Mass Transport, Momentum Transport and Fluidization in a 2D Bubbling Fluidized Bed

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Overview

- Background
- Laser Doppler Velocimetry (LDV) Measurement Technique
- Single Phase Gas Jet in Empty Bed
- Gas Jets in Bubbling Bed
- Effect of Emulsion Fluidization Level on Jet Dynamics
- Turbulence Measurements
- Modeling Effort
- Conclusions

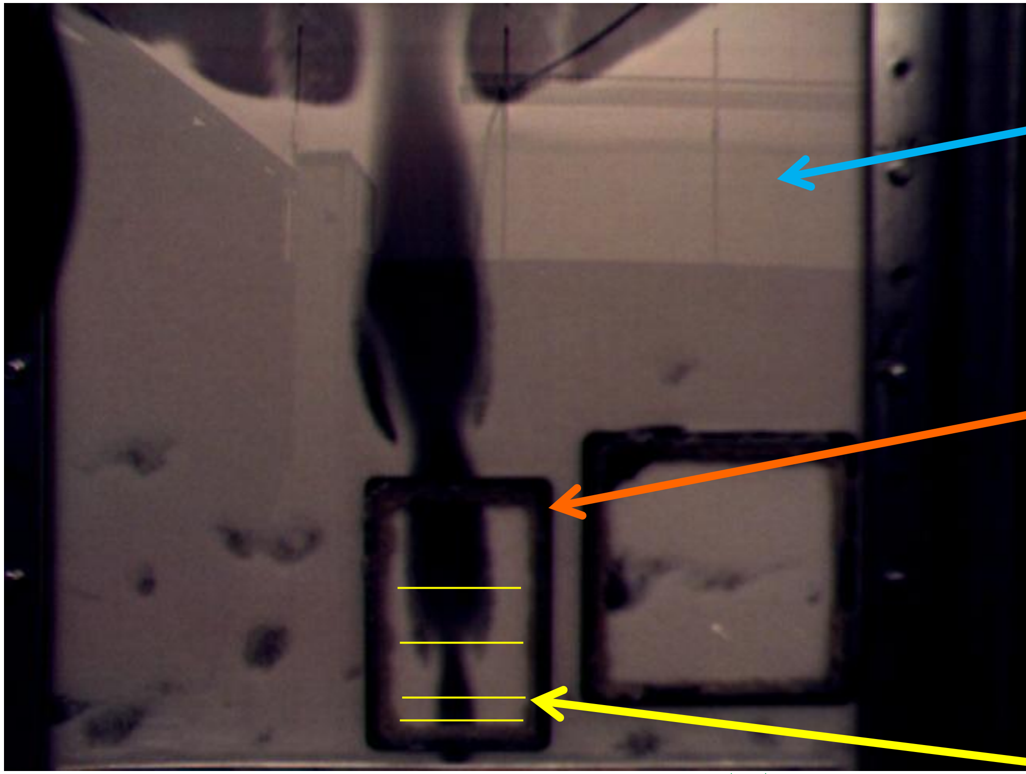
Background

Jets in Fluidized Beds

- High speed gas jets are injected into a bed emulsion, rapidly entraining and mixing bed particles and interstitial gas
- Jet dynamics are critical to the efficiency and design of the system
- Quantitative non-intrusive measurements of the mass and momentum transport in the jet plume are needed for characterization and modeling
  - Requires knowledge of the particulate and gas phase velocity profiles
  - Not widely reported in the literature

C. Xuereb, C. Laguerie, T. Baron. “Etude du comportement de jets continues horizontaux ou inclines introduits dans un lit fluidise par un gaz Deuxieme partie: profiles de vitesse du gaz dans les jets horizontaux,” Powder Tech. 64 (3), 271-283 (1991)

Our 2D Fluidized Bed



838 μm SMD HDPE **micropellets**

Quartz viewing windows

(102 mm x 153 mm x 5mm thick)

Acrylic walls

(457 mm wide x 12.7 mm gap)

Velocity profile scans at

y = 60, 70, 100, 130 mm

V_{fl}/V_{mf} = 1.15

Vertical Gas Jet
(orifice flush with
distributor surface)

D_j = 9.2 mm, V_j = 92 m/s

LDV Measurement Technique

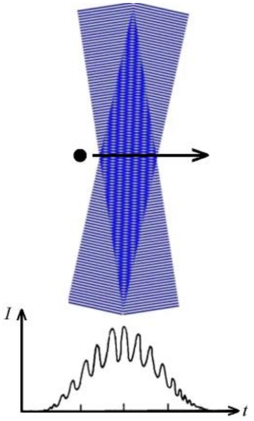
LDV in Two Phase Gas-Particle flow

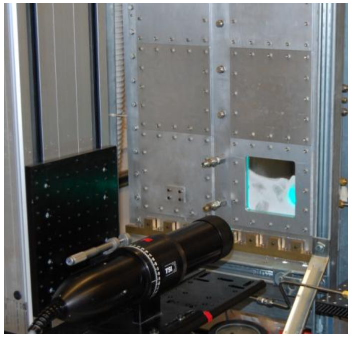
- *Particle speed*
  ~ frequency of scattered light

- Simultaneously measure bed particle (~1,000 μm) and jet gas (~1 μm tracers) velocity profiles (2 component)

  - Jet gas is seeded by rapidly condensing moisture in the air to produce ice crystals
    ($\boldsymbol{T_j}$ = -5°C, $\boldsymbol{\rho_j}$ = 1.32 kg/m³)

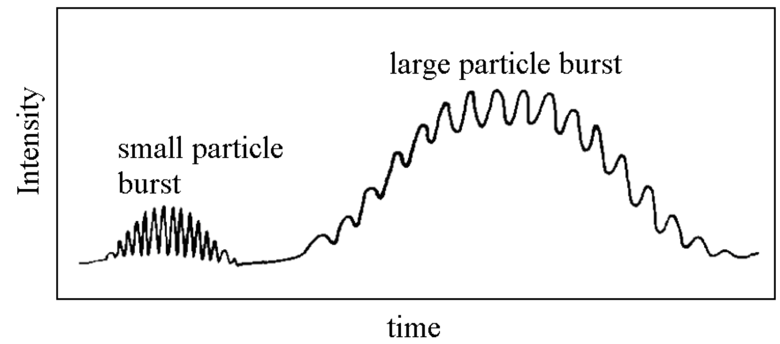
  - Burst intensity subranging to distinguish the two phase measurements

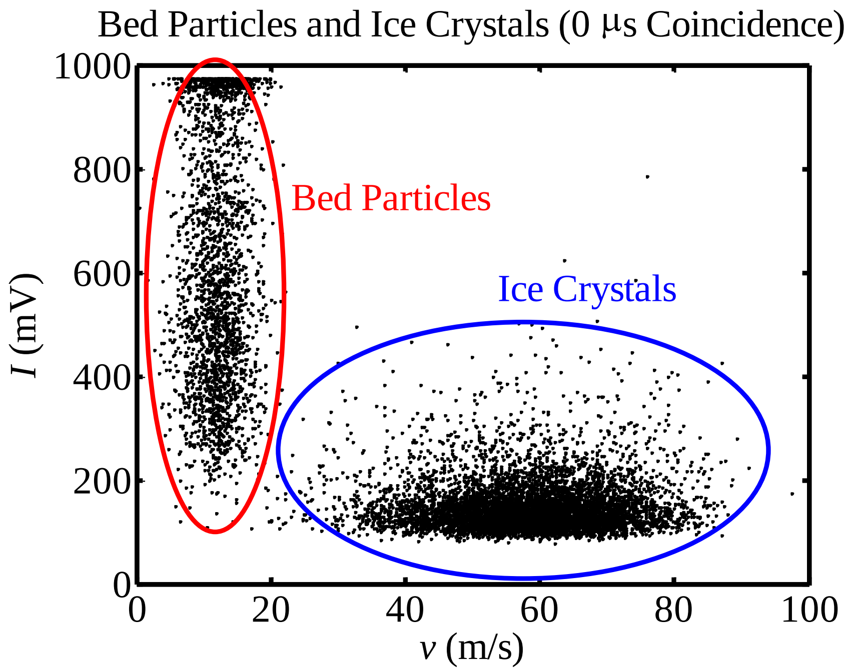




Intensity Subranging

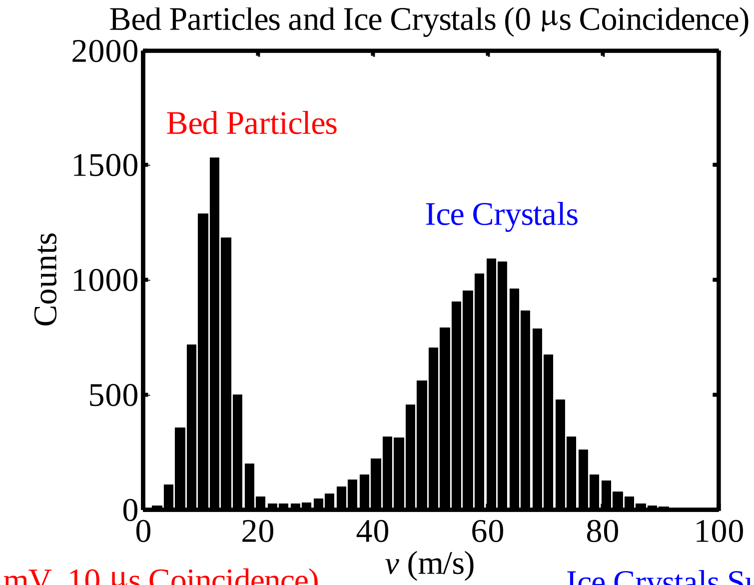
- Bed particles ($d_p >> \delta_f$) produce larger amplitude Doppler bursts than gas tracer ice crystals ($d_p \sim \delta_f$)
  - 99% of bed particle bursts > 200 mV
  - 99% of ice crystal bursts < 500 mV
- Coincidence
  - Gas tracers: 0 μs
  - Bed Particles: 10 μs

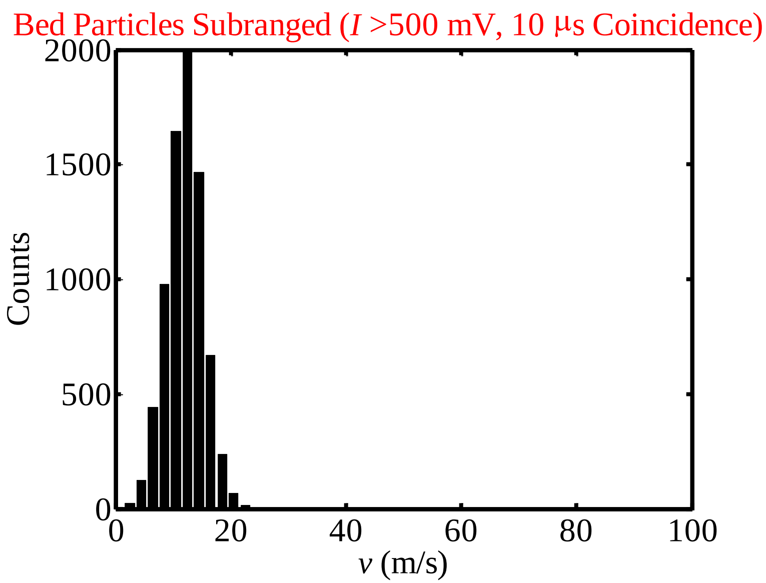


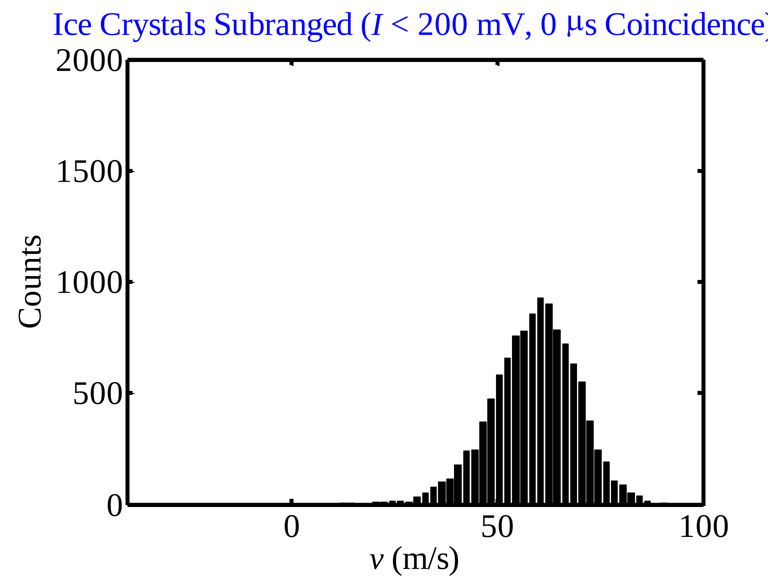


R. S. Barlow & C. Q. Morrison. "Two-phase velocity measurements in dense particle-laden jets," Exp. Fluids. 9 (1-2) 93-104 (1990)

Velocity Histogram Separation



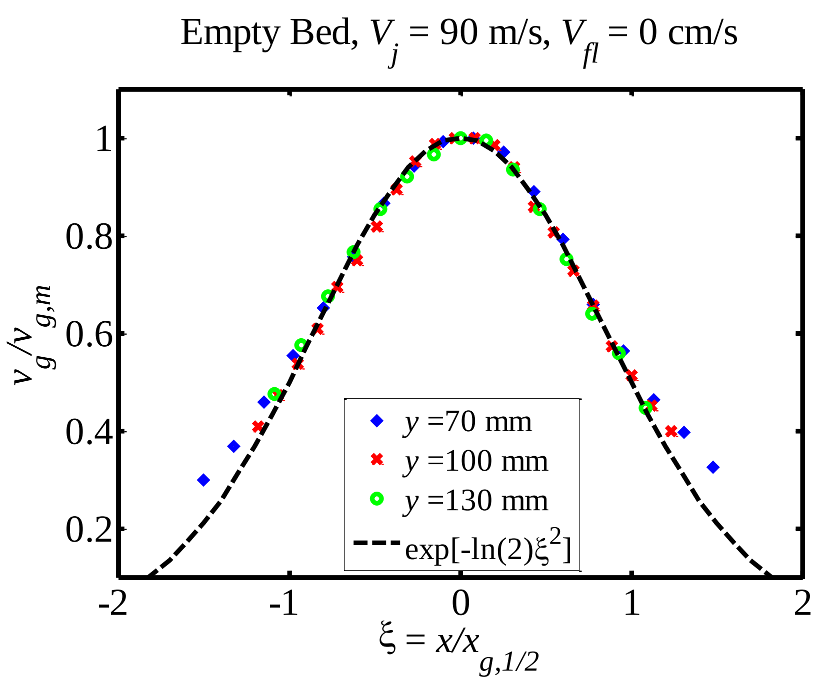


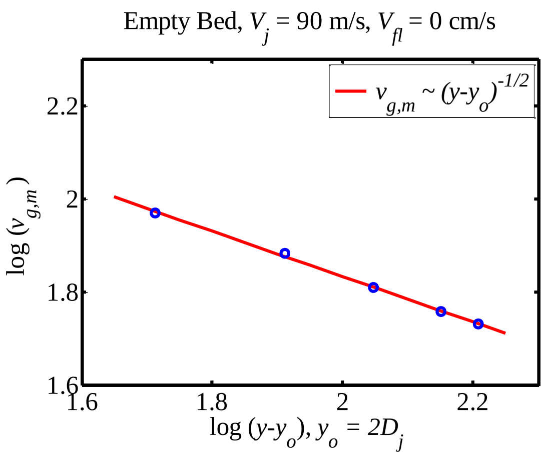


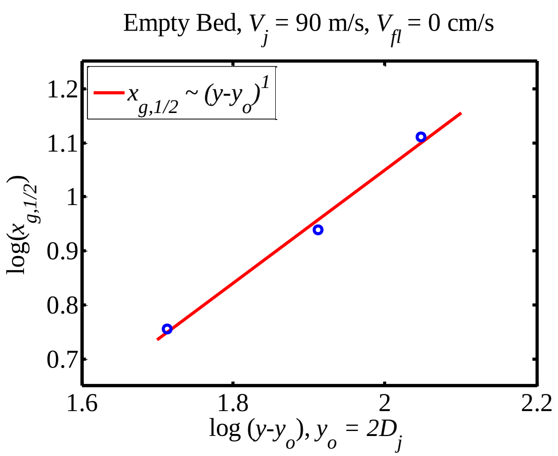
Single Phase Gas Jet

Empty Bed Transverse Velocity Profiles

- Single phase gas jet plume velocity profiles are self-similar with a Gaussian bell-curve shape
- Centerline axial velocity decay and velocity profile width expansion are consistent with a free 2D turbulent jet





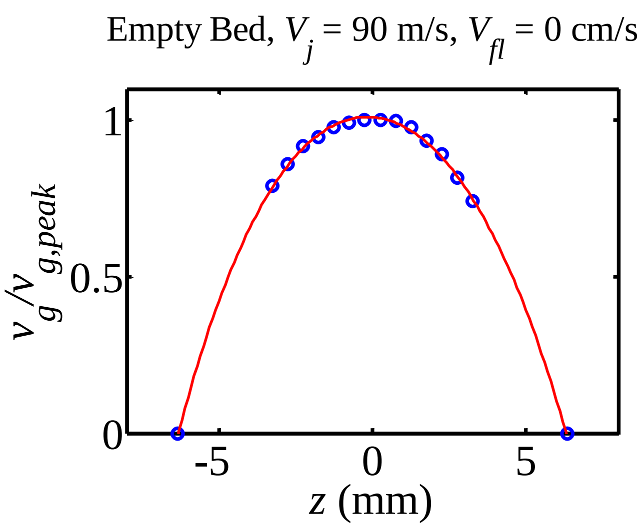


Mass and Momentum Transport Calculations

- The **3D nature** of flow must be accounted for

$$v_{g,avg}^2 = \frac{1}{w}\int_w [v(z)]^2 dz \approx C_2 v_{g,peak}^2 \qquad C_2 = 0.55$$

$$v_{g,avg} = \frac{1}{w}\int_w v(z)dz \approx C_1 v_{g,peak} \qquad C_1 = 0.7$$



- Self-similar velocity profiles enable transport values to be calculated from velocity centerline and half-point values.

Axial mass transport

$$\dot{m}_g = C_1 \rho_g w \int_{-b}^{b} v_g dx = 2.09\, C_1 \rho_g w \left(v_{g,m} x_{g,1/2}\right)$$

Axial momentum transport

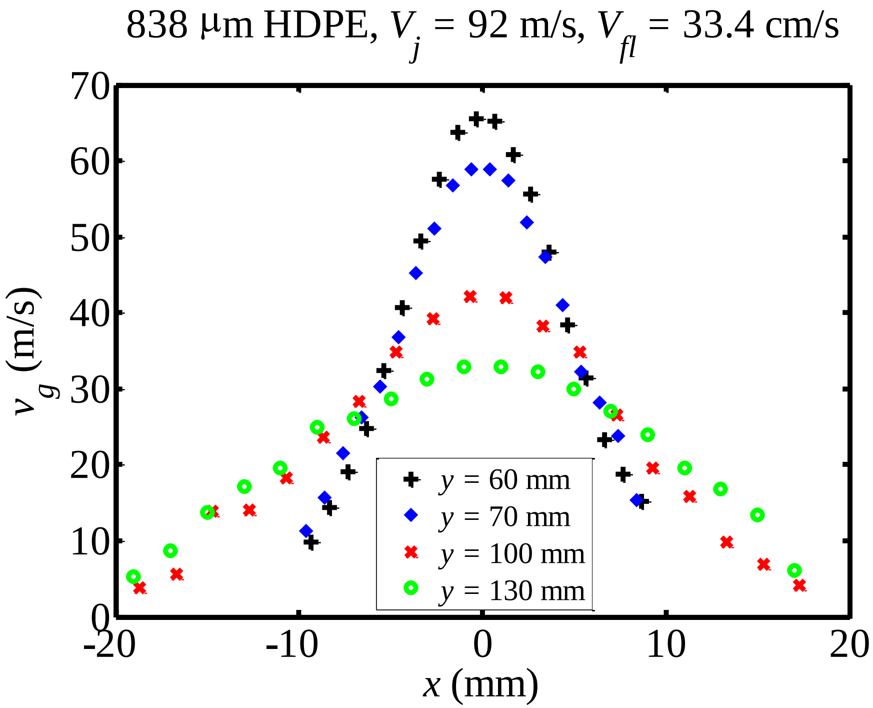
$$\dot{J}_g = C_2 \rho_g w \int_{-b}^{b} v_g^2 dx = 1.5\, C_2 \rho_g w \left(v_{g,m}^2 x_{g,1/2}\right)$$

Gas Jets in a Bubbling Bed

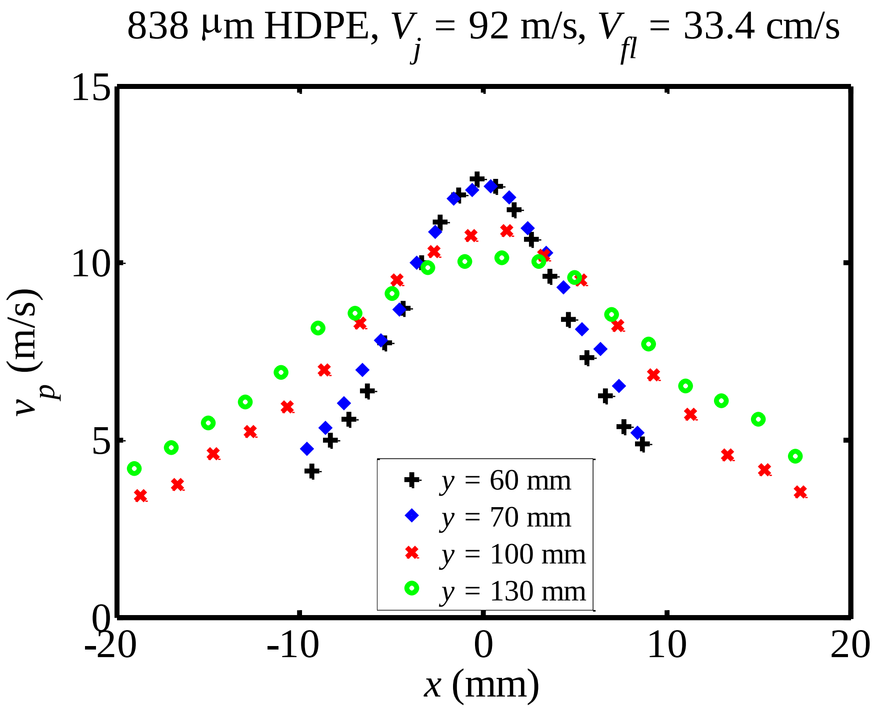
Bubbling Bed Vertical Jet Velocity Profiles

- Jet gas and bed particle velocities obtained simultaneously
  - 838μm HDPE particles
  - Fluidization: V_{fl} = 33.4 cm/s ($\mathbf{V_{fl}/V_{mf} = 1.15}$)

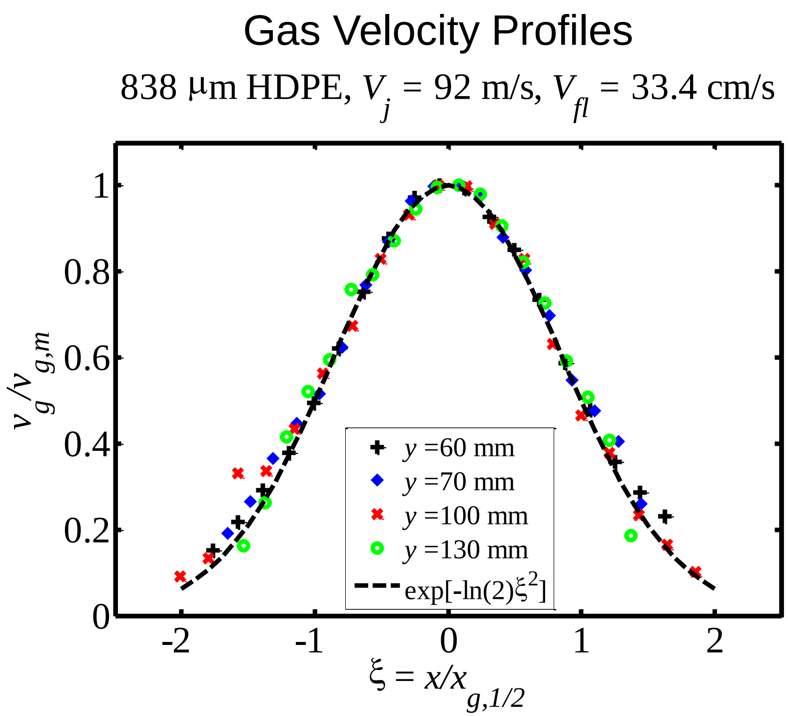
Gas Velocity Profiles

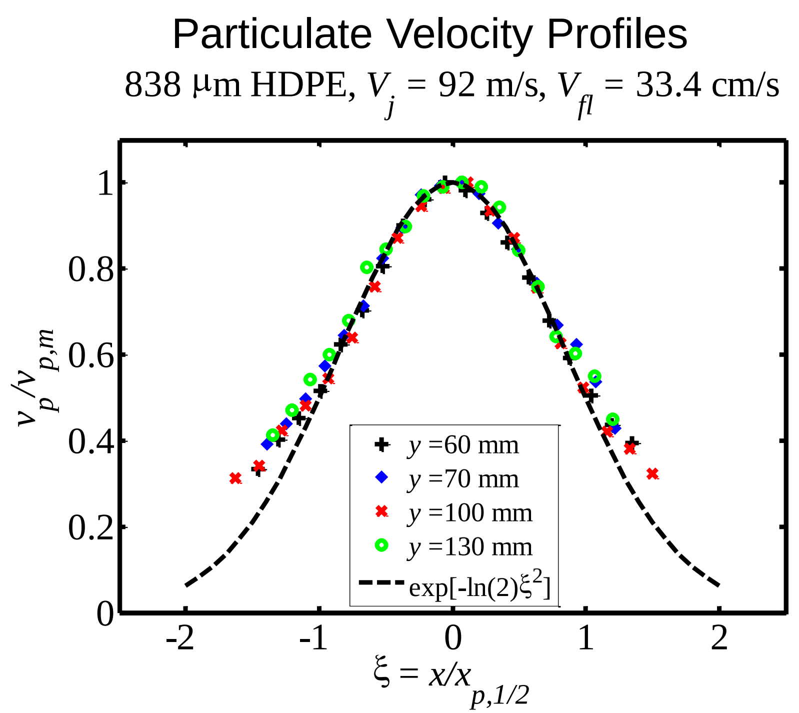


Particle Velocity Profiles



Transverse Velocity Profile Self-Similarity



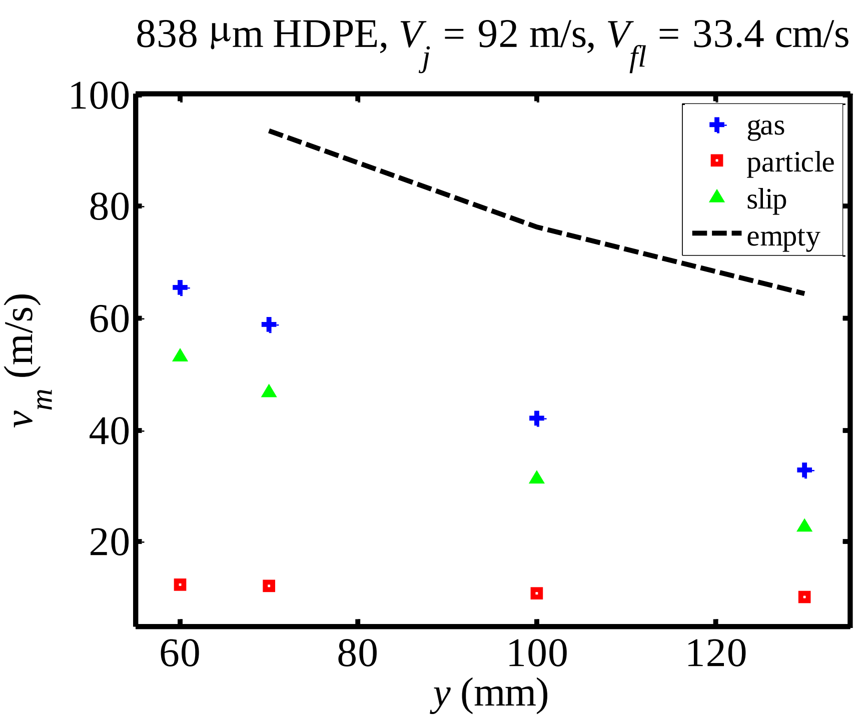


- The gas and particulate phase velocity profiles appear self-similar, thus they can be fully characterized by
  - Centerline velocity: $v_m(y)$
  - Velocity profile width: $x_{1/2}(y)$

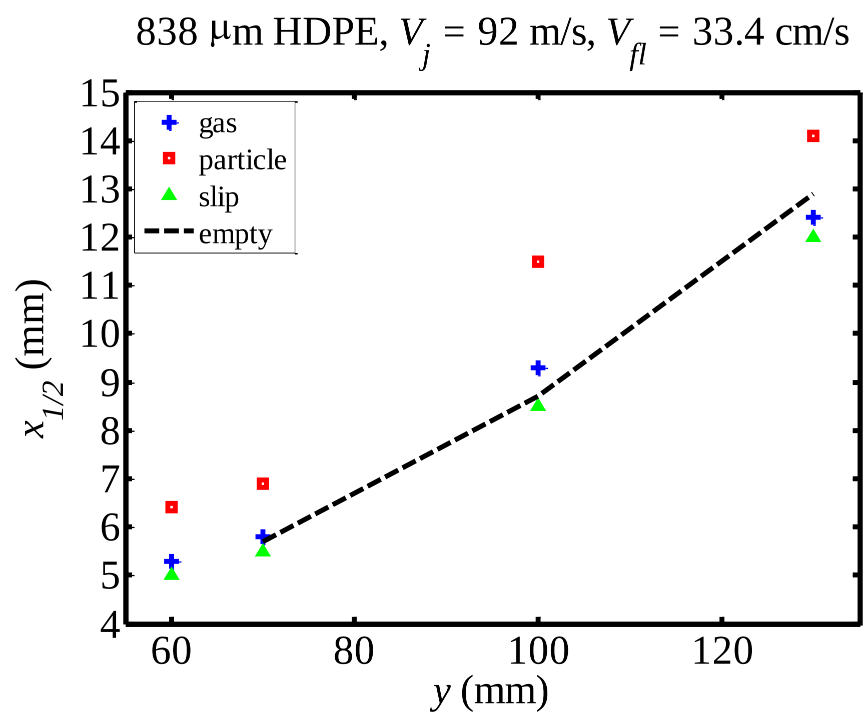
Centerline Velocity and Profile Width

- The presence of bed particles significantly reduces the gas phase velocity
- Velocity profile width for the gas phase in the bubbling and empty bed is very similar

Axial Velocity Profile



Velocity Profile Expansion



Volumetric Void Fraction (ε)

- Indirectly determined from a momentum balance using the measured velocity profiles

$$\dot{J}_j = \dot{J}_g + \dot{J}_p$$

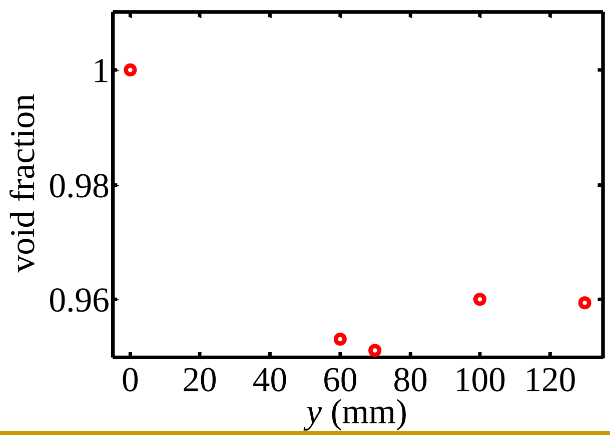
$$\dot{J}_p = (1-\varepsilon) C_2 \rho_p w \int_{-b}^{b} v_p^2 dx$$

$$\dot{J}_g = \varepsilon C_2 \rho_g w \int_{-b}^{b} v_g^2 dx$$

$$\varepsilon = \frac{\dot{J}_j - wC_2 \int_{-b}^{b} \rho_p v_p^2 dx}{wC_2 \left[\int_{-b}^{b} \rho_g v_g^2 dx - \int_{-b}^{b} \rho_p v_p^2 dx \right]}$$

- Void Fraction > 95% in the dilute jet plume

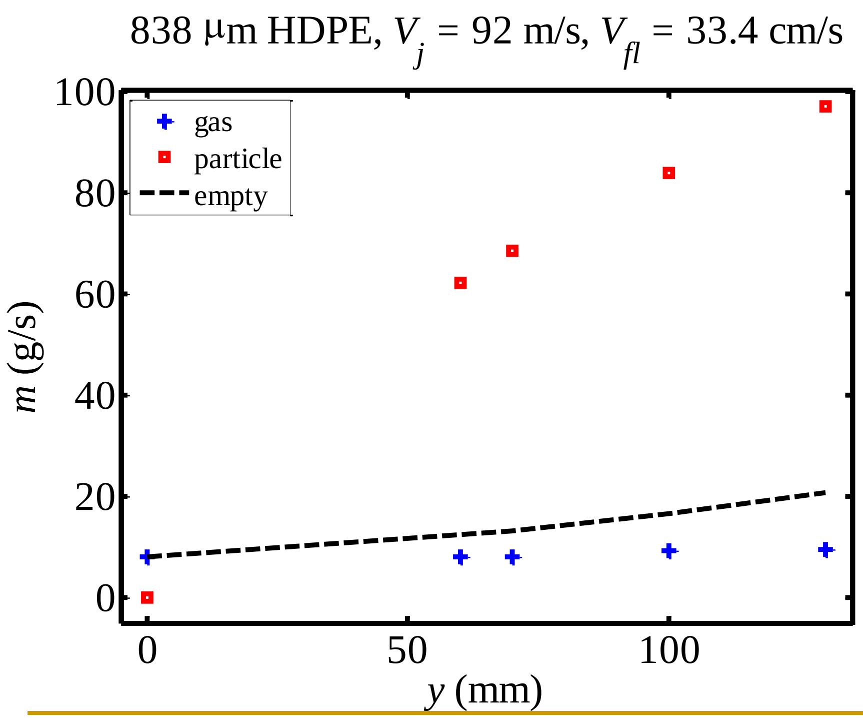
838 μm HDPE, V_j = 92 m/s, V_{fl} = 33.4 cm/s



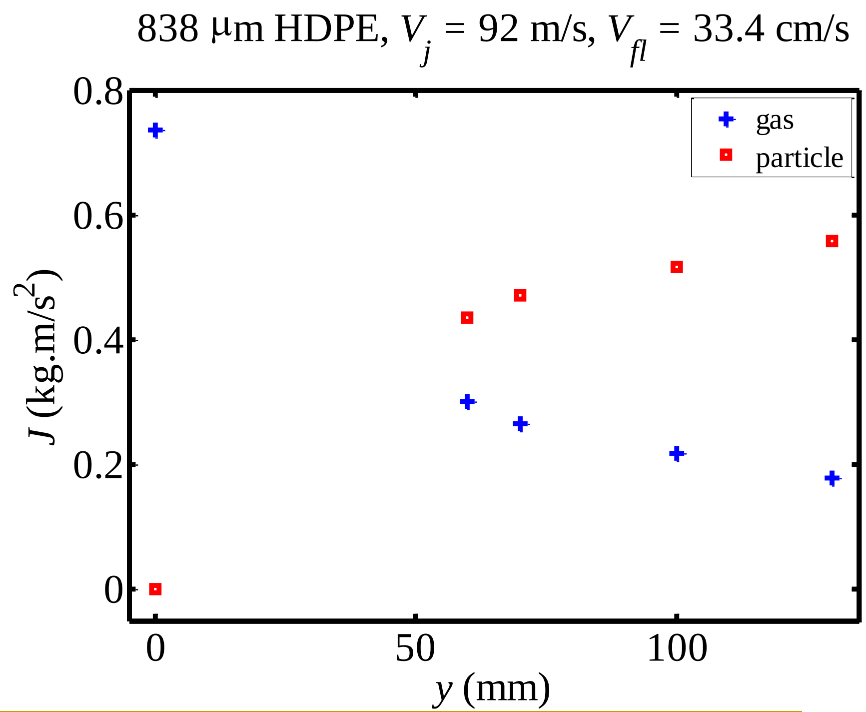
Mass Flow and Momentum Transfer

- Bed particles are entrained into the jet plume while the gas phase mass flow remains nearly constant for this fluidization level
- Momentum is rapidly transferred from the jet gas to the entrained particles

Mass flow in jet plume



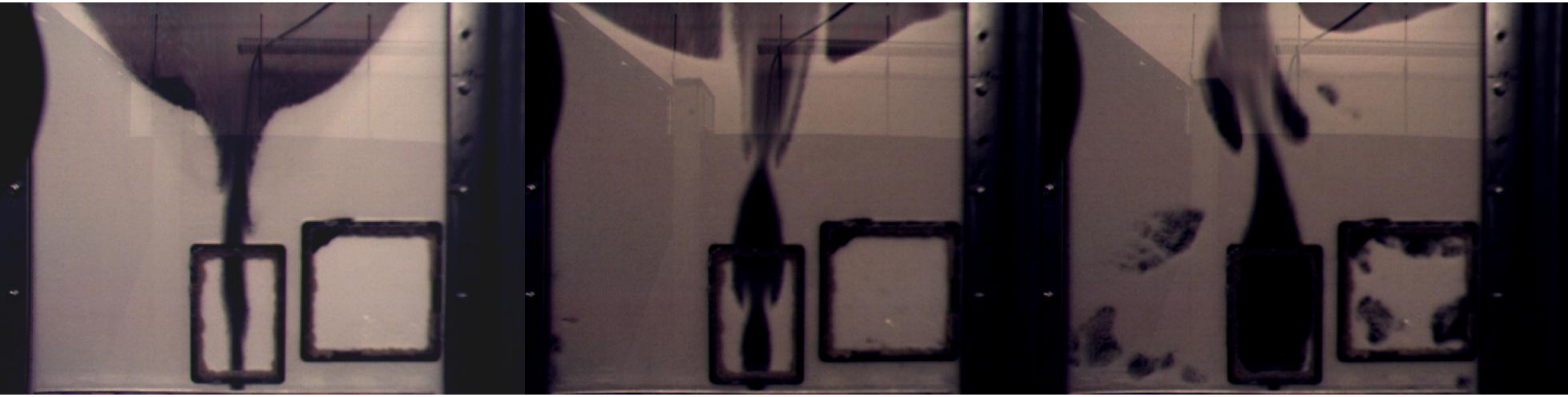
Momentum transfer in jet plume



Effect of Emulsion Fluidization State

Effect of Fluidization on Jet Dynamics

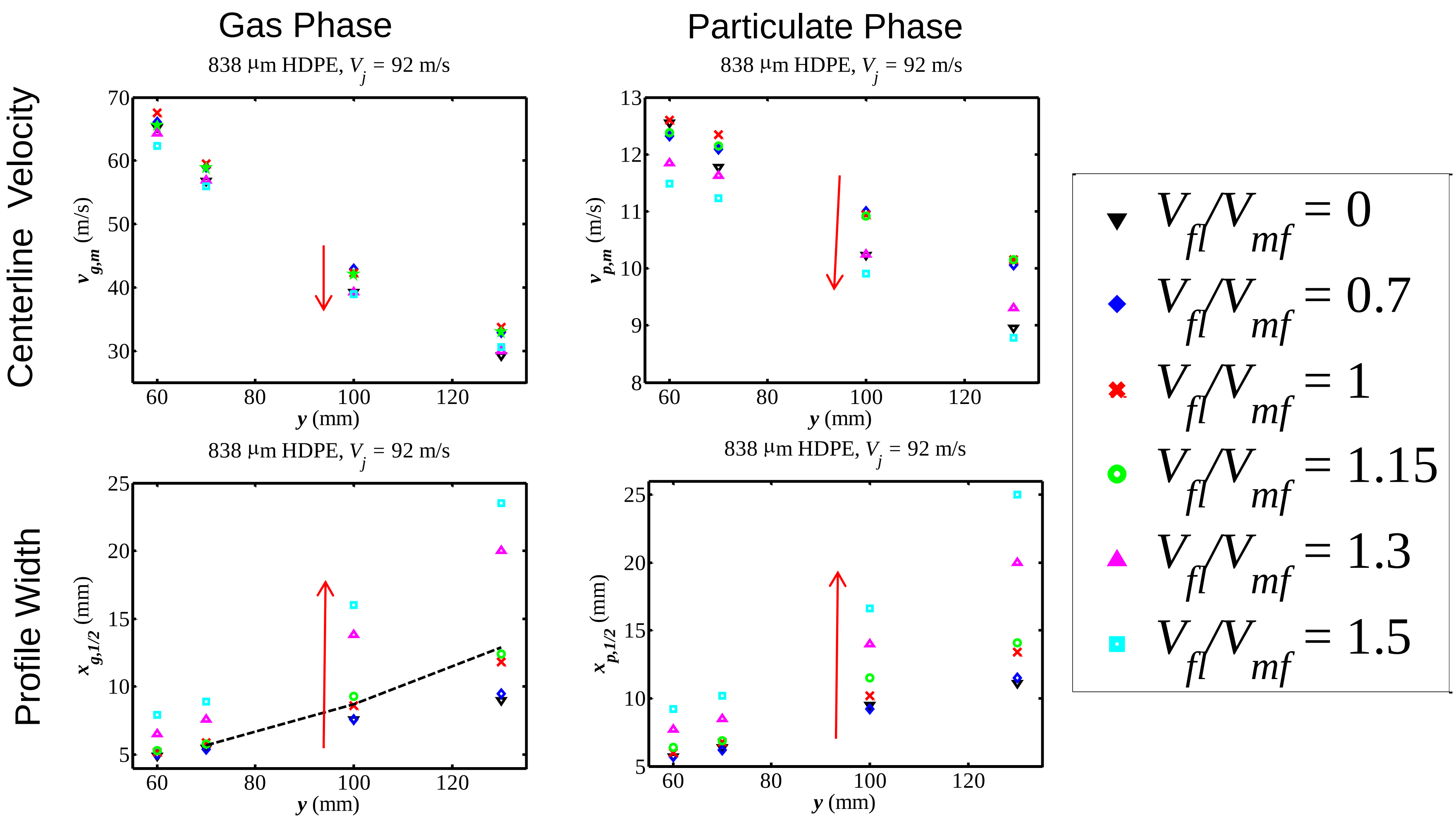
- Fluidization level varied from spouted bed to 50% beyond minimum fluidization
- 838 μm HDPE micropellets
- $V_j = 92\ m/s$



$V_{fl}/V_{mf} = 0$ $V_{fl}/V_{mf} = 1$ $V_{fl}/V_{mf} = 1.5$

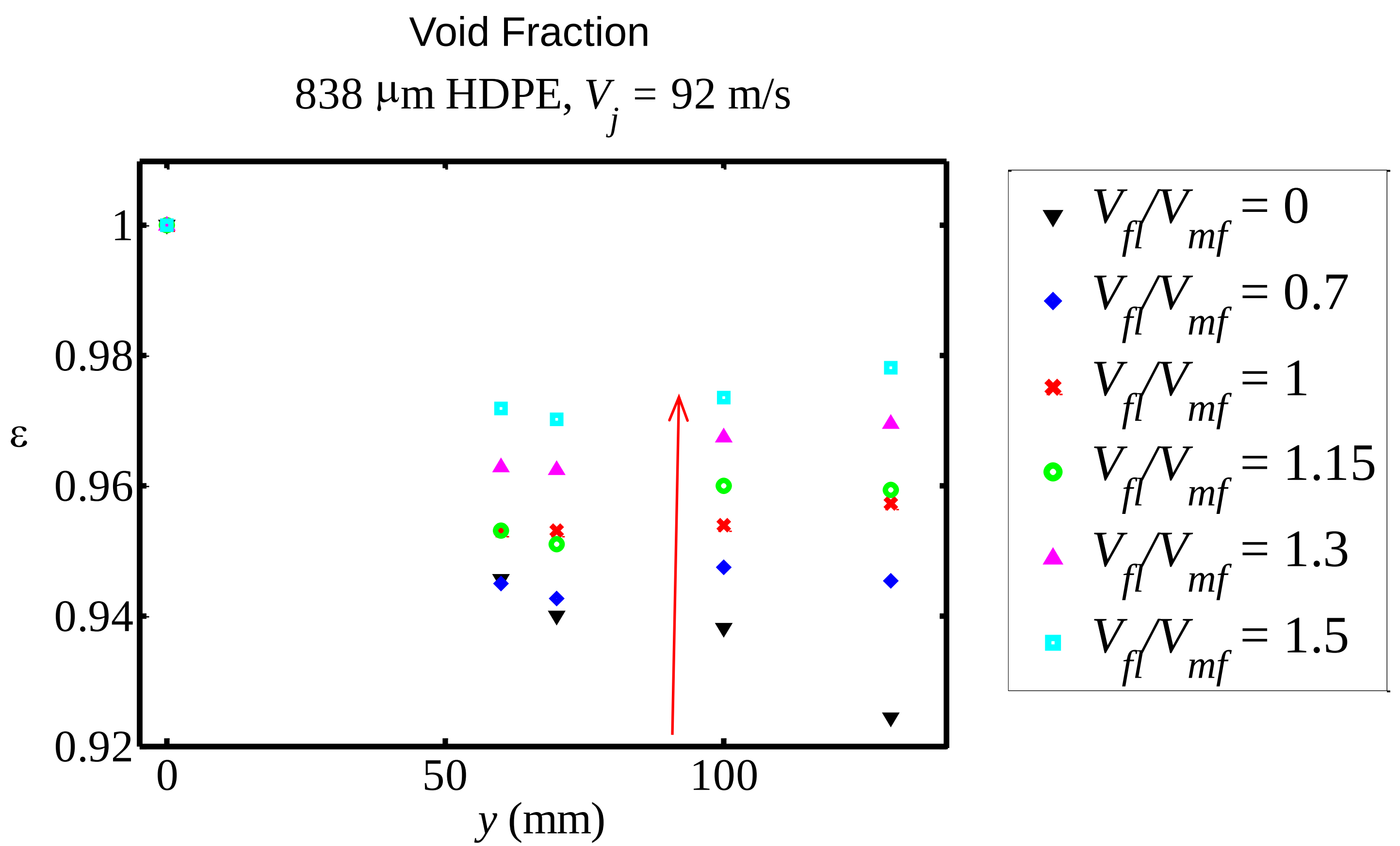
Effect of Fluidization on Velocity Profiles

- Increasing the fluidization velocity decreases the maximum centerline velocity and widens the velocity profiles for both phases



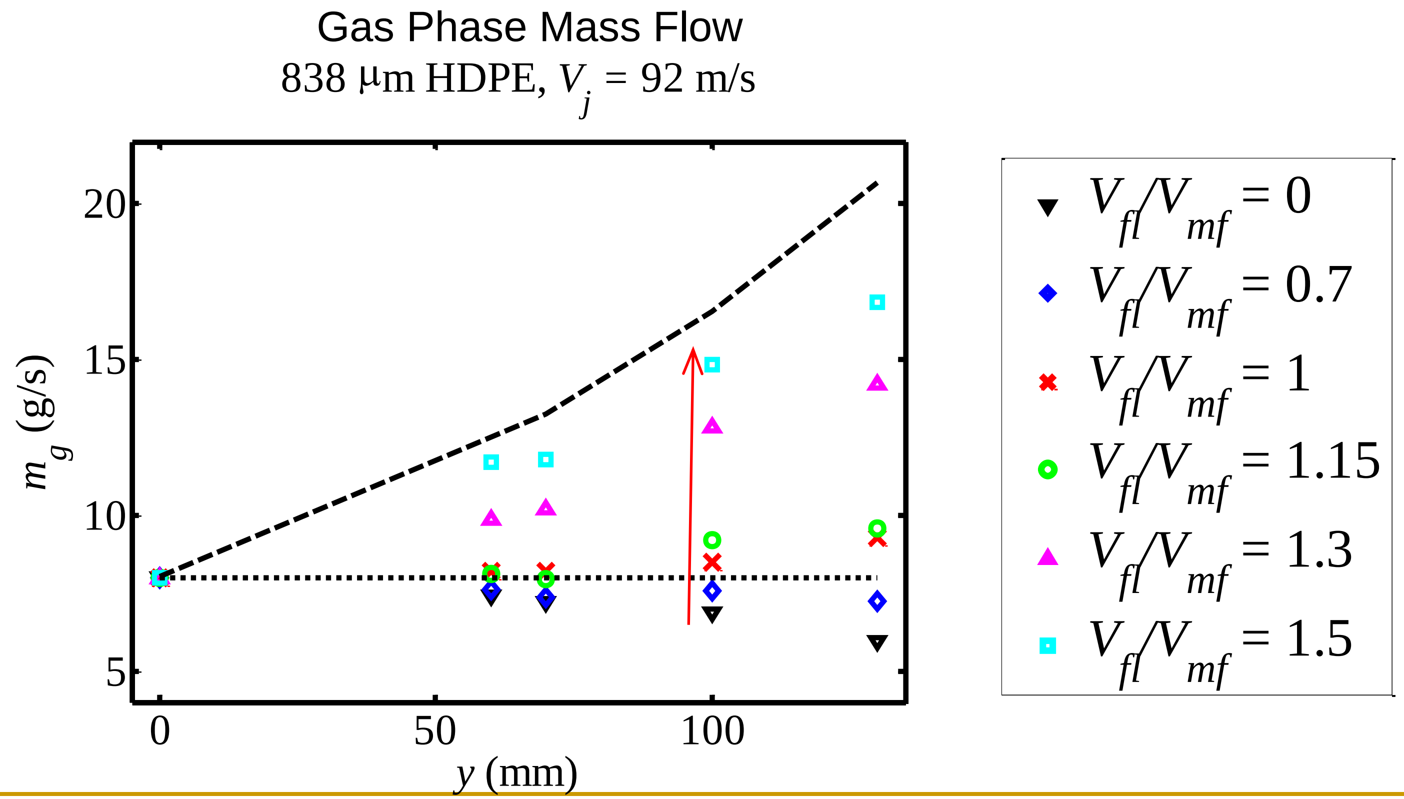
Effect of Fluidization on Void Fraction

- Void fraction in the jet plume increases with emulsion fluidization



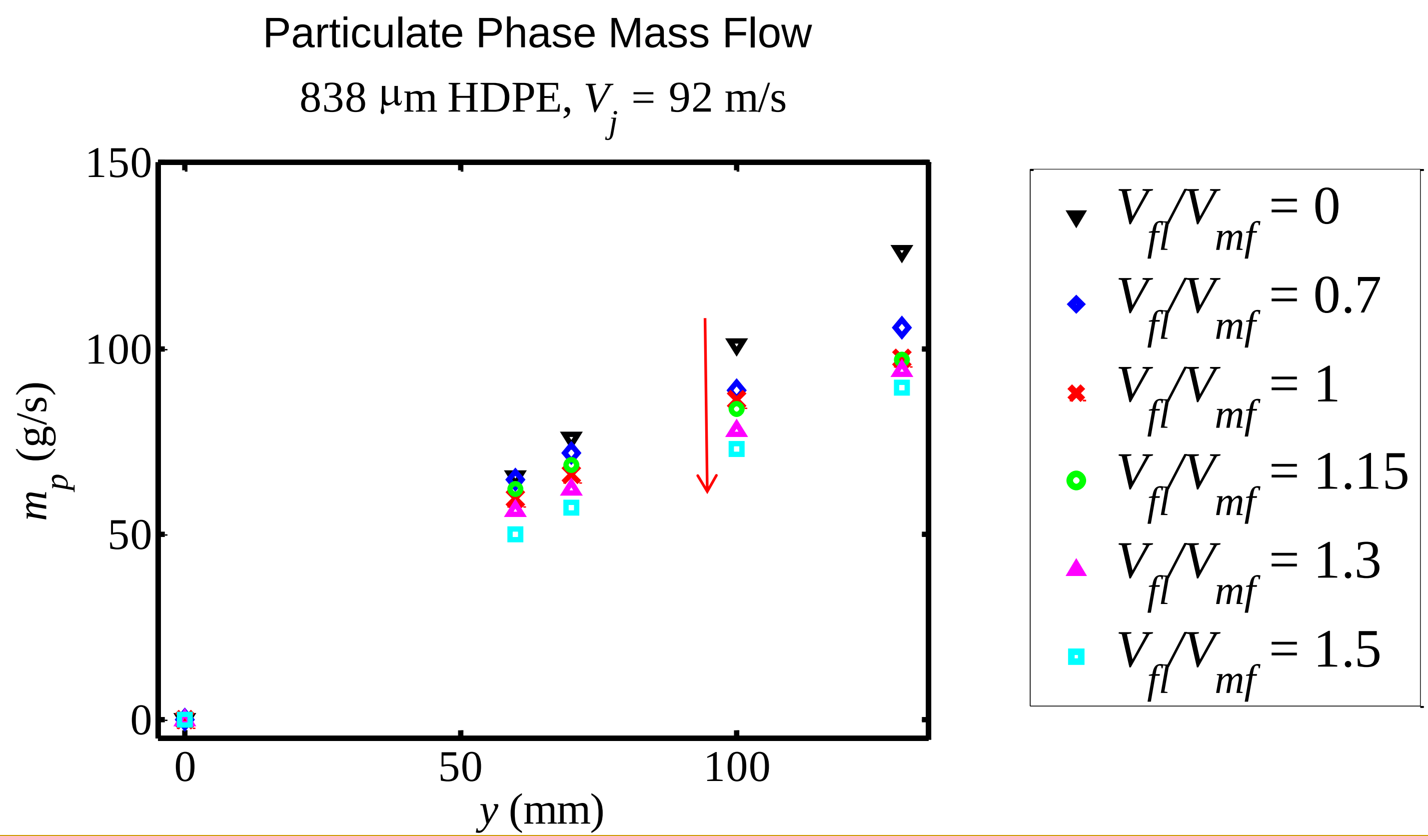
Effect of Fluidization on Mass Transport

- As the fluidization rate increases, the gas phase mass flow increases
  - *Below minimum fluidization, jet gas diffuses into the emulsion to locally fluidize the particles*
  - *Above minimum fluidization, interstitial gas and bubbles in the emulsion are entrained into the jet plume*



Effect of Fluidization on Mass Transport

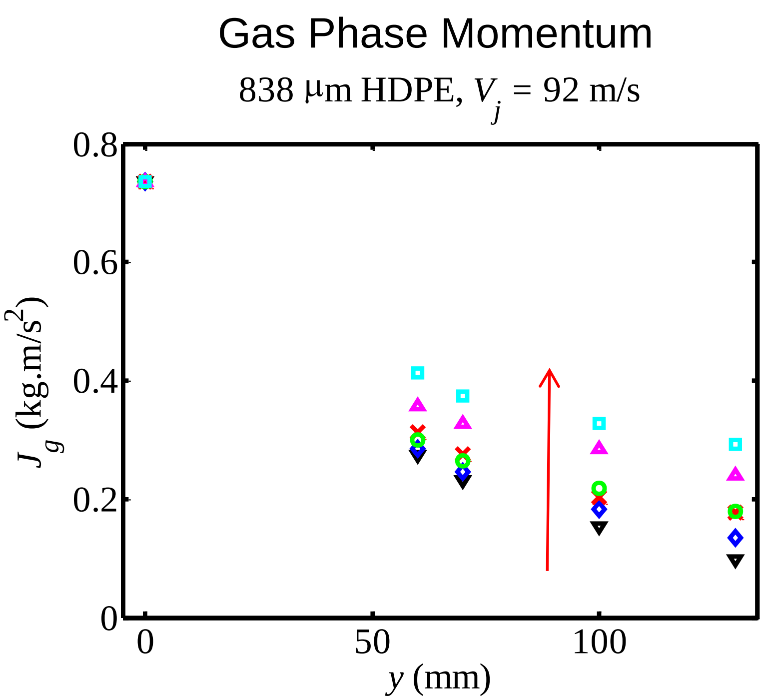
- Particulate phase mass flow in the plume decreases with increasing fluidization due to competition with the interstitial gas entrainment

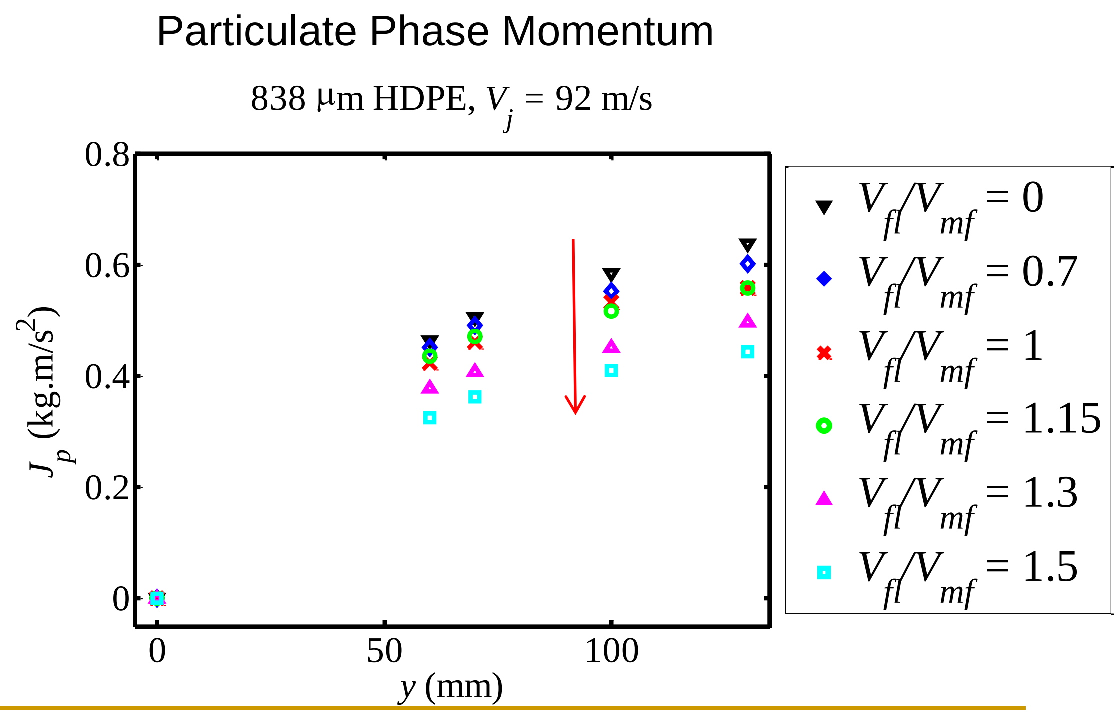


Effect of Fluidization on Momentum Transport

- As the fluidization rate increases, the gas phase momentum increases due to increased interstitial gas entrainment
- Particulate phase momentum decreases with increasing fluidization

$$\dot{J}_j = \dot{J}_g + \dot{J}_p$$





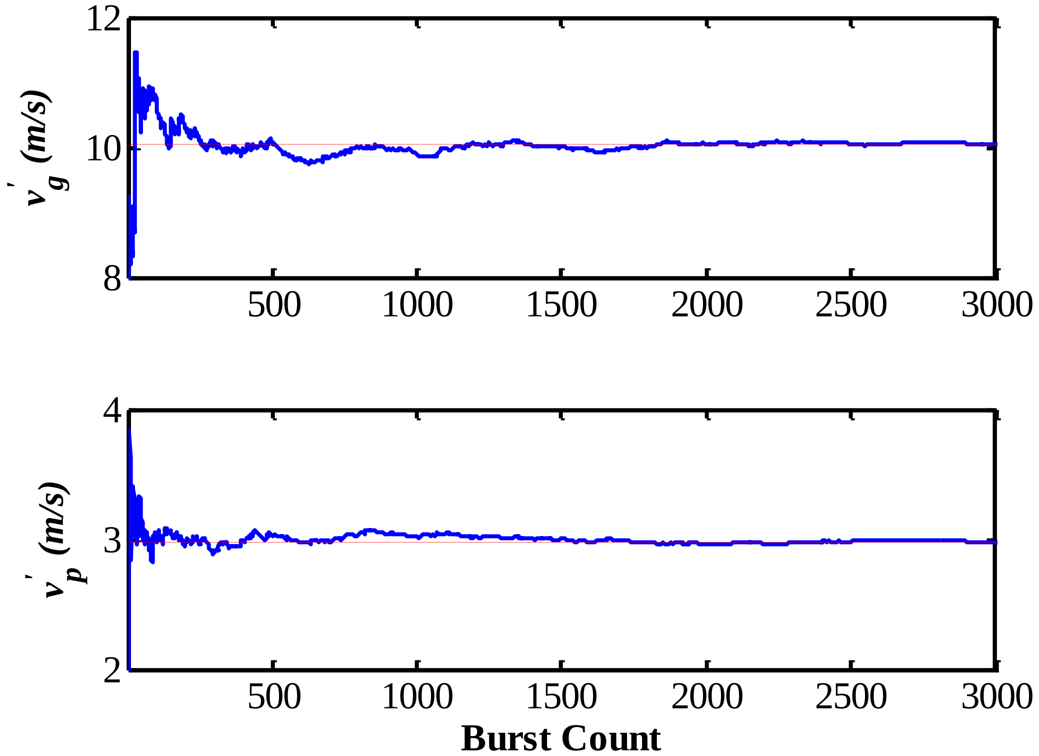
Turbulence Measurements

Importance

- The jet plume of a bubbling bed is a region of turbulent mixing
- Experimental measurements have been restricted to plume size, plume shape, gas mean velocity, solids mean velocity and solids concentration
- Turbulence data will help in developing fundamentally rigorous models to describe momentum transport in bubbling beds
- Fluctuating velocity data will be valuable in validating gas-solid turbulence equations used in Eulerian framework

M. Filla, L. Massimilla, and S. Vaccaro. “Gas jets in fluidized beds and spouts: A comparison of experimental behaviour and models,” Can. J. Chem. Eng. (61): 370, 1983.

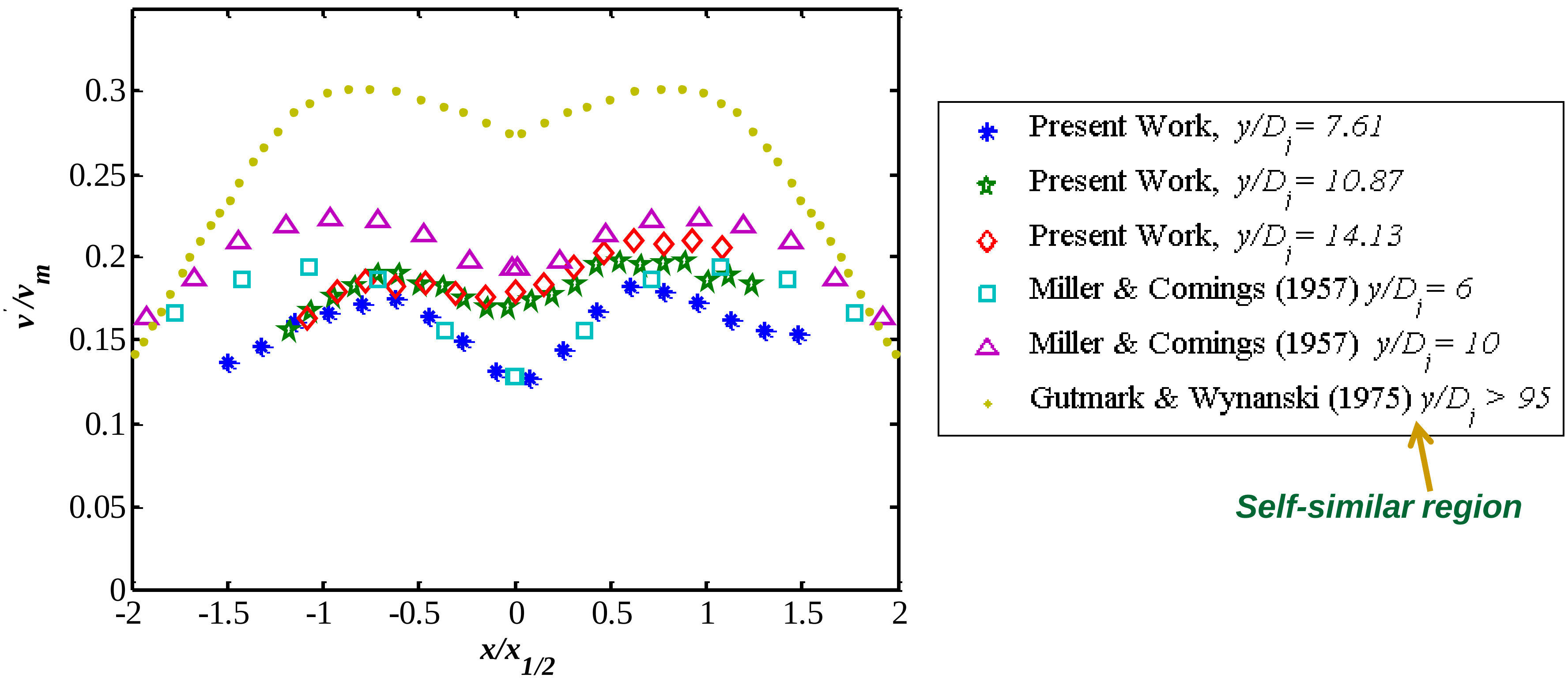
Experimental Procedure



$$v' = \sqrt{\sum \frac{(v-\bar{v})^2}{N}}$$

- The same LDV technique used for mean velocities is employed to measure fluctuating velocities in each phase
- To be conservative, only measurements with Doppler burst counts greater than 1000 are considered

Single Phase Turbulence



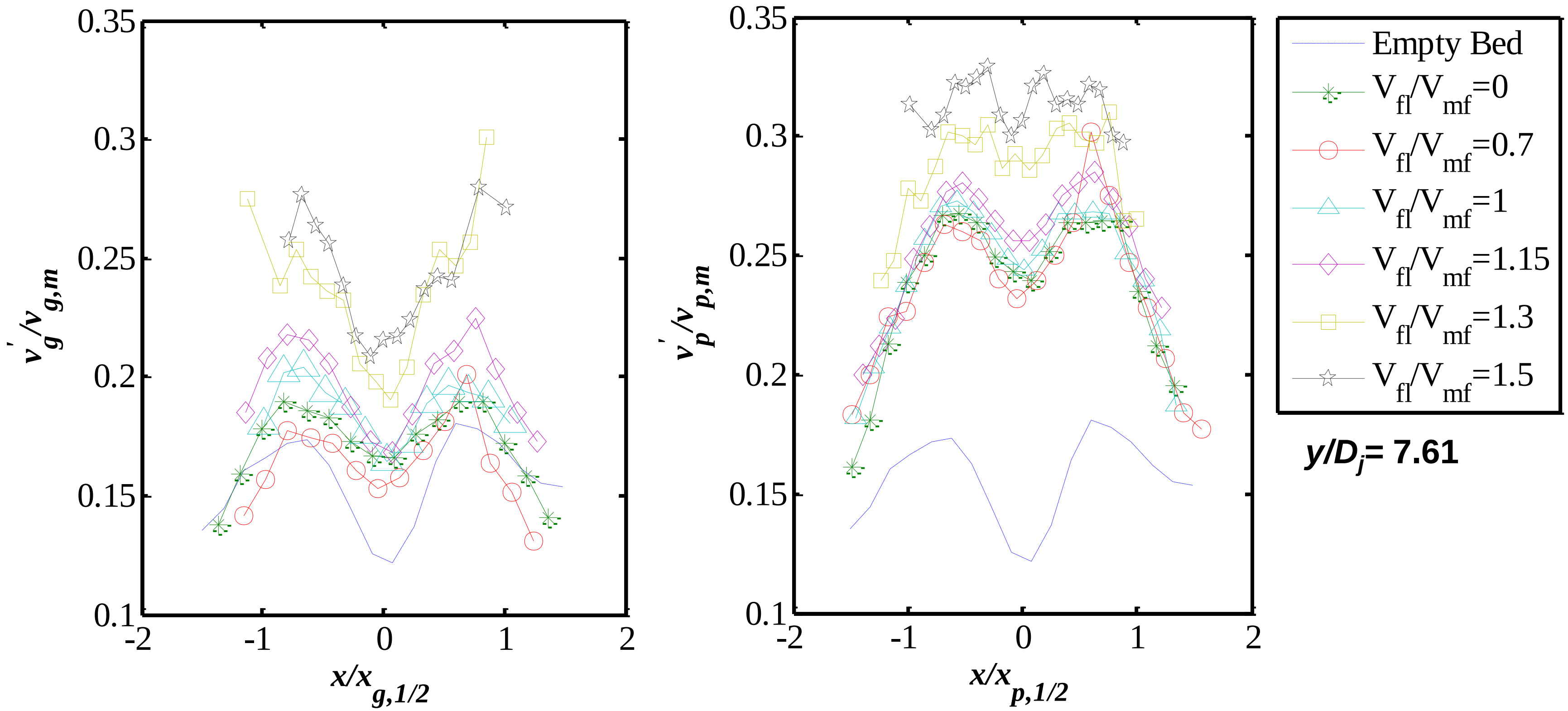
- Data lies in the non-self similar or potential core region of turbulence
- Shows good agreement with literature
- Negligible influence of bounding walls seen

D.R. Miller, and E.W. Comings, “Static pressure distribution in the free turbulent jet,” J. Fluid Mech. (**3**): 1, 1957.

E. Gutmark, and I. Wygnanski, “The planar turbulent jet,,” J. Fluid Mech. (**73**): 465, 1976.

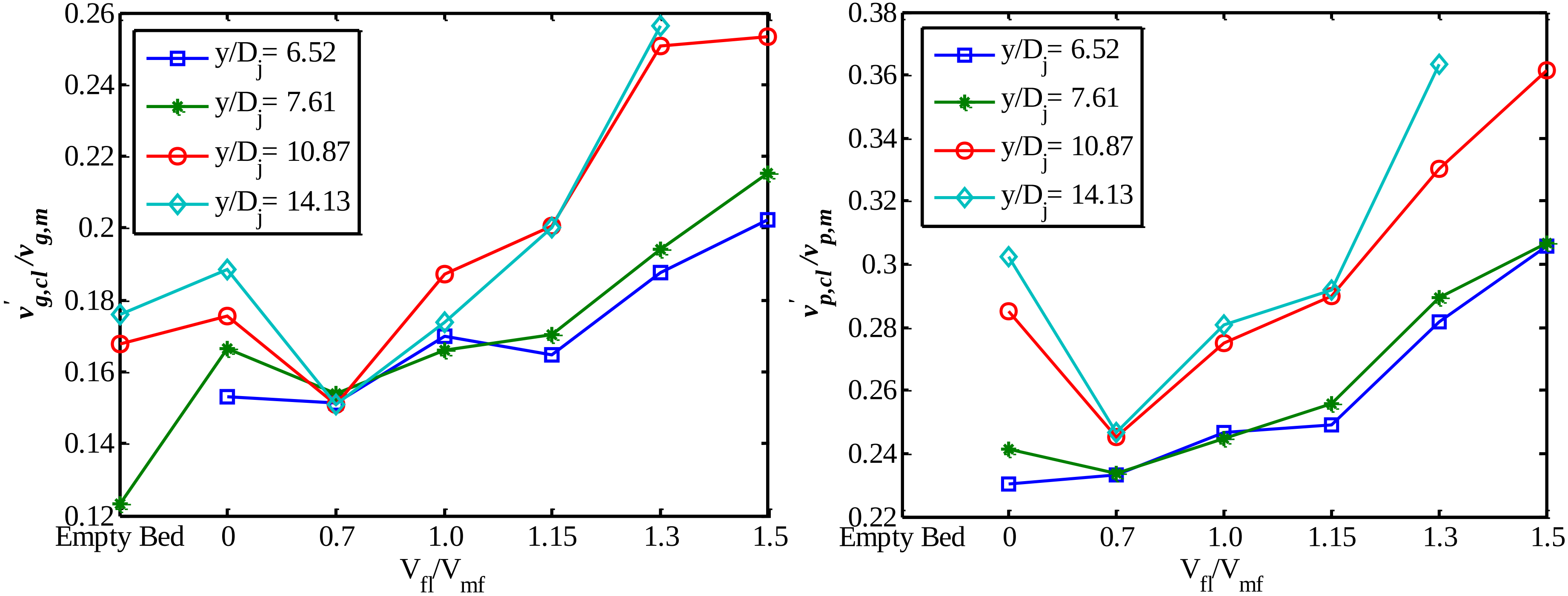
D. Rangarajan , and J. S. Curtis, “Effect of spanwise width on rectangular jets with sidewalls,” J. Fluids. Eng. T. ASME, submitted 2011.

Bubbling Bed Fluctuating Velocity Profiles



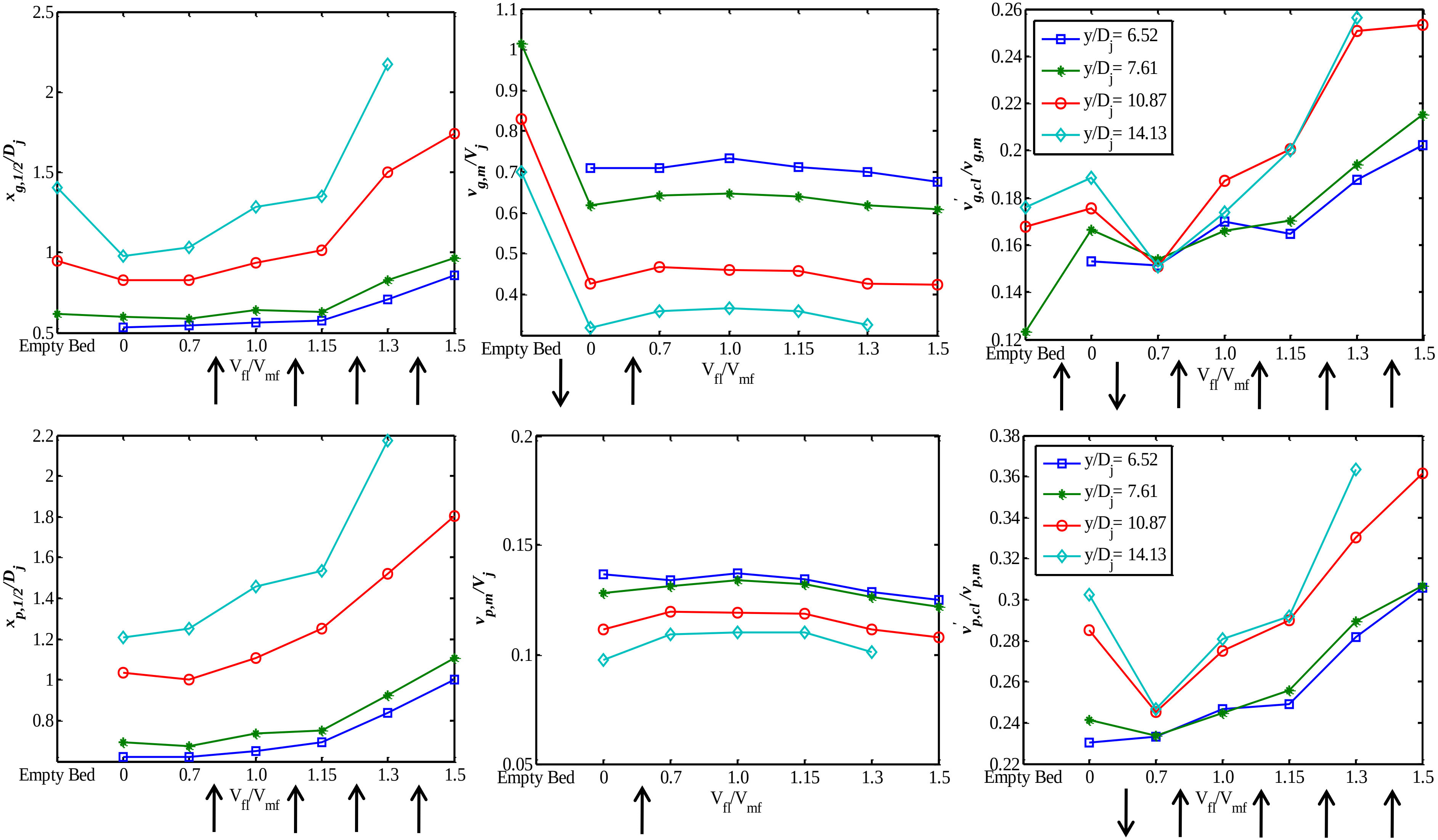
- Particle fluctuations are ~50% greater than gas fluctuations
- Profile shapes for both phases similar to single phase turbulence
- Deviation in shape at higher fluidization state due to plume boundary fluttering

Effect of Fluidization on Turbulence



- There is an increase in gas turbulence in Spouted Bed compared to Empty Bed
- Effect of increasing distributor velocity is to initially decrease and then increase fluctuations in both phases
- Particle and gas fluctuations complement each other

Relationship with mean quantities



Fluctuating intensity $\sim \frac{x_{1/2}}{v_m}$

Coupling via Fluctuating Velocity

$$St = \frac{t_p}{t_g} = \frac{\rho_p d_p^2 V_j}{18\mu_g D_j} \sim 21{,}000$$

$$\mathrm{Re}_p = \frac{(v_g - v_p) d_p \rho_g}{\mu_g} \sim 1500 - 3000$$

- High ***St*** suggests particle motion is unlikely to be affected by gas-phase turbulence
- High ***Re$_p$*** suggests gas turbulence enhancement due to vortex shedding caused by particles

Hestroni, G., “Particles-turbulence interaction”, *Int. J. Multiphase Flow*, **15** (1989) 5

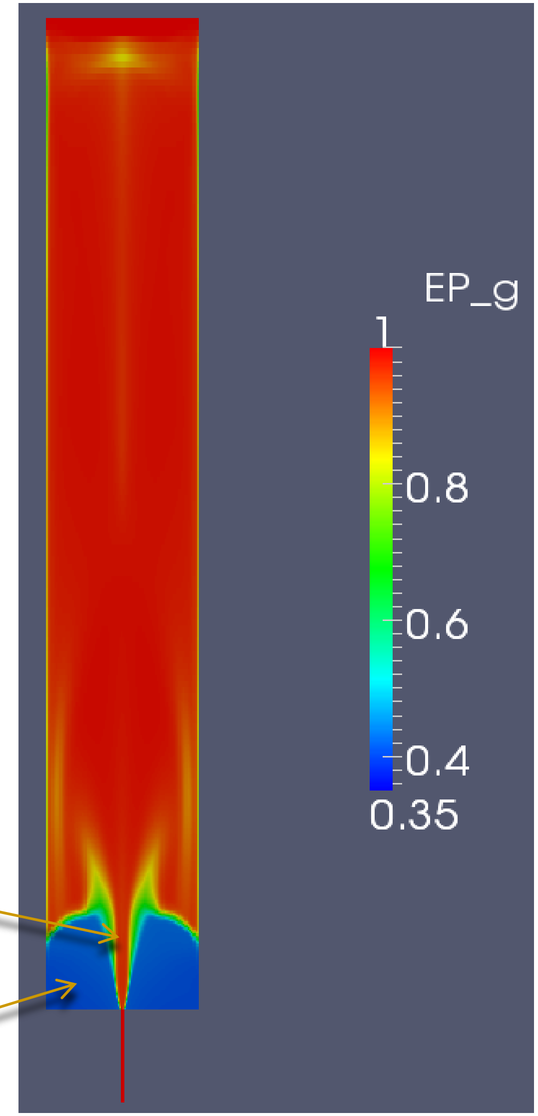
Modeling Effort

Modeling Framework

- Eulerian two-fluid modeling
- Solved using MFIX code
- Inclusion of friction and turbulence interaction terms from existing works

$$\varepsilon\rho_g\left[\frac{\partial \underline{V}_g}{\partial t}+\underline{V}_g\cdot\nabla\underline{V}_g\right]=-\varepsilon\nabla P-\nabla\cdot\varepsilon\underline{\underline{\tau}}_g+\varepsilon\rho_g\underline{g}-\underline{F}_D$$

$$\nu\rho_s\left[\frac{\partial \underline{V}_s}{\partial t}+\underline{V}_s\cdot\nabla\underline{V}_s\right]=-\nu\nabla P+\underline{F}_D+\nu\rho_s\underline{g}-\nabla\cdot\underline{\underline{\sigma}}_s$$



Dilute region dominated by turbulent and collisional/kinetic stresses

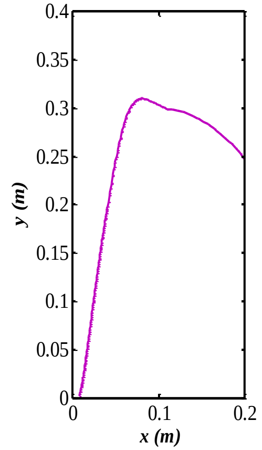
Dense region dominated by frictional stress

Use of Experimental Data for Validation

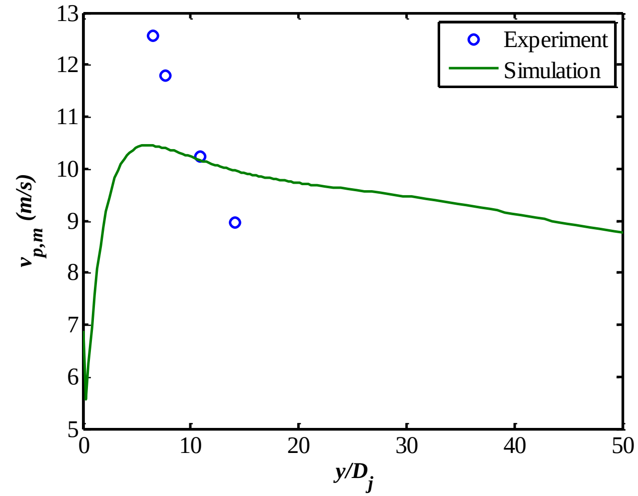
Experimental data	Compare with	Validate
Minimum fluidization velocity	Minimum fluidization velocity	Frictional pressure
Plume size and shape from photograph	Solids fraction contour	Frictional viscosity
Gas and particle mean axial velocity	Gas and solids axial velocity	Overall performance of model
Gas phase axial fluctuating velocity	Turbulent kinetic energy assuming same anisotropy as planar single phase jet	Gas-particle turbulence interaction
Particle axial fluctuating velocity	Granular temperature assuming isotropy	Gas-particle turbulence interaction

Spouted Bed: Srivastava-Sundaresan friction and no turbulence interaction

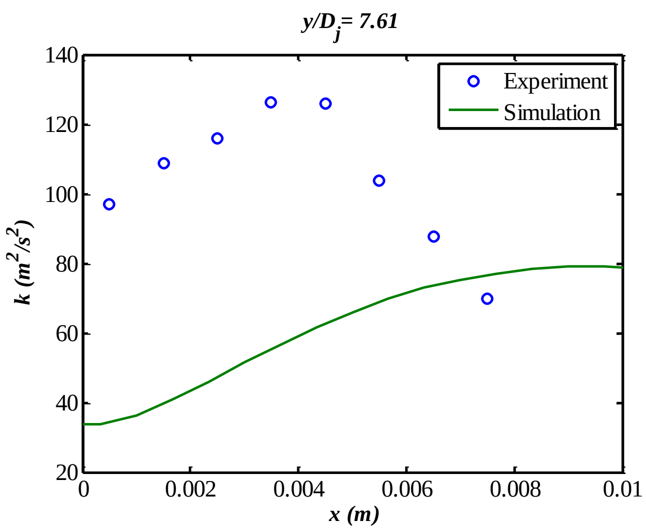
Bulk Flow



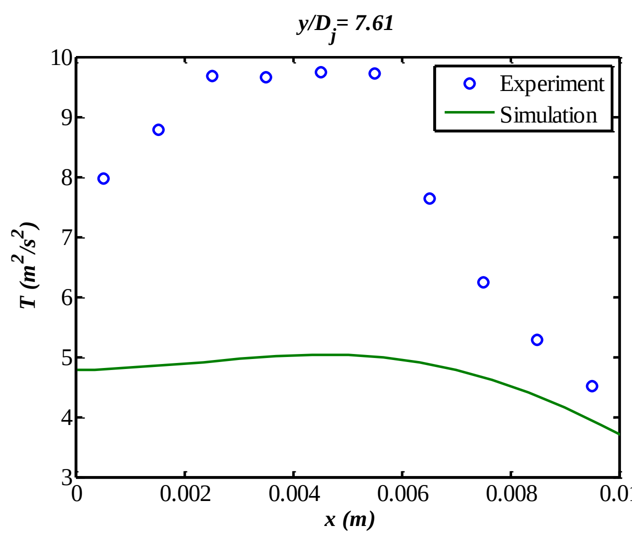
Particle mean velocity decay



Gas turbulence



Granular temperature



Srivastava, A., and Sundaresan, S., “Analysis of a frictional-kinetic model for gas-particle flow,” *Powder Technol.*, **129** (2003) 72

Improvement in friction and turbulence interaction models required

Conclusions

- A procedure has been developed to simultaneously measure gas and particulate phase velocities based on LDV burst intensity and coincidence subranging
- Mass and momentum transport of the two phases inside the jet plume of a bubbling bed was calculated from the measured velocity profiles
- Maintaining constant gas jet inlet conditions changes in mean and fluctuating quantities were investigated for varying emulsion fluidization states
- The use of experimental data to validate the Eulerian two-fluid model is presently being studied