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

- Doctoral: MD Rashedul Sarker
- Masters: ASM Raufur Chowdhury

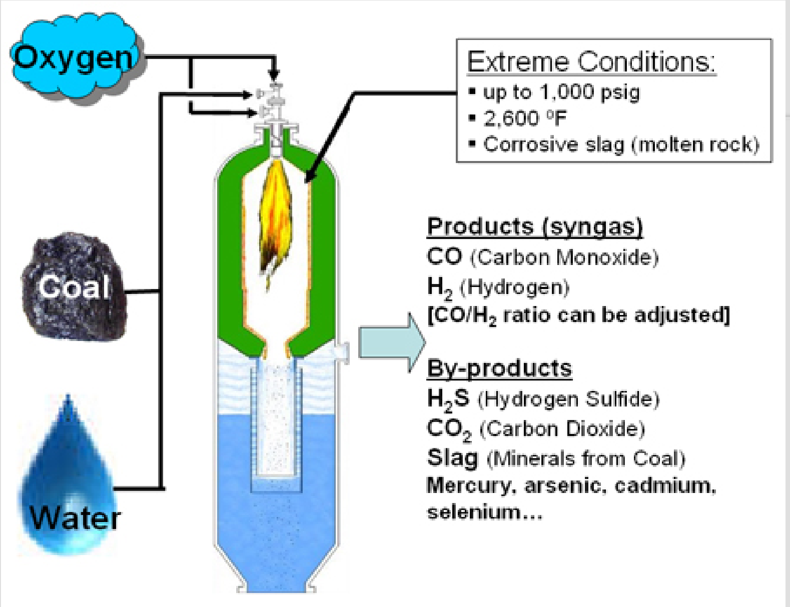
<u>Graduates</u>

Mario Ruvalcaba- PhD - (Now at Federal Mogul)

MD Rashedul Sarker- MS - (Continuing on at UTEP)

MD Mahamudur Rahman- MS - (Now at Drexel Univ)

Introduction



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

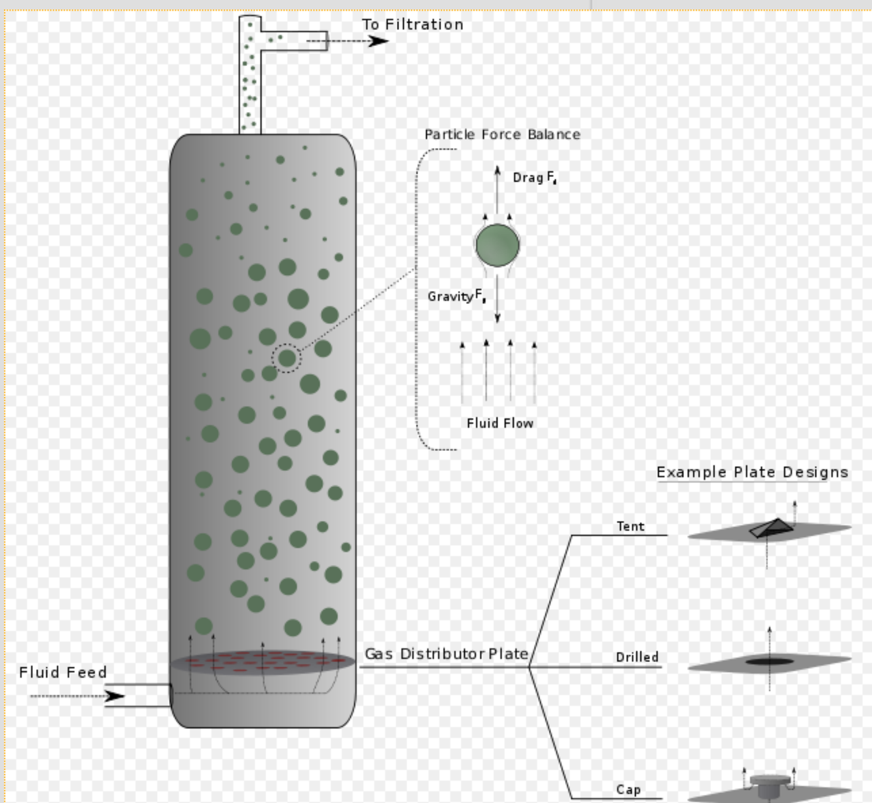
$$\text{Feedstock} \xrightarrow{\text{Heat, Pressure, Steam}} CO + H_2 \text{ (Syngas)}$$

- **Gasifier:**
  - Types of gasifiers used commercially:

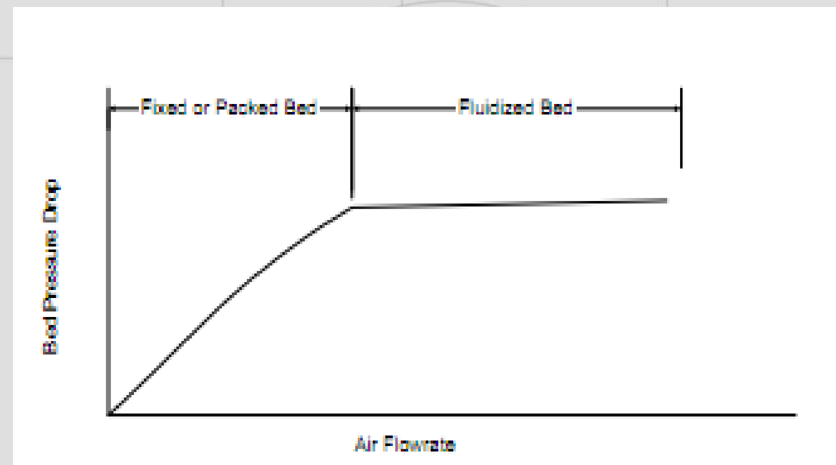
Counter-current fixed bed	Fluidized bed
Co-current fixed bed	Entrained flow

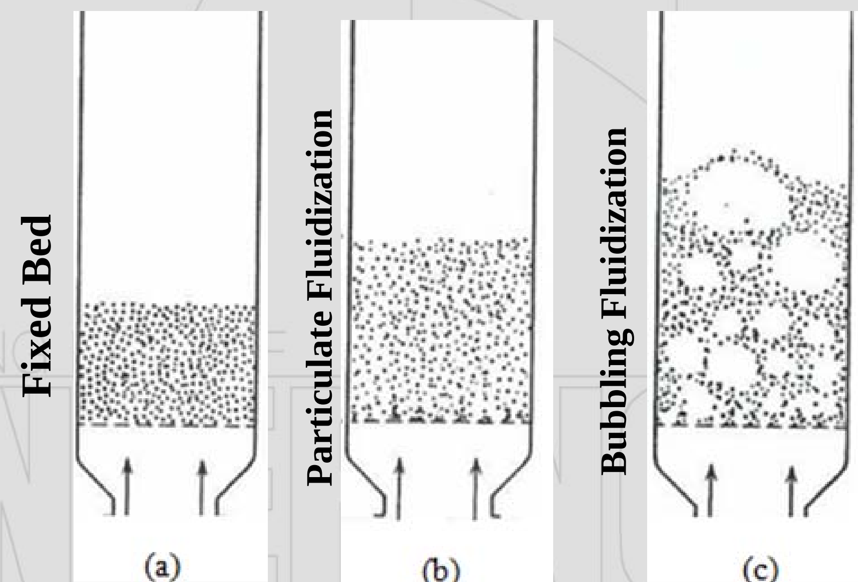
Introduction

- **Fluidized Bed Reactor:**
  - 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.

- 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 Obtain Full-Field Visualization of Motions of Non-Spherical Particles

Objective 2: To Evaluate Drag Force on Non-Spherical Particles

Objective 3: To Incorporate Experimental Data for Non-Spherical Particles in Computational Code (MFIX and FLUENT)

Tasks- Overview

Year 1:

- Task 1: Development of Algorithm for Detection of Non-Spherical Geometries, Particle Pair Identification, Trajectory, and Velocity Components
- Task 2: Design of the Experimental Setup: Production and Categorization of Non-Spherical Particles
- Task 3: Integration of the Imaging Instrumentation and Diagnostics with the Experimental Setup

Year 2:

- Task 4: Terminal Velocity Determination of Free Falling Non-Spherical Particles
- Task 5: Map fluidization velocities in bed
- Task 6: Obtain Drag Relations for Non-Spherical Particles

Year 3:

- Task 7: Modeling of Pressure Drop and Velocities in Fluidized Bed for Particles
- Task 8: Implement Experimental Drag Relations Using Numerical Model

Overview

Multiple Particle Experiments

- Gas-Solid Bed
- Pressure Drop vs Gas Velocity
- Obtain Benchmark and Non-Spherical Data

Individual Particle Experiments

- Individual (only a few) Particles
- Obtain Drag Force Relationship
  $C_D = f(\text{Re}, \phi)$

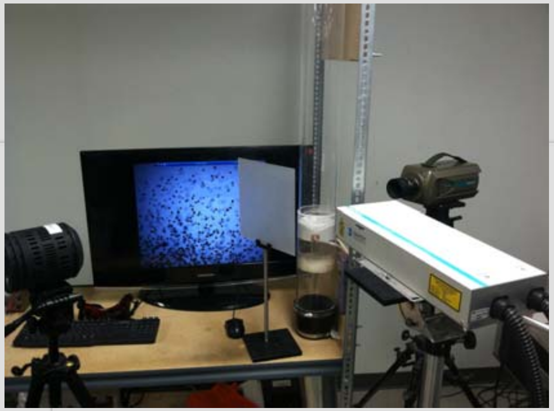
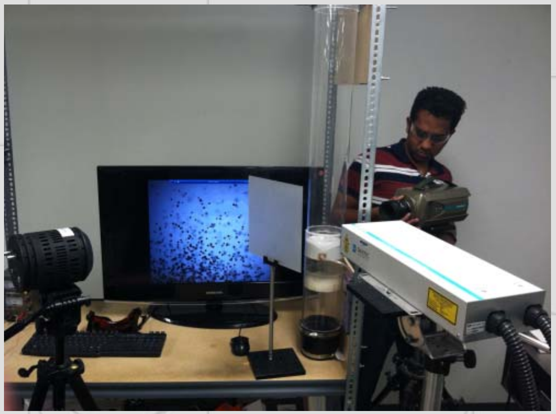
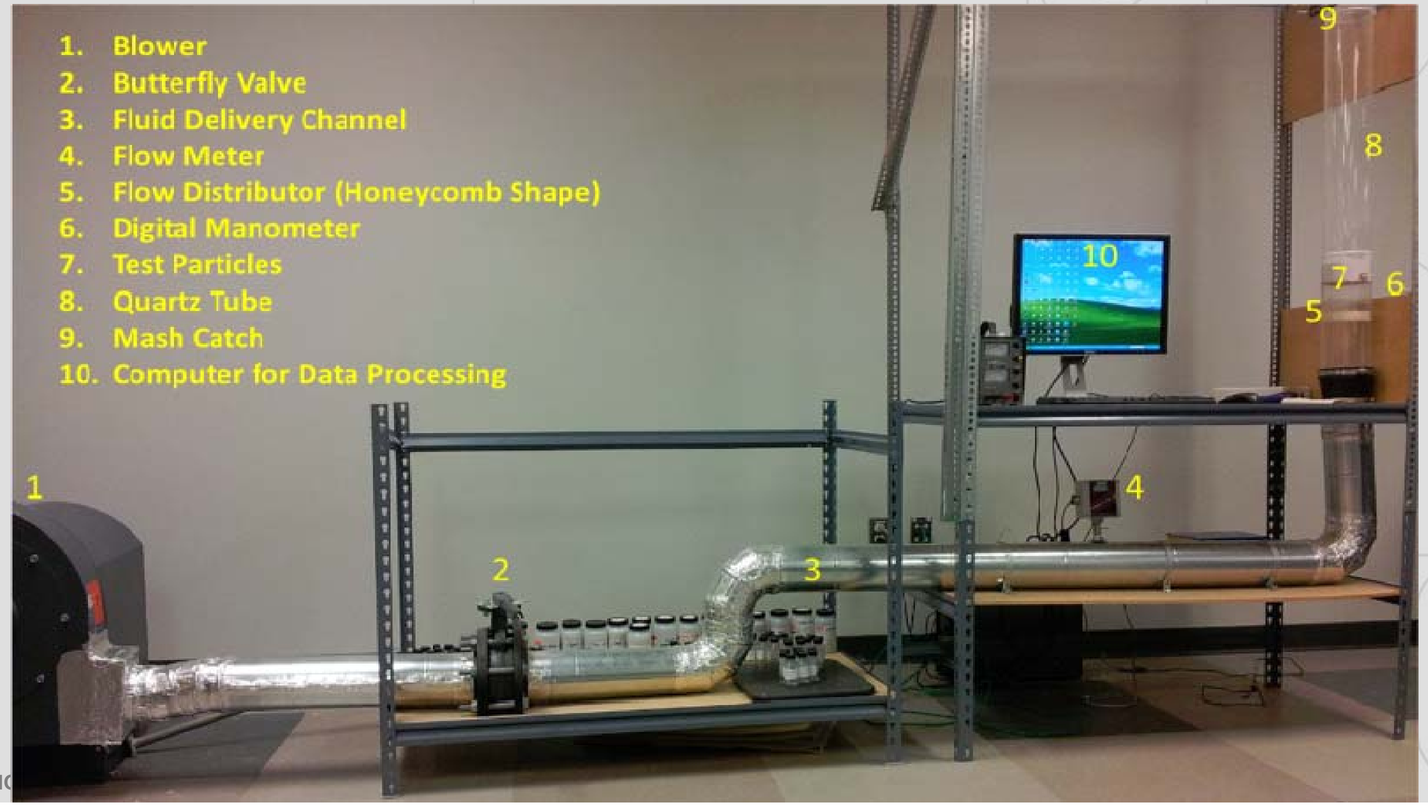
Computational Modeling

- Implement $C_D = f(\text{Re}, \phi)$ Model into Code
- Use Pressure Drop vs Gas Velocity as Validation Tool (Non-spherical)

Outline

- Experimental Method
  - Experimental Setup
  - Particle Production and Categorization
  - Experimental Benchmarking
  - Drag force measurements
- Computational modeling
  - Benchmarking with experimental data
  - Drag model development
  - Implementation into FLUENT/MFIX
- Results
  - Comparisons with Computational Data

Experimental Method

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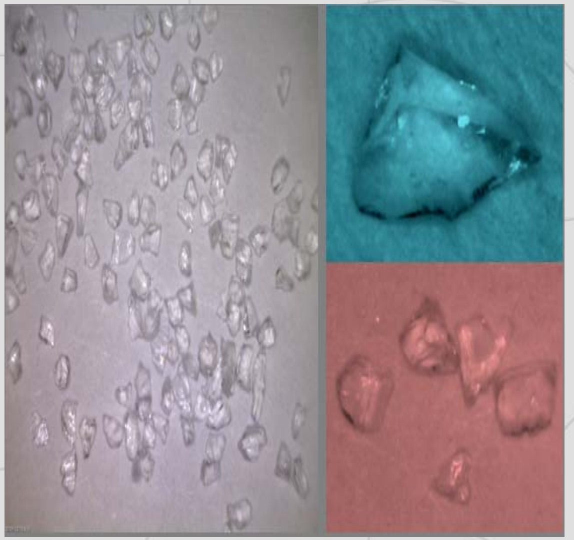
Experimental Method

Spherical
Mean Diameter = 1 mm



Non-spherical
Mean Diameter = 0.9-1 mm

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Experimental Method

Sieve Shaker and Sieves

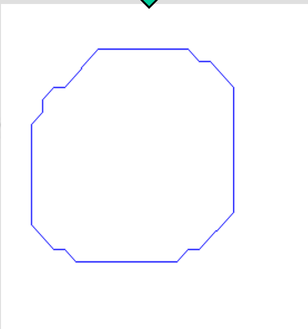
Hydraulic Compressor

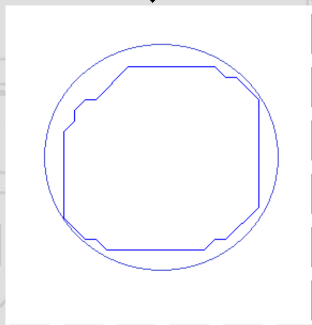
Experimental Method

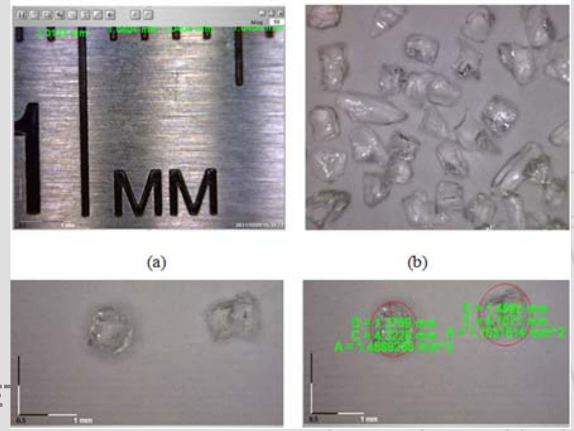
Sphericity – Roundness of a 3D object

$$\phi = \frac{\textit{Volume of the Particle}}{\textit{Volume of the Circumscribed Sphere}}$$

$$\phi = \frac{\textit{Diameter of Particle}}{\textit{Diameter Circumscribed by Sphere}}$$







$$\phi = \frac{d_{sv}}{d_v}$$

$$\textit{Volume Diameter} = d_v = \sqrt[3]{\frac{6\,Vol}{\pi}}$$

$$\textit{Surface Volume Diameter} = d_{sv} = \frac{d_v^3}{d_s^2}$$

$$\textit{Surface Diameter} = d_s = \sqrt{\frac{A_p}{\pi}}$$

Experimental Method

Sphericity – Roundness of a 3D object

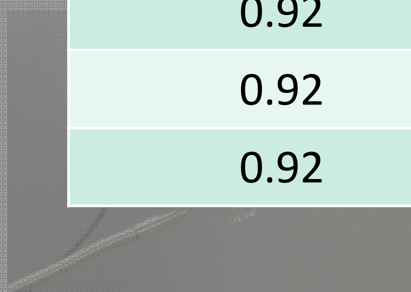
$$\phi = \frac{\text{Volume of the Particle}}{\text{Volume of the Circumscribed Sphere}}$$

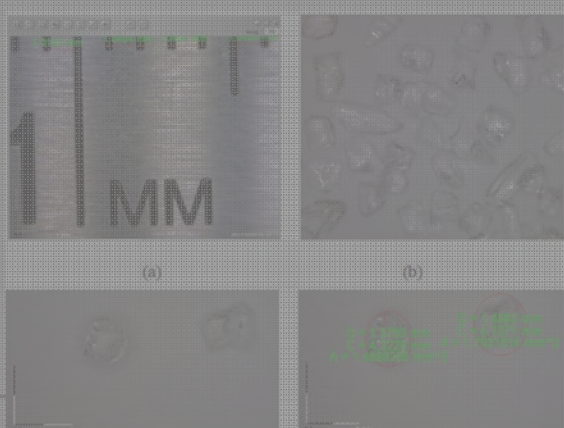
$$\phi = \frac{d_{sv}}{d_v}$$

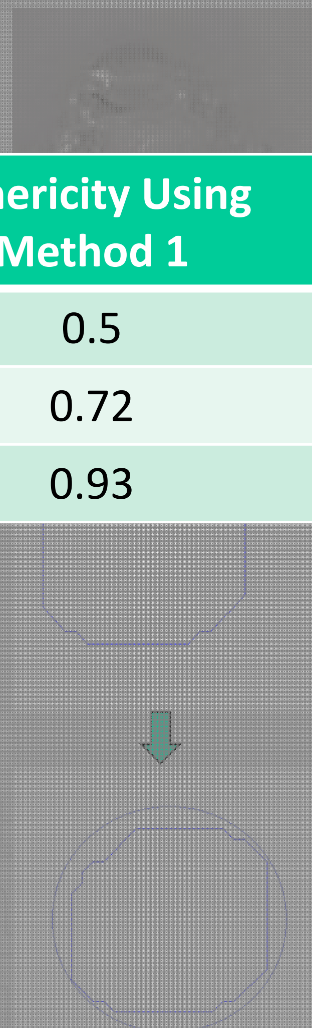
$$d_v = \sqrt[3]{\frac{6\,Vol}{\pi}}$$

$$\ldots\text{eter} = d_{sv} = \frac{d_v^3}{d_s^2}$$

$$\text{Surface Diameter} = d_s = \sqrt{\frac{A_p}{\pi}}$$







Sieve Mean Diameter (mm)	Sphericity Using Method 1	Sphericity Using Method 2
0.92	0.5	0.48
0.92	0.72	0.69
0.92	0.93	0.90

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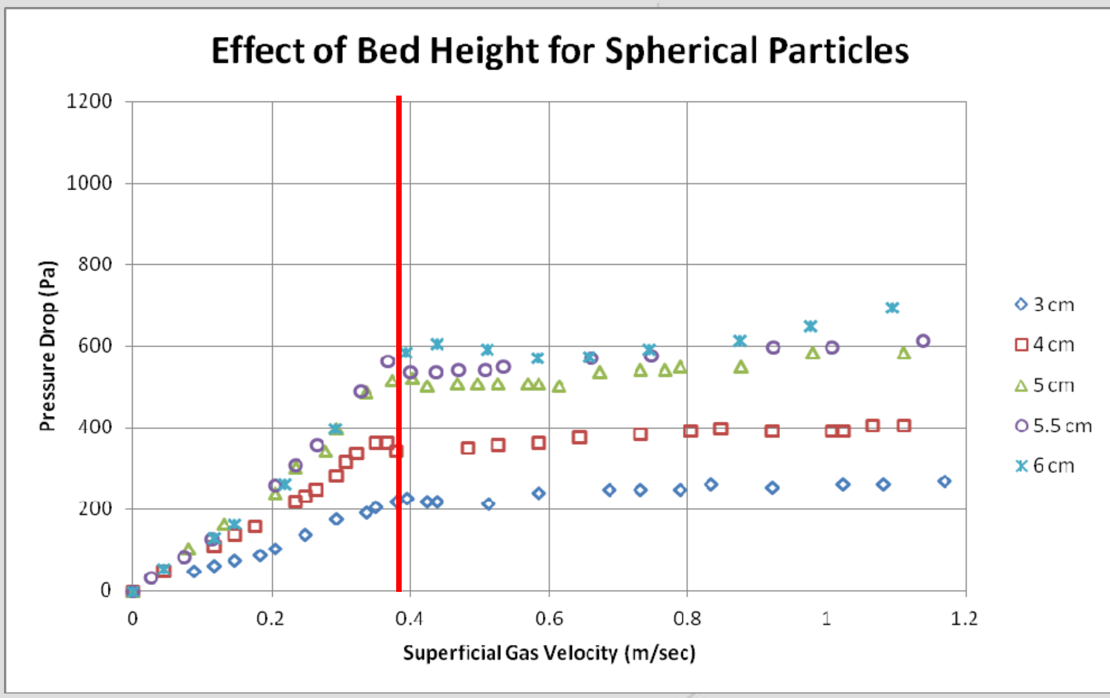
Experimental Method



V_{mf} Predicted (m/s)	V_{mf} Measured (m/s)
0.4	0.39
↓	0.36
	0.4
	0.4
	0.43

- Spherical particles at different bed heights

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

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

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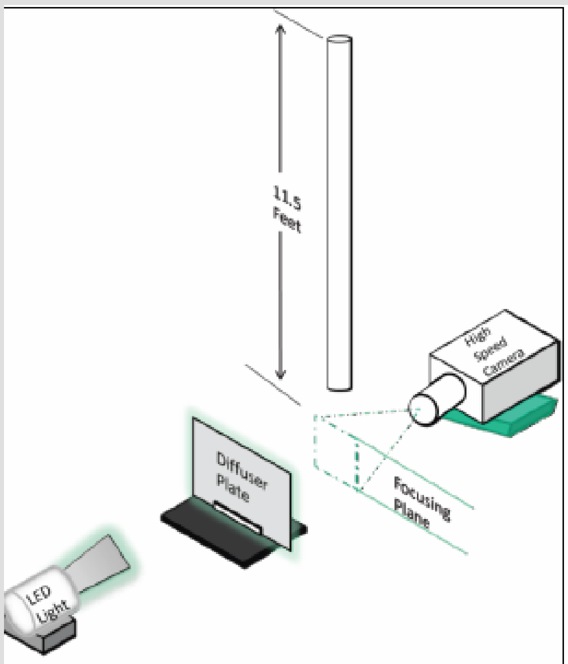
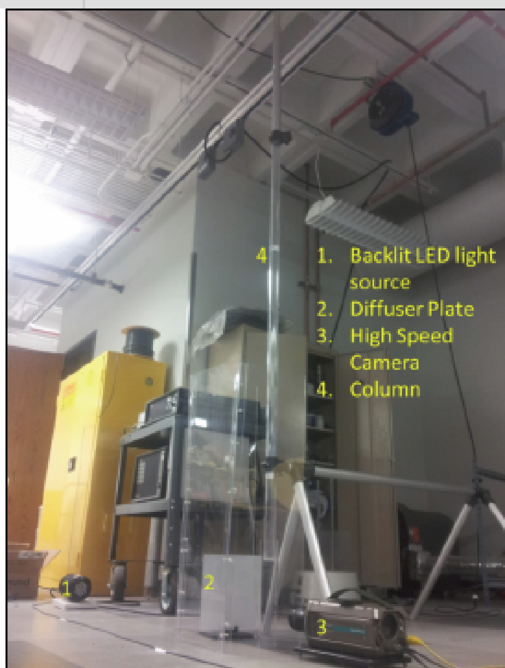
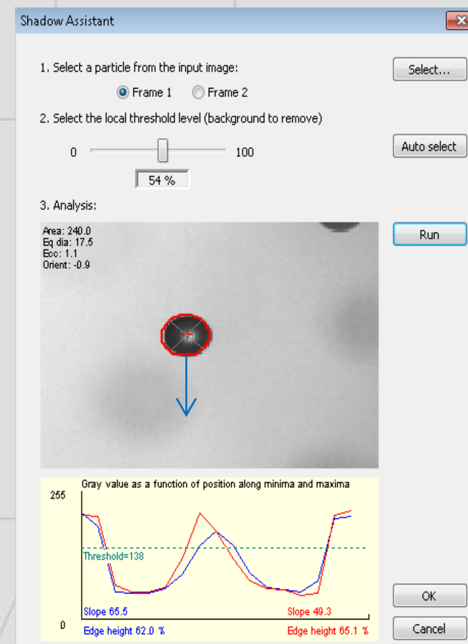


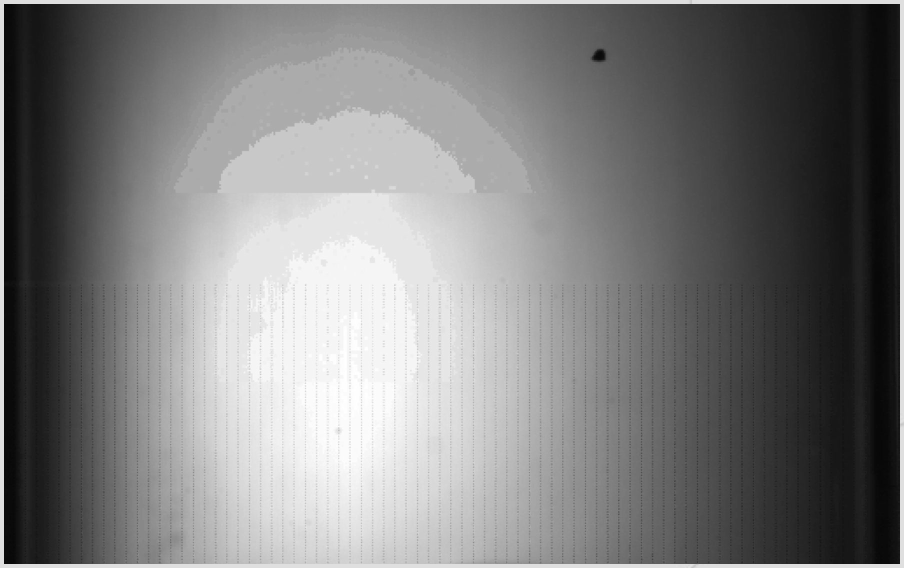


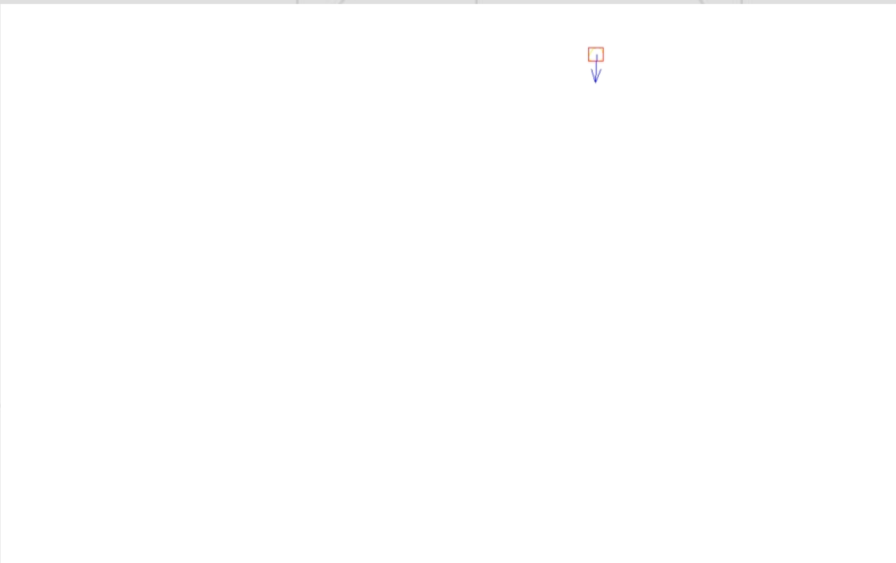


$$C_D = \frac{F_D}{\frac{1}{2}\rho A V_t^2}$$

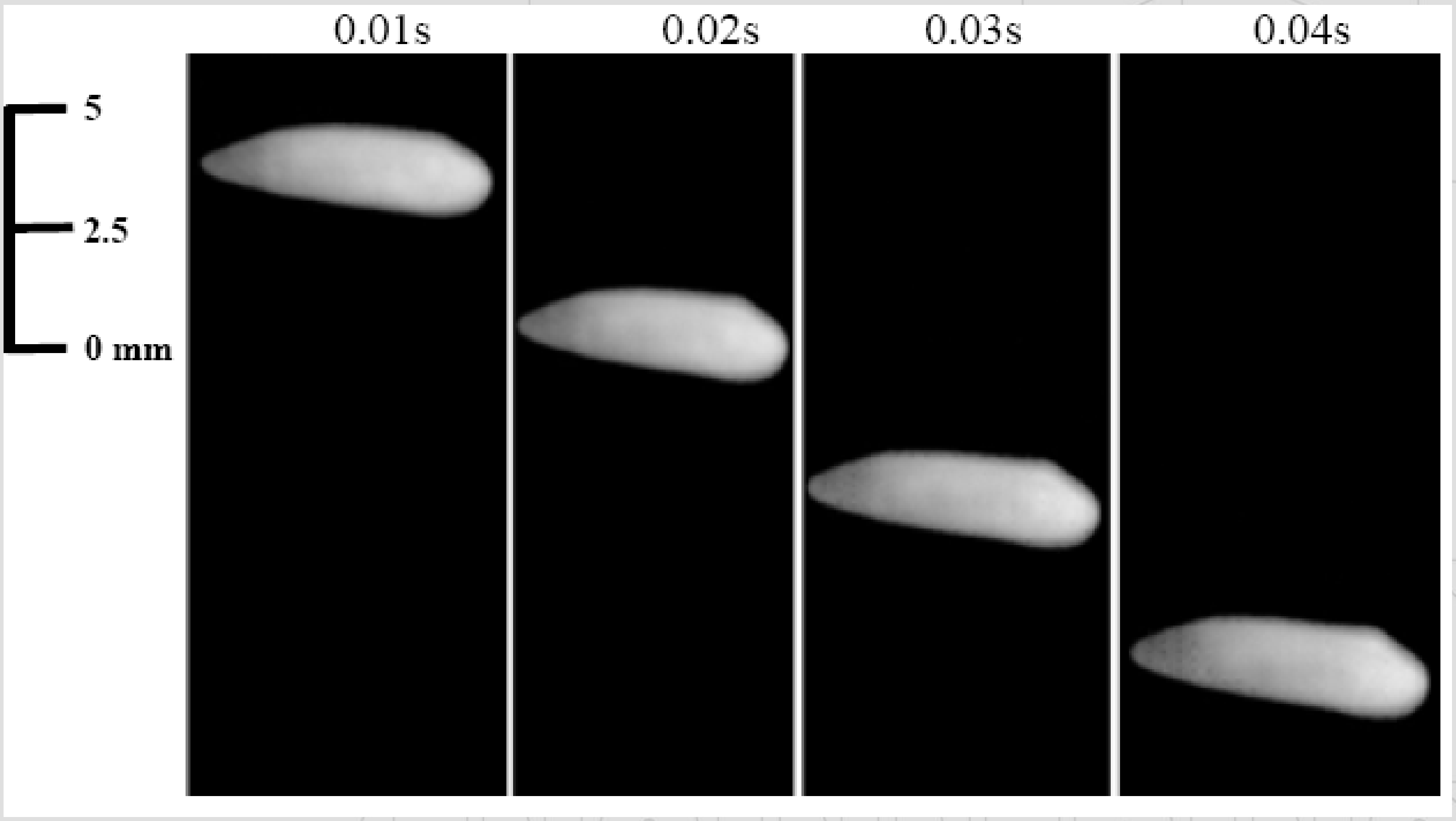
$$F_D = F_w - F_B$$

Experimental Method

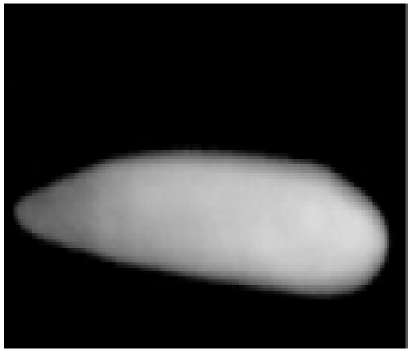




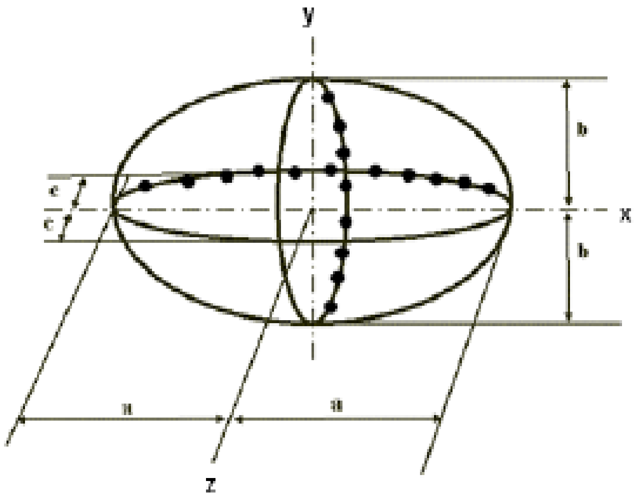
Experimental Method



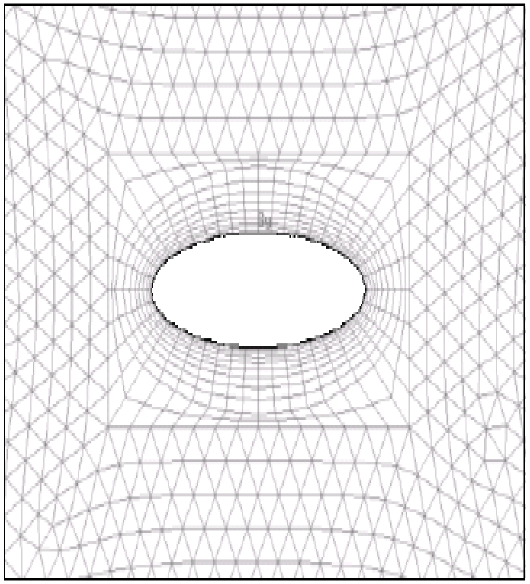
Experimental Method

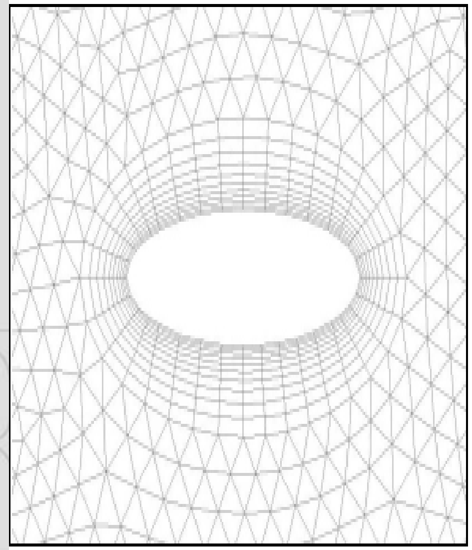


a)

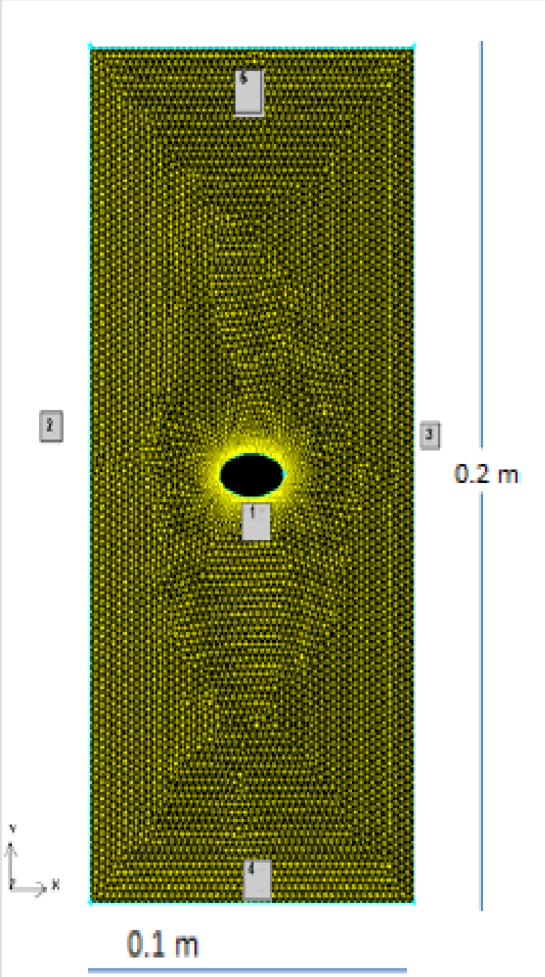


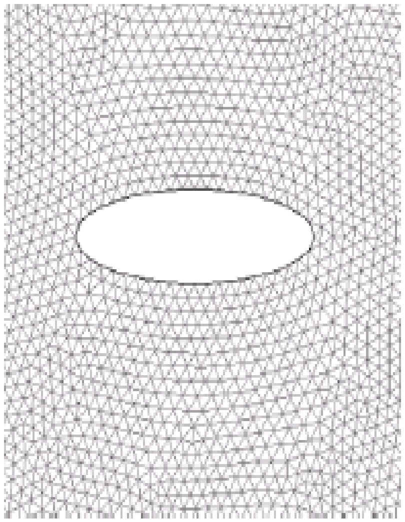
b)





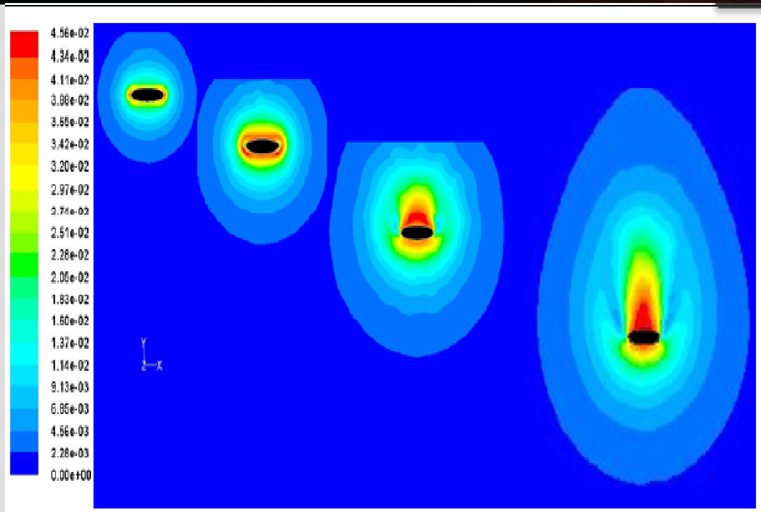
Experimental Method

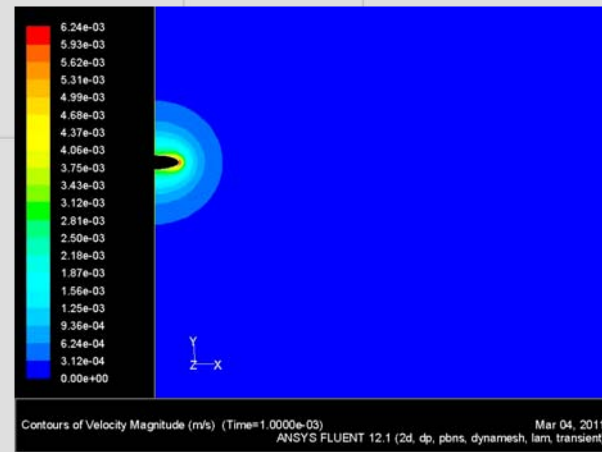




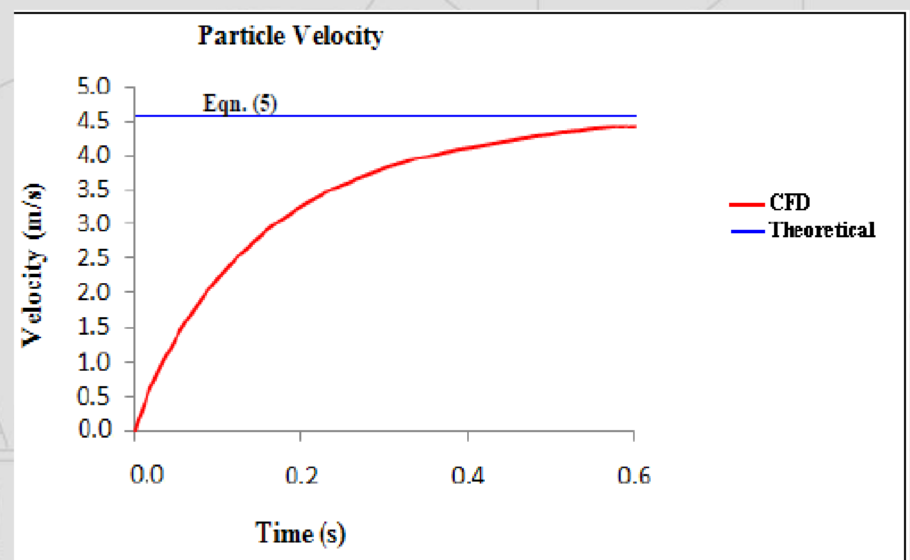
Boundary No.	Boundary Condition
1	Moving Wall
2	Pressure Outlet
3	Pressure Outlet
4	No-Slip Wall

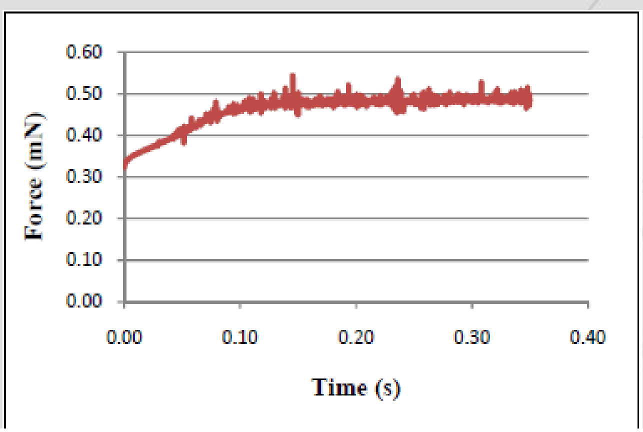
Experimental Method





Results	Numerical	Experimental
Re	1058	1081
C_D	0.55	0.58





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Computational

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

Computational

- **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.

Computational

- 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

Computational

- Syamlal and O'Brien (1989)

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

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

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

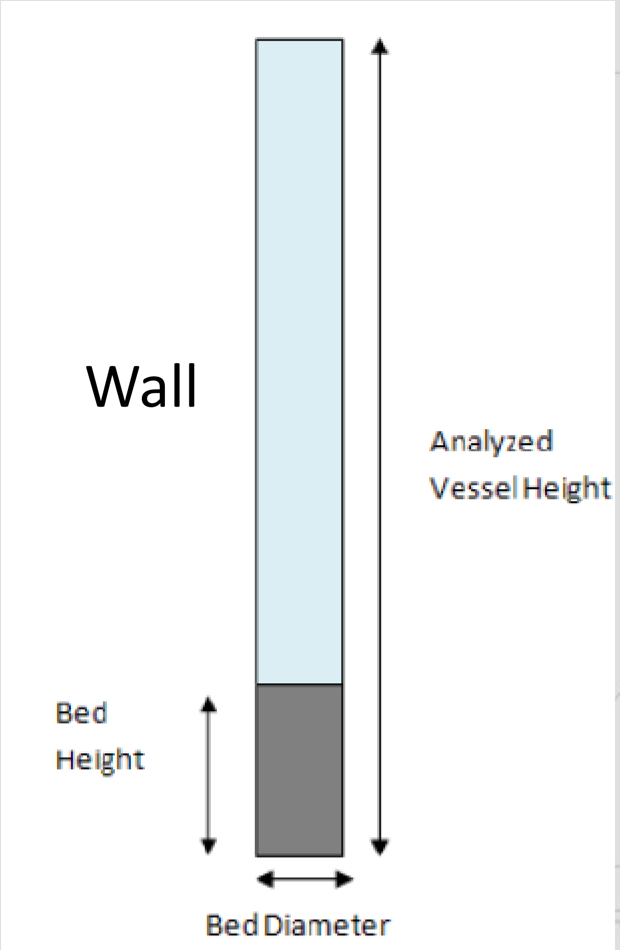
$$A = {\varepsilon_g}^{4.14}$$

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

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

Computational

Pressure Outlet



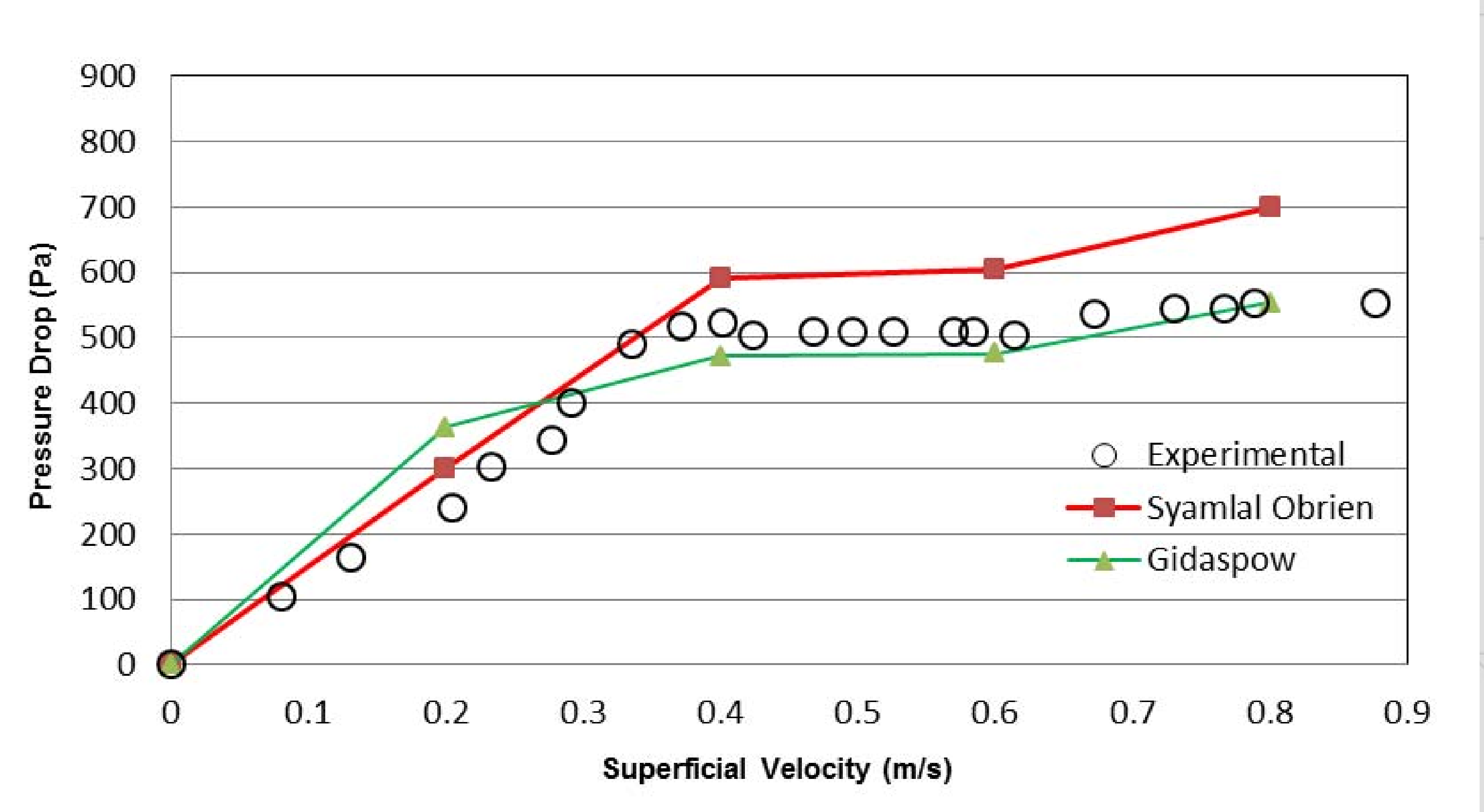
Velocity Inlet

	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

Bed Section	
Gas Void Fraction (ε_g)	0.41
Gas Velocity (v_g)	0 - 1.5 m/s

Computational



Spherical Particles
Bed Height 5.0 cm

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Computational

$$C_D = \frac{24}{Re}(1 + A Re^B) + \frac{C}{1 + \frac{D}{Re}}$$

ϕ range from 0.47 – 0.92

$$A = \exp(-142.71 + 555.63\phi - 533.1\phi^2)$$

$$B = 0.2\phi - 0.149$$

$$C = \exp(47.3 - 258.33\phi + 464.8\phi^2 - 275.7\phi^3)$$

$$D = \exp(-161.8 + 855.9\phi - 1502\phi^2 + 870.4\phi^3)$$

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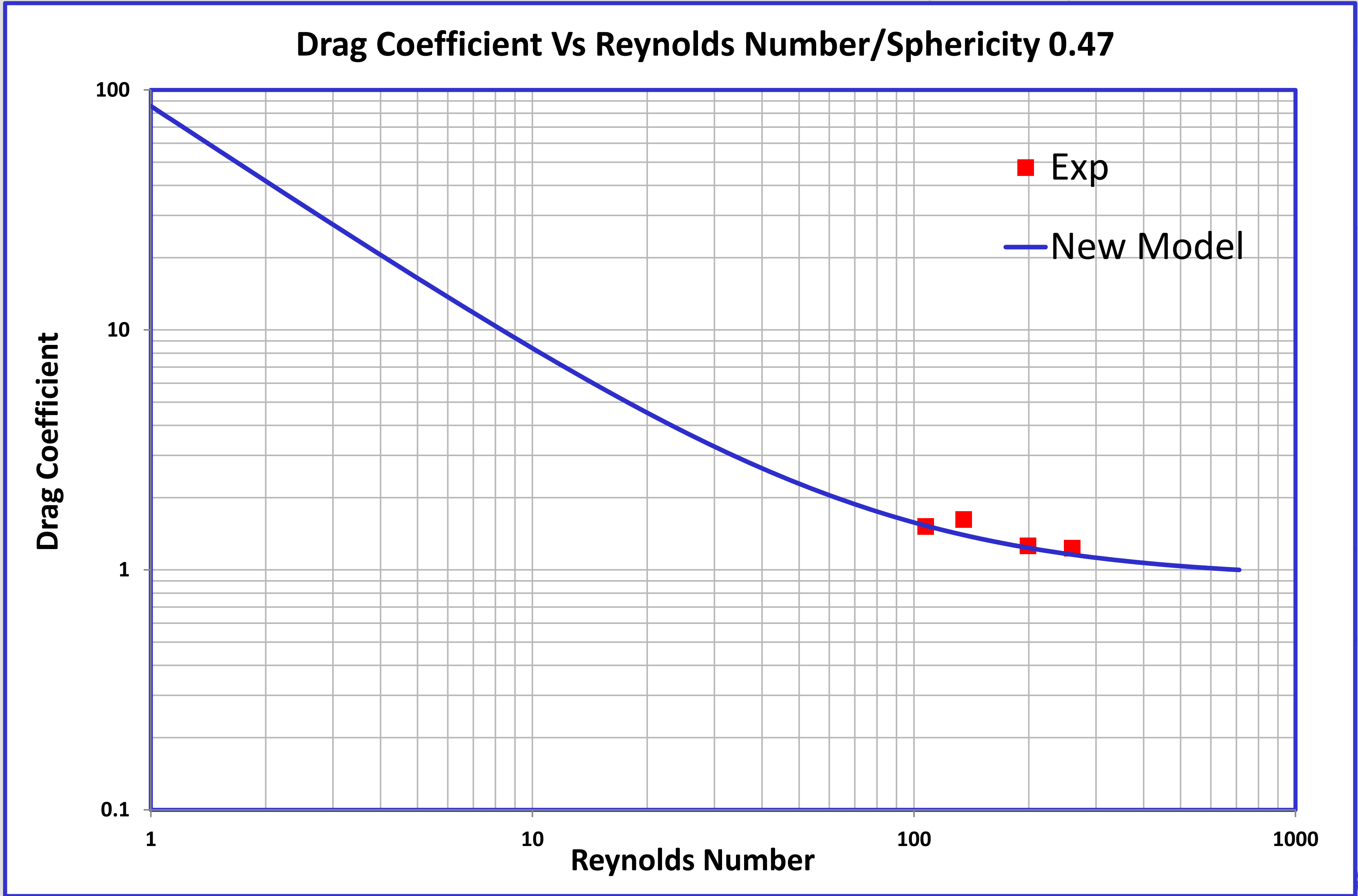
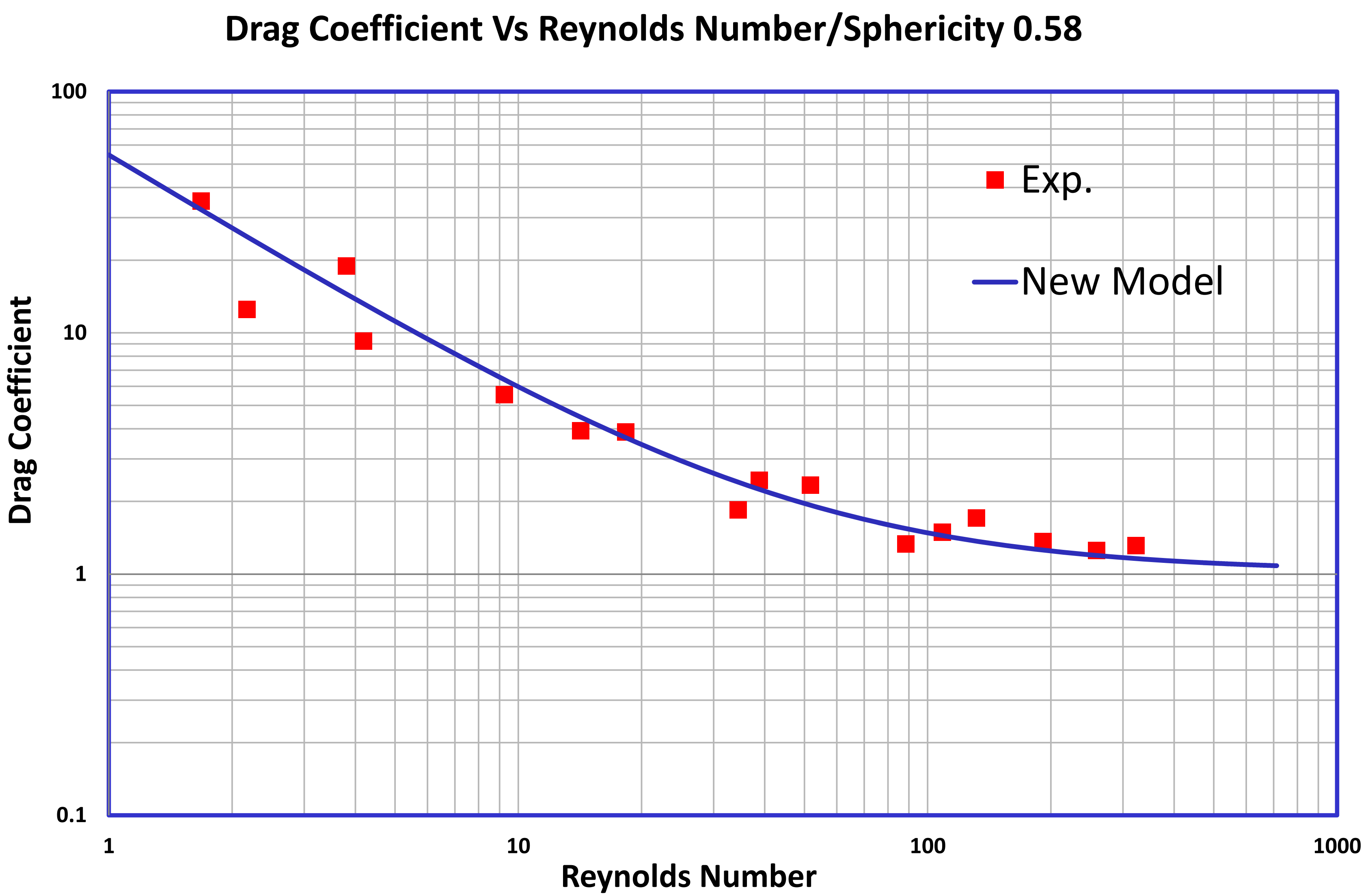
Haider A., and Levenspiel O., "Drag Coefficient and Terminal Velocity of Spherical and Non-Spherical Particles", *Powder Technology*, 1989, Vol. 58, pp. 63-70.

Computational



Computational



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Computational

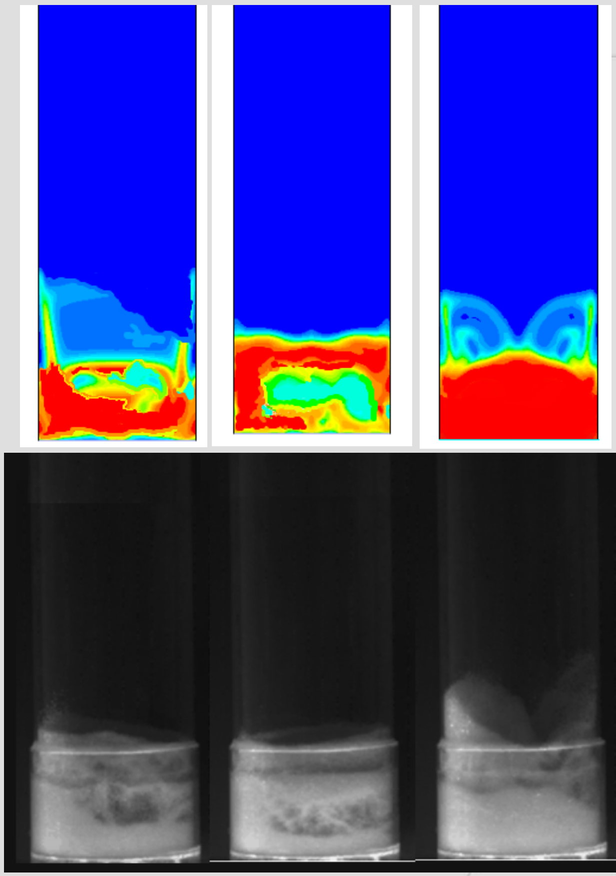
```c
#include "udf.h"
#include "sg_mphase.h"

# define pi 4.*atan(1.)
#define diam2 1.e-3

DEFINE_EXCHANGE_PROPERTY(custom_drag_syam, cell, mix_thread, s_col, f_col)
{
 Thread *thread_g, *thread_s;
 real x_vel_g, x_vel_s, y_vel_g, y_vel_s, abs_v, slip_x, slip_y,
      rho_g, rho_s, mu_g, reyp, afac,
      bfac, void_g, vfac, fdrgs, taup, k_g_s;

 /* find the threads for the gas (primary) and solids (secondary phases).
These phases appear in columns 2 and 1 in the Interphase panel respectively*/

 thread_g = THREAD_SUB_THREAD(mix_thread, s_col);/*gas phase*/
 thread_s = THREAD_SUB_THREAD(mix_thread, f_col);/* solid phase*/

 /* find phase velocities and properties*/

 x_vel_g = C_U(cell, thread_g);
 y_vel_g = C_V(cell, thread_g);

 x_vel_s = C_U(cell, thread_s);
 y_vel_s = C_V(cell, thread_s);

 slip_x = x_vel_g - x_vel_s;
 slip_y = y_vel_g - y_vel_s;

 rho_g = C_R(cell, thread_g);
 rho_s = C_R(cell, thread_s);

 mu_g = C_MU_L(cell, thread_g);

 /*compute slip*/
 abs_v = sqrt(slip_x*slip_x + slip_y*slip_y);

 /*compute reynolds number*/

 reyp = rho_g*abs_v*diam2/mu_g;

 /* compute particle relaxation time */

 taup = rho_s*diam2*diam2/18./mu_g;

 void_g = C_VOF(cell, thread_g);/* gas vol frac*/

 /*compute drag and return drag coeff, k_g_s*/

 afac = pow(void_g,4.14);

 if(void g<=0.85)
   bfac = 0.26*pow(void_g, 1.28);
  else
   bfac = pow(void_g, 9.56872);

  vfac = 0.5*(afac-0.06*reyp+sqrt(0.0036*reyp*reyp+0.12*reyp*(2.*bfac-
               afac)+afac*afac));
 fdrgs =
 void_g*((24/reyp)*(1+0.8943*pow(reyp,0.3952))+(4.3215/(1+(160.1567/reyp))))/
               (24.0*pow(vfac,2));


  k_g_s = (1.-void_g)*rho_s*fdrgs/taup;


  return k_g_s;
```

```
#  Fluidized Bed Simulation
#
#  Mario A. Ruvalcaba         11-05-12
#
# Run time for F90 allocatable arrays on Octane -- 3.3 h
# Run-control section
#
  RUN_NAME = 'Fluidized-Bed'
  DESCRIPTION = 'Fluidized Bed Simulation'
  RUN_TYPE = 'new'
  UNITS = 'cgs'
  TIME  = 0.0     TSTOP = 1.0     DT = 1.0E-3     DT_MIN = 1.0E-12
  NORM_G = 0.0d0     NORM_S = 0.0d0     MAX_NIT = 30
  DISCRETIZE = 9*2
  ENERGY_EQ = .FALSE.
  SPECIES_EQ = .FALSE.    .FALSE.
#
# Physical Parameters
#
  UR_FAC(1) = 0.5
 #
 # Initial Conditions Section
 #
       !              Bed        Freeboard
   IC_X_w           =  0.0            0.0
   IC_X_e           =  12.0           12.0
   IC_Y_s           =  0.0            5.5
   IC_Y_n           =  5.5           50.0

   IC_EP_g          =  0.35           1.0

   IC_U_g           =  0.0            0.0
   IC_V_g           =@(45.8/0.45)    45.8

   IC_U_s(1,1)      =  0.0            0.0
   IC_V_s(1,1)      =  0.0            0.0

   IC_P_star        =  0.0            0.0
   IC_T_g           = 300.0          300.0

 #
 #  Boundary Conditions Section
 #
       !                 Inlet      Outlet
   BC_X_w           =    0.0       0.0
   BC_X_e           =    12.0      12.0
   BC_Y_s           =    0.0      50.0
   BC_Y_n           =    0.0      50.0

   BC_TYPE          =    'MI'     'PO'

   BC_EP_g          =    1.0

   BC_U_g           =    0.0
   BC_V_g           =  100.0

   BC_P_g           = 1.013E6    1.013E6
   BC_T_g           = 300.0


 #
 #  Output Control
 #
   RES_DT = 0.01
          !
          ! EP_g P_g      U_g  U_s  ROP_s     T_g  X_g
          !      P_star   V_g  V_s            T_s1 X_s      Theta  Scalar
          !               W_g  W_s            T_s2
   SPX_DT = 0.01 0.1      0.1  0.1  100.      100. 100.     100.0  100.0

   NLOG   = 100
   full_log = .true.
```

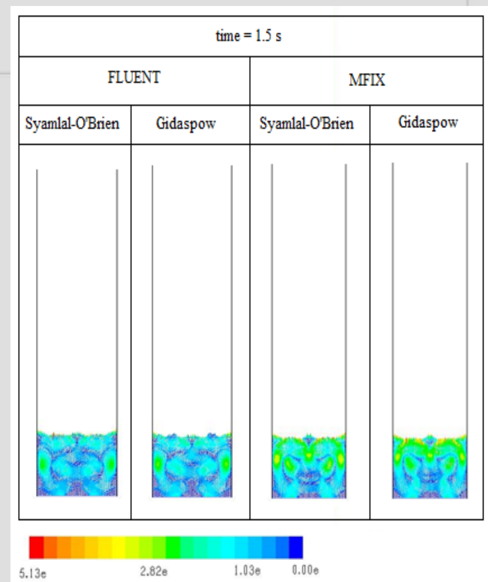
Outline

- Experimental Method
  - Experimental Setup
  - Particle Production and Categorization
  - Experimental Benchmarking
  - Drag force measurements
- Computational modeling
  - Benchmarking with experimental data
  - Drag model development
  - Implementation into FLUENT/MFIX
- Results
  - Comparisons with Computational Data

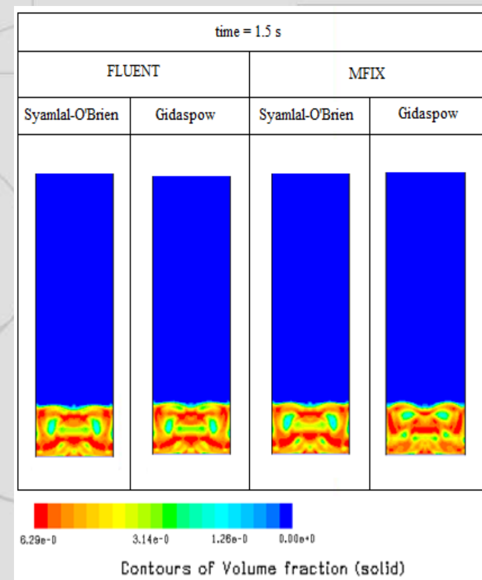
Results



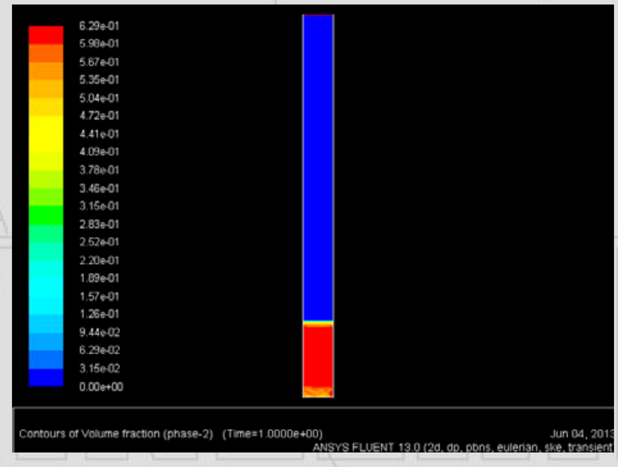
Comparison of bubbling behavior at times t = 2, 5, 7s



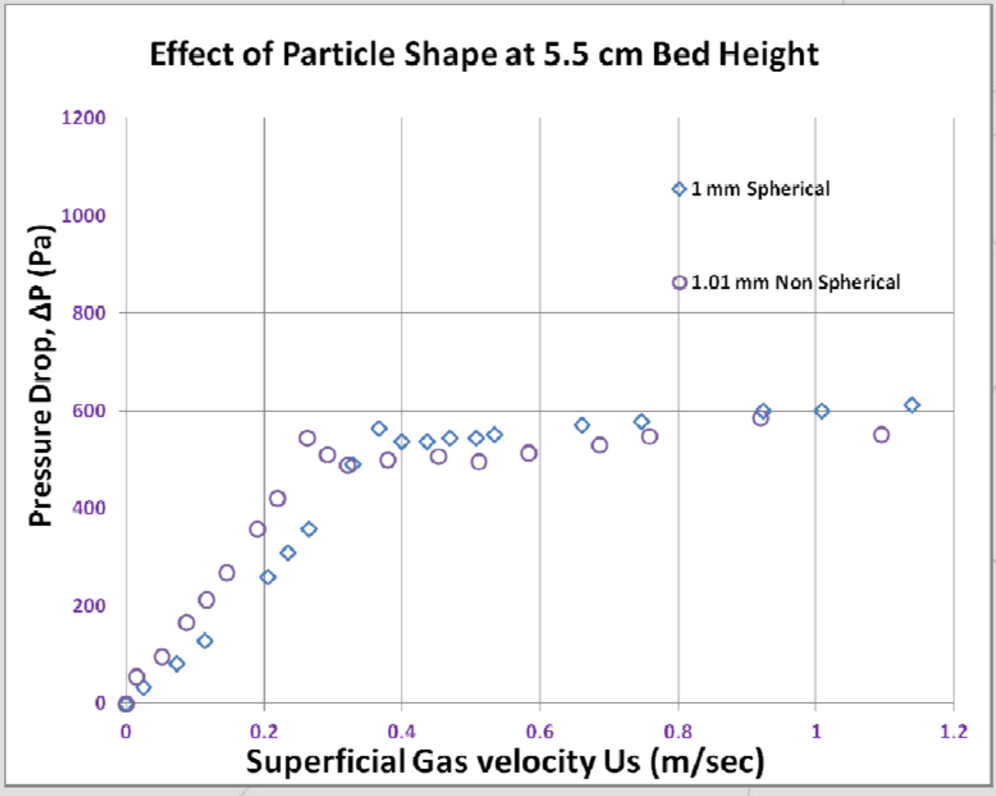
Solid particles velocity field



Solid-phase volume fraction

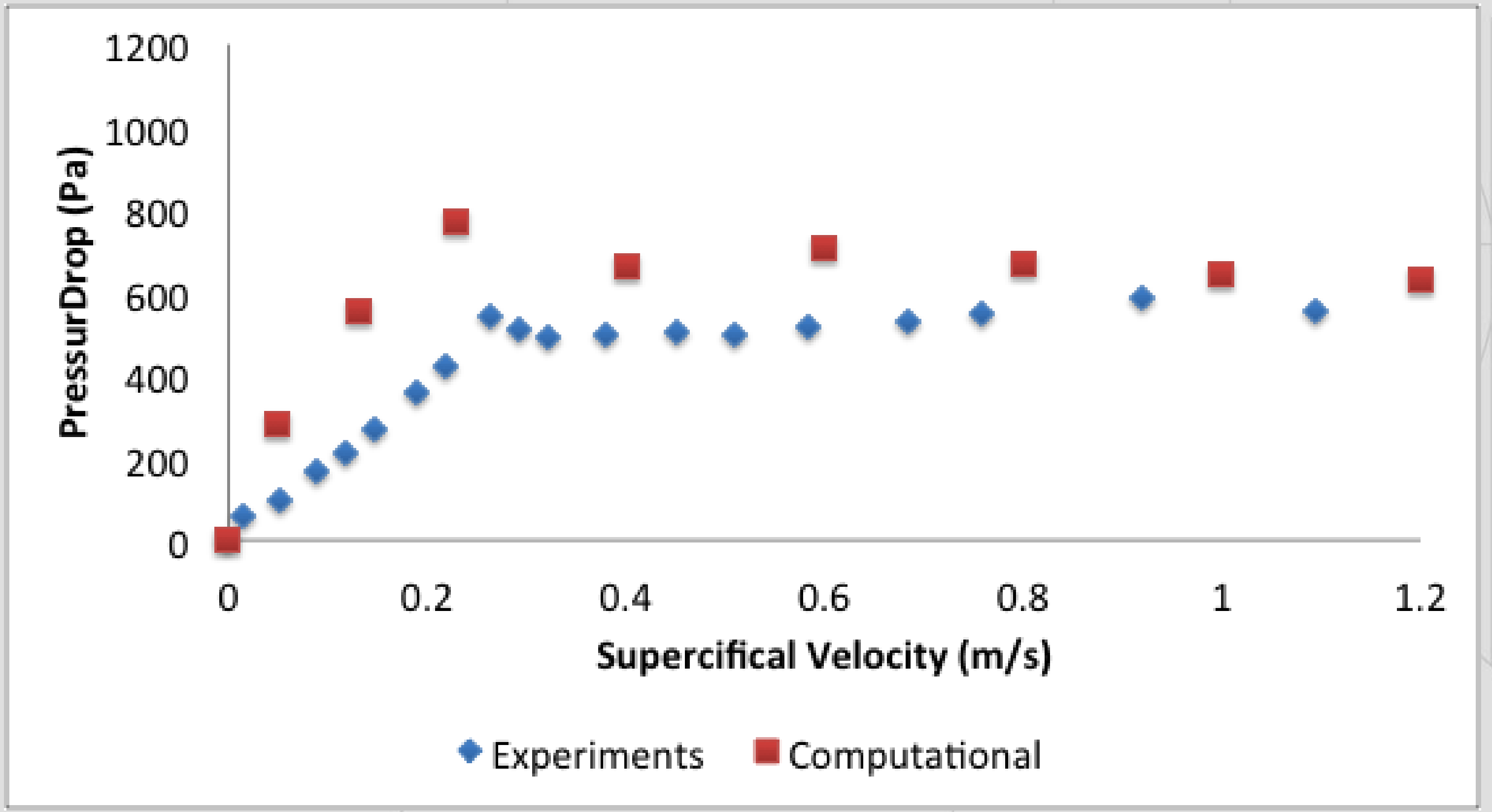


Results



- 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.

Results



Non-Spherical Particles with new drag model comparison

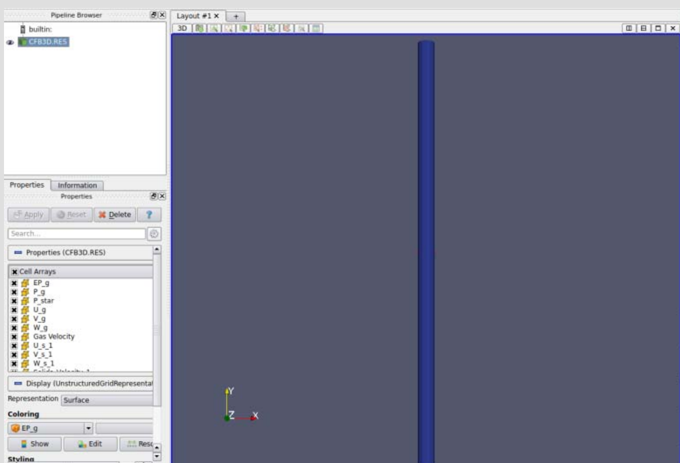
Summary and Highlights to Date

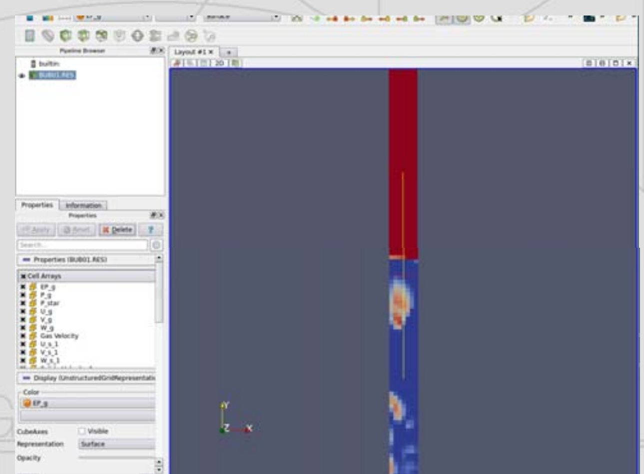
- Fluidized bed design & experimental setup
  - Benchmark tests
  - High-Speed Imaging
  - Drag Measurements
- Development of computational model
  - Benchmark tests
- Empirical drag model
  - Development
  - Implementation

Follow Up Efforts

- Complete comparison of results to existing models
  - Spherical and non-spherical

- Completion of Implementation of Drag Model in MFIX
  - Comparison with experiments





Holtzer A., and Sommerfeld M., “New Simple Correlation Formula for the Drag Coefficient of Non-Spherical Particles”, Powder Technology, Vol. 184, 2008, pp. 361-365

Publications and Presentations

JOURNAL PAPER

1. 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," 2013 (In Preparation).

CONFERENCE PAPERS

1. Sarker, MD, Chowdhury, ASM, Love, N., and Choudhuri, A., "Effect of Particle Density on Minimum Fluidization and Flow Behaviors," 11th *International Energy Conversion Engineering Conference and Exhibit*, AIAA, San Jose, CA, July 15 – 17, 2013 (Accepted).

2. Sarker, MD, **Love, N.**, and Choudhuri, A., "Flow Field Visualization and Drag Analysis of Particles in a Gas-Solid Fluidized Bed Using a Non-Intrusive Optical Technique," AIAA-2013-0597, **51st *Aerospace Sciences Meeting and Exhibit***, AIAA, Grapevine, TX, January 7 – 10, 2013.

3. 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.

4. 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.

5. 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.

6. 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.

Contact Information

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