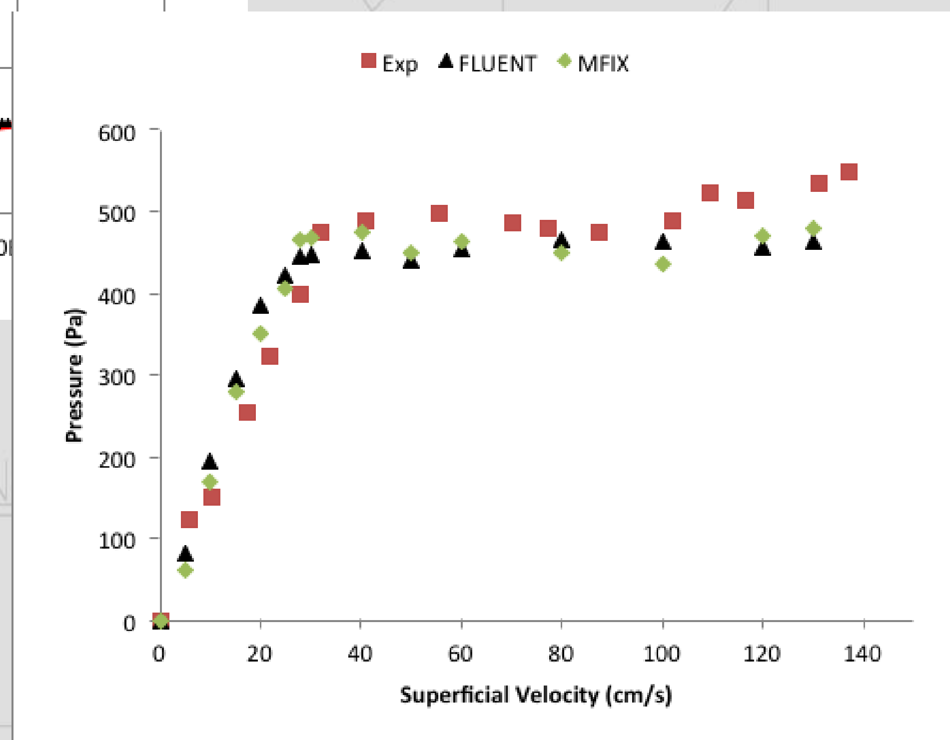




Implementation of Model



$$C_D = \frac{24}{Re}[1 + 0.8943Re^{0.3952}] + \frac{4.3215}{\left[1 + \frac{160.1567}{Re}\right]}$$



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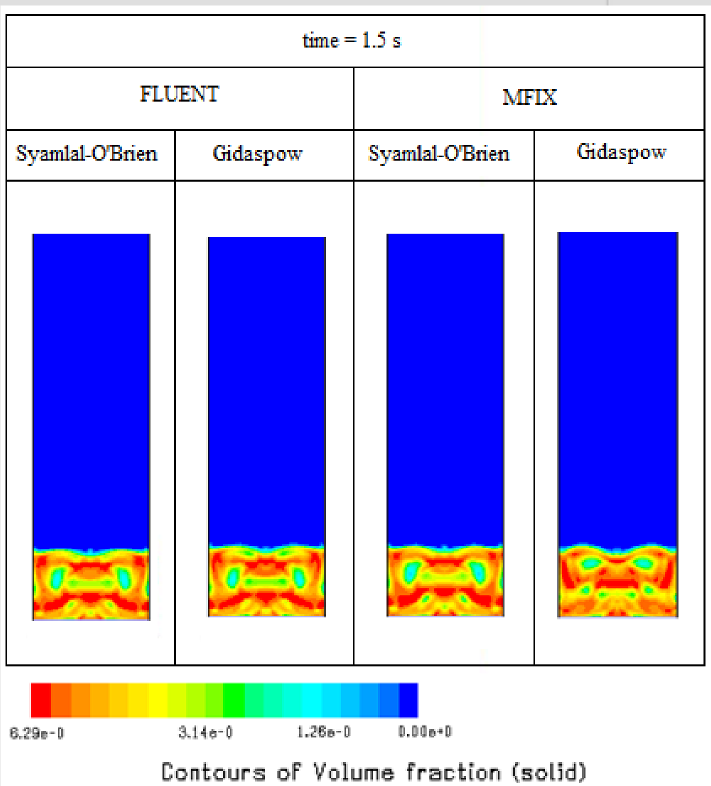
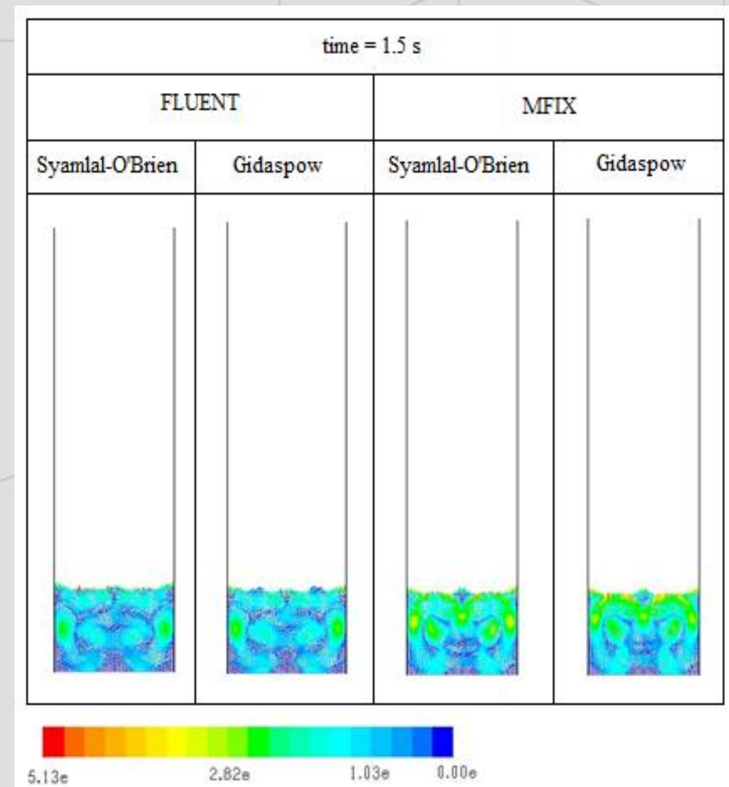
  - High-speed camera Images

Results

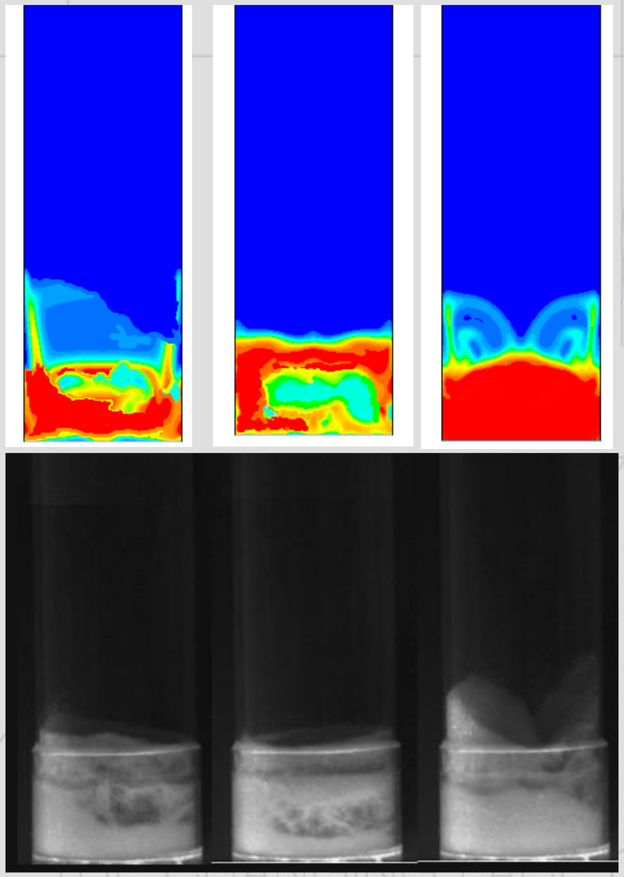


Solid-phase volume fraction



Solid particles velocity field

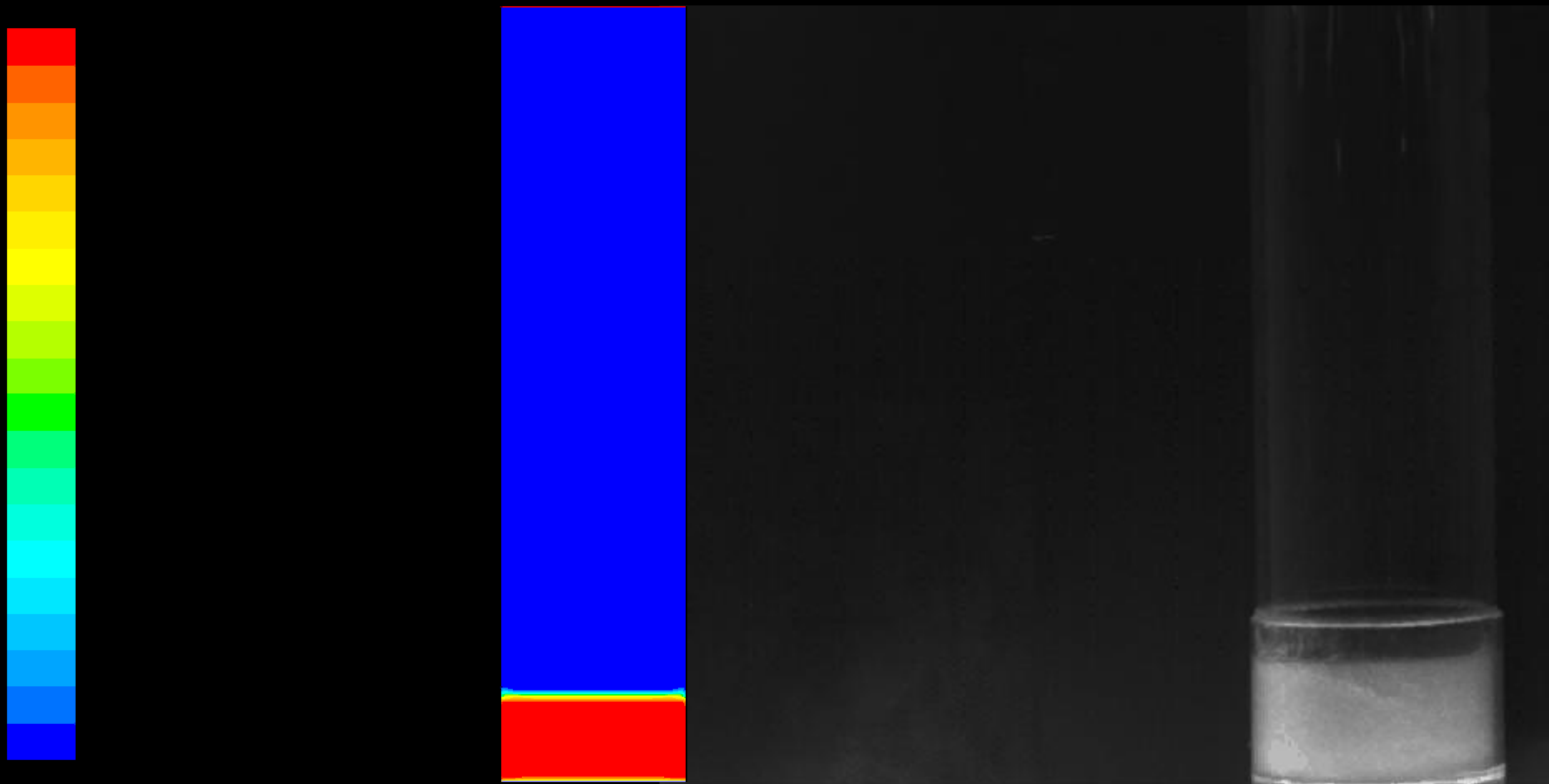
Results



Comparison of bubbling behavior
at times t = 2, 5, 7s

Results

Gidaspow

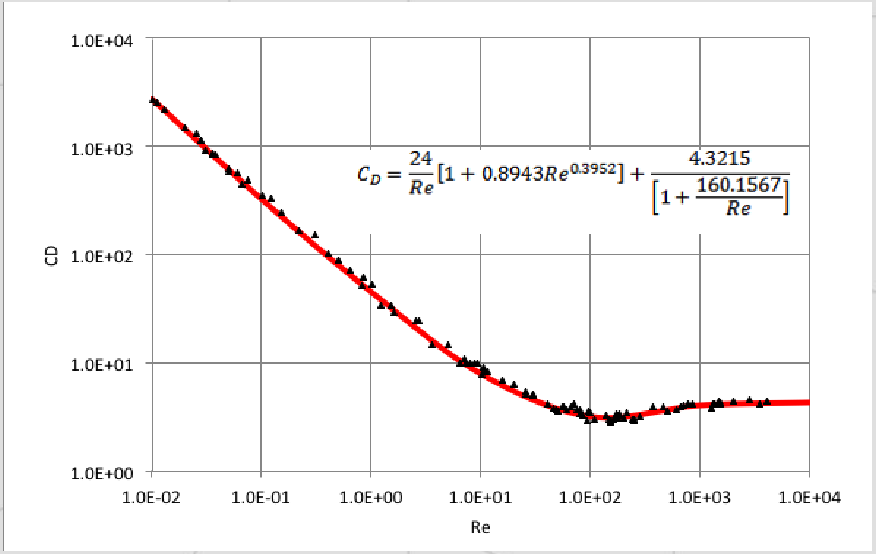


Summary and Highlights to Date

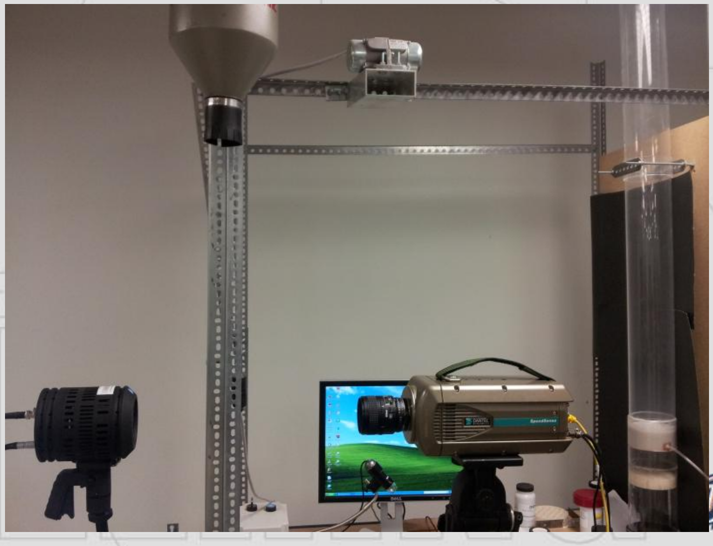
- Fluidized bed design & experimental setup
  - 1st Generation and 2nd Generation
  - Benchmark tests complete
- Development of computational model
  - Benchmark tests complete
  - Empirical drag model implementation
- High-speed imaging

Anticipated Efforts for the Upcoming Year

- Obtaining Velocity and Drag for Non-Spherical Particles
  - C_D vs. Re
  - Various geometry particles
  - Validation with experiments/model



- Implementation of newly acquired shadow sizing system for the:
  - Detection of Non-Spherical Geometries,
  - Particle size
  - Trajectory,
  - Velocity Components



Contact Information

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