LDV Measurements and Analysis of Gas and Particulate Phase Velocity Profiles in a Vertical Jet Plume in a 2D Bubbling Fluidized Bed

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Overview

- Background
- Laser Doppler Velocimetry (LDV) Measurement Technique
- Single Phase Gas Jet in the Empty 2D Bed
- Gas Jets in the Bubbling Bed
    - Gas and particulate phase velocity profile measurements
    - Mass flow and momentum transport calculations
    - Effect of the emulsion fluidization level on jet dynamics
- Summary and Future Work

Background

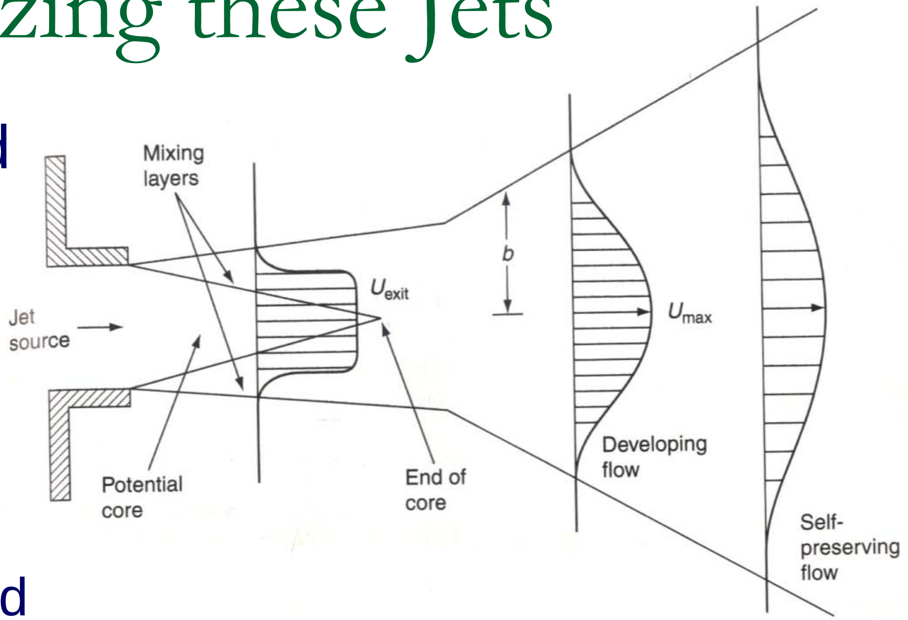
Jets in Fluidized Beds

- High speed gas jets are injected into a bed emulsion, rapidly entraining and mixing bed particles and interstitial gas
- The jet plume is a region of fast chemical reactions
  - Jets of steam are sprayed into fluidized bed reactors during the gasification of coal or biomass
  - Jet dynamics are critical to the efficiency and design of the system
- Quantitative 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

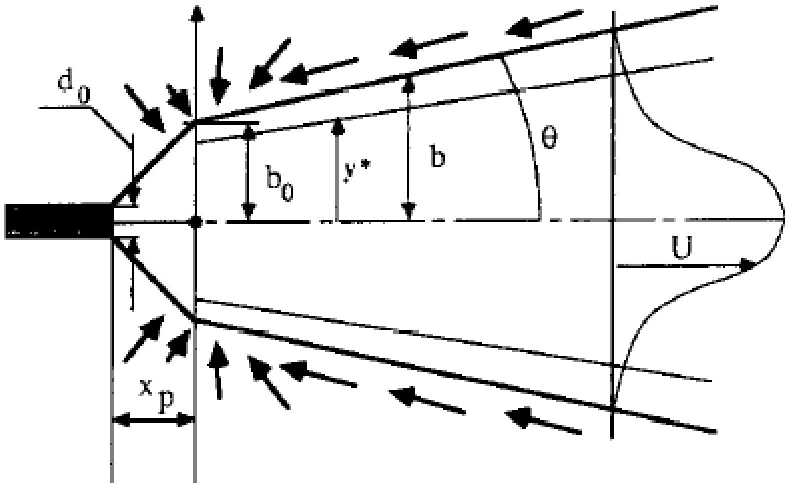
C. Xuereb, C. Laguerie, T. Baron. “Etude du comportement de jets continues horizontaux ou inclines introduits dans un lit fluidise par un gaz Deuxieme partie: profiles de vitesse du gaz dans les jets horizontaux,” Powder Tech. 64 (3), 271-283 (1991)

Prior Work Characterizing these Jets

- Gas velocity profiles considered analogous to single phase jets
    - Bell Curve Transverse Profile
    - Power Law Axial Profile
    - Linear Plume Expansion
    - Coefficients are often empirical functions of particle properties and fluidization state

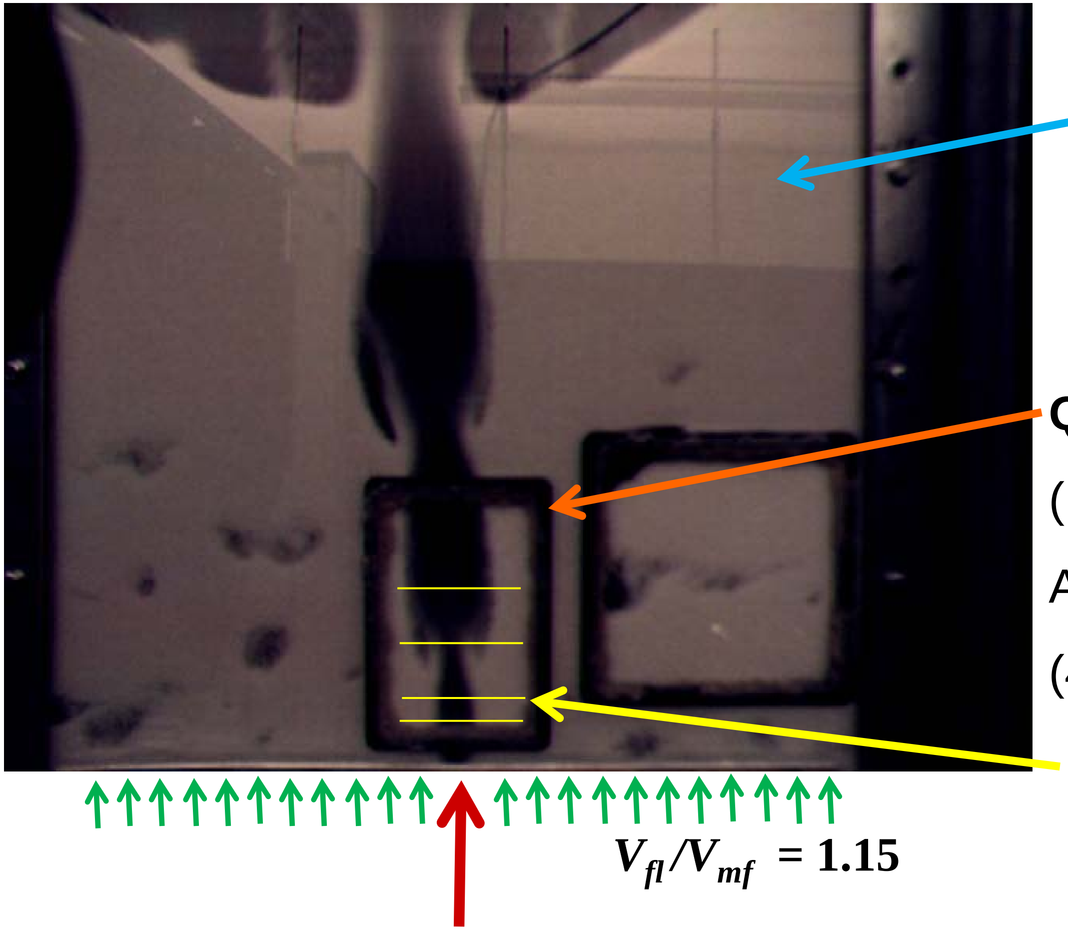


- Particle velocity profiles derived from particle acceleration models
    - Entrainment
    - Drag



P.E. Roach. “The penetration of jets into fluidized beds,” Fluid. Dyna. Res. (11): 197-216, 1993.

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

Prior Measurement Techniques

- Experimental data is difficult to obtain since the gas – particle flow in a fluidized bed is ***opaque and harsh***.
- Non-intrusive but ***qualitative*** methods to determine jet plume geometry and fluctuations
  - High speed video
  - Pressure measurements
  - X-ray imaging
- Quantitative but ***intrusive*** probes to measure velocity or concentration
  - Pitot tubes
  - Optical probes
  - Triboelectric probes

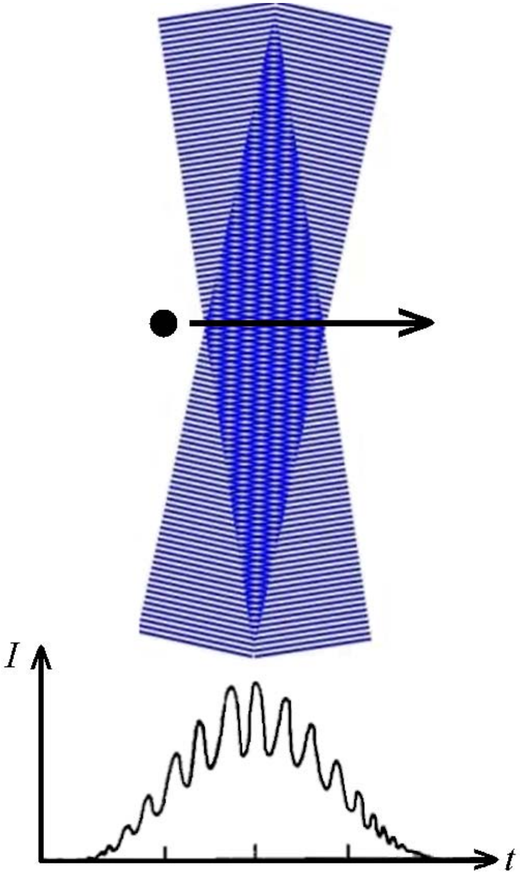
LDV Measurement Technique

Laser Doppler Velocimetry (LDV)

- Particle scatters light as it traverses the fringe pattern established by intersecting laser beams (δ_f ~ 3.5 μm)

Particle speed ~ frequency of scattered light

- Directional ambiguity
  - One of the beams is frequency shifted (f_B = 40 MHz) by an acousto-optic element (Bragg Cell) causing the light fringes to move (~140 m/s)
  - ***Shifted beam intensity fluctuates at 2f_B, which causes problems for large particle measurements***



$$\text{measured velocity: } v = (f - f_B)\delta_f$$

A. Mychkovsky , N. Chang, S.Ceccio. "Spurious LDV signals due to Bragg Cell laser intensity modulation," Appl. Opt. (48) 3468-3474 (2009)

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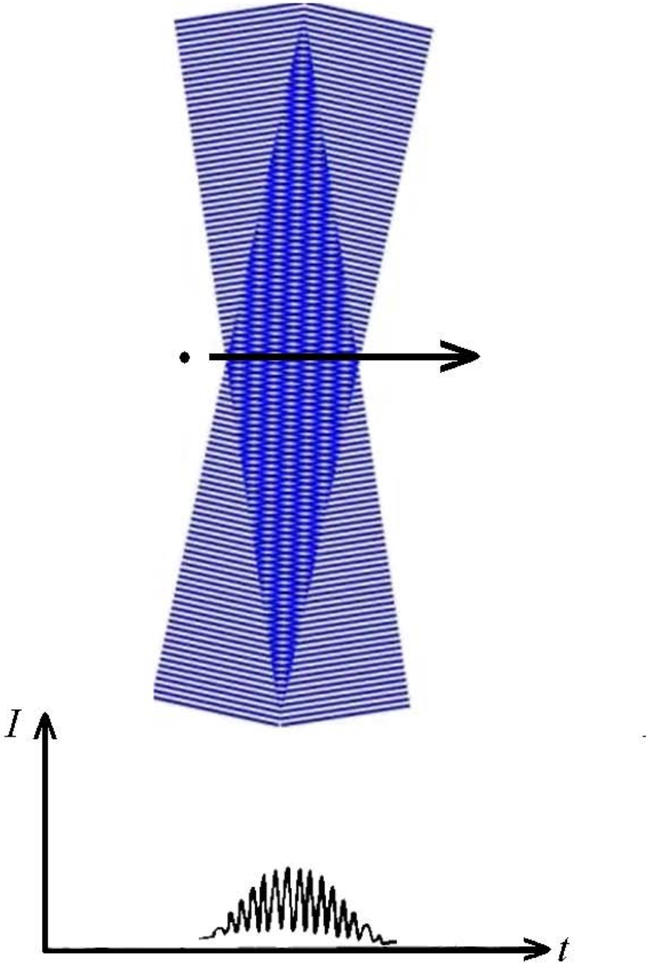
LDV Bursts

- Traditional case: particles are small ($d_p < d_f$) so that the fringe visibility is not greatly affected by laser intensity fluctuations

- Large particles span several fringes so that the intensity of the beam fluctuation is greater than the visibility of the Doppler burst



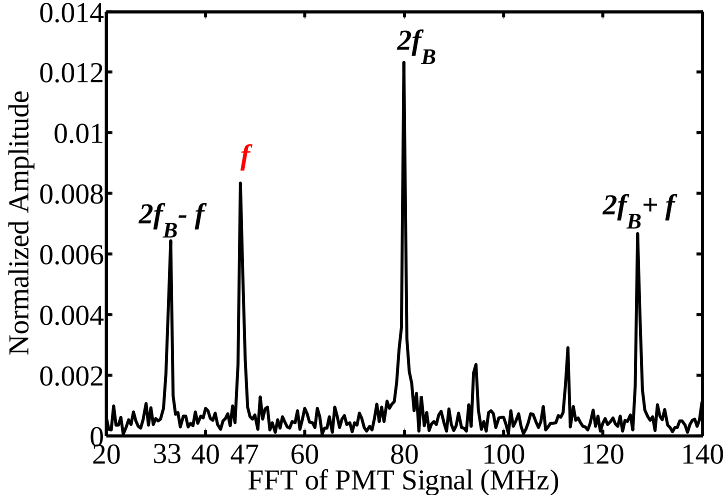
LDV Signal Contamination

- Intensity modulation causes frequency mixing

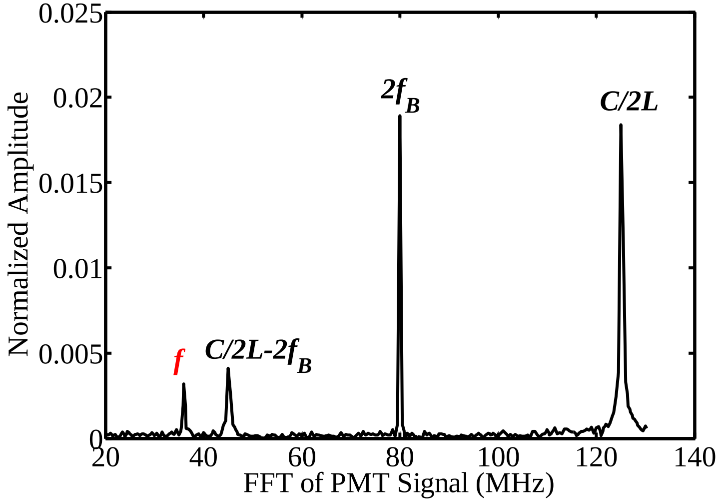
$$\cos(2\pi 2 f_B t)\cos(2\pi f t) = \frac{1}{2}\cos[2\pi(2 f_B + f)t] + \frac{1}{2}\cos[2\pi(2 f_B - f)t]$$

- Laser beam intensity fluctuates at $C/2L$ (125 MHz for a 1.2 m laser tube)
- ***Mixed peaks*** problematic due to proximity to Doppler burst frequency (f)
- Resolve problem by orienting LDV fringe motion in the direction of the bulk particle motion ($f < 40$ MHz) and use appropriate band pass filters

Bragg Mixing



Laser Mode Hop Mixing



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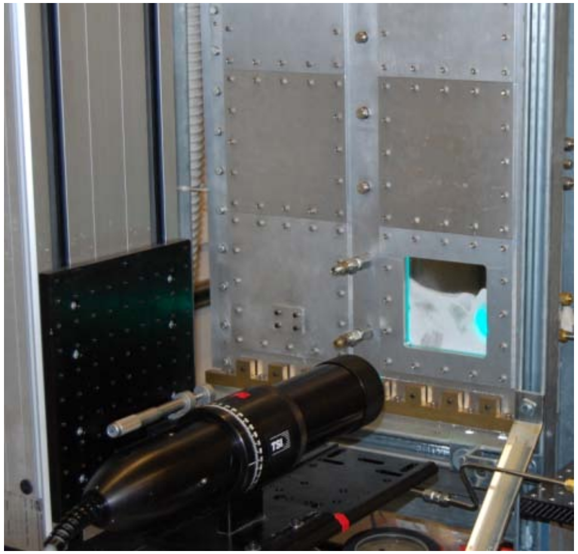
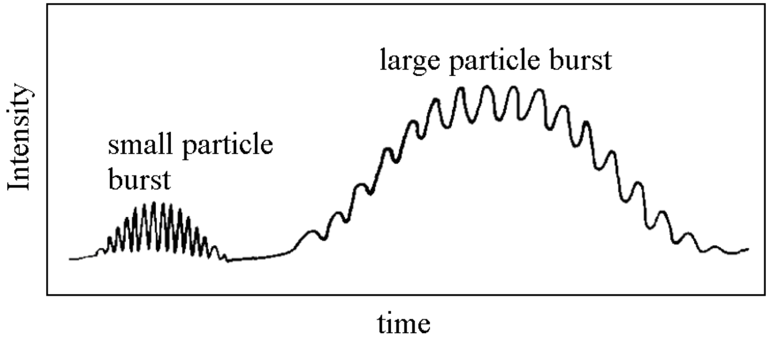
LDV in Two Phase Gas-Particle flow

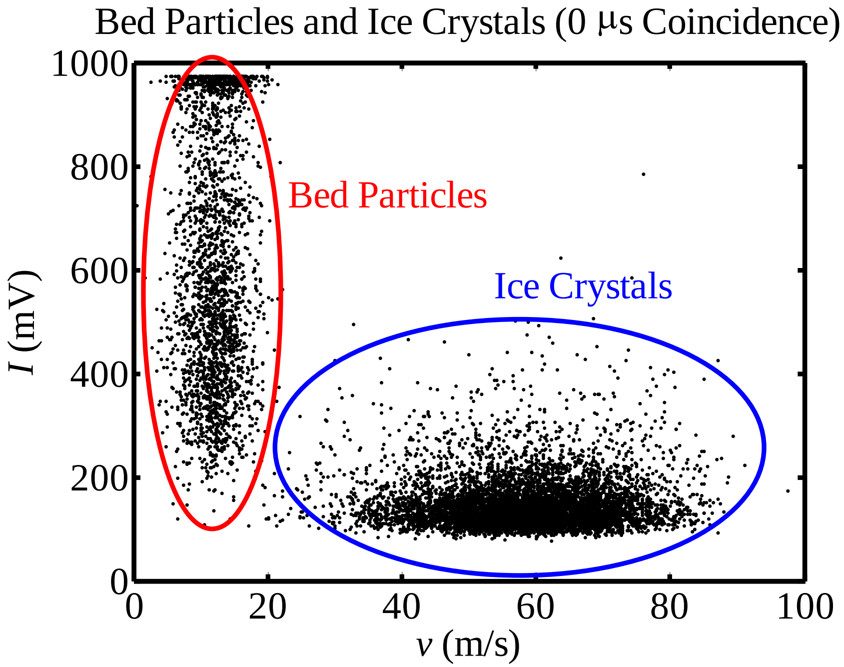


- Simultaneously measure bed particle (~1,000 μm) and jet gas (~1 μm tracers) velocity profiles (2 component)
  - Jet gas is seeded by rapidly condensing moisture in the air to produce ice crystals (T_j = -5°C, ρ_j = 1.32 kg/m^3)
  - Burst intensity subranging to distinguish the two phase measurements

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

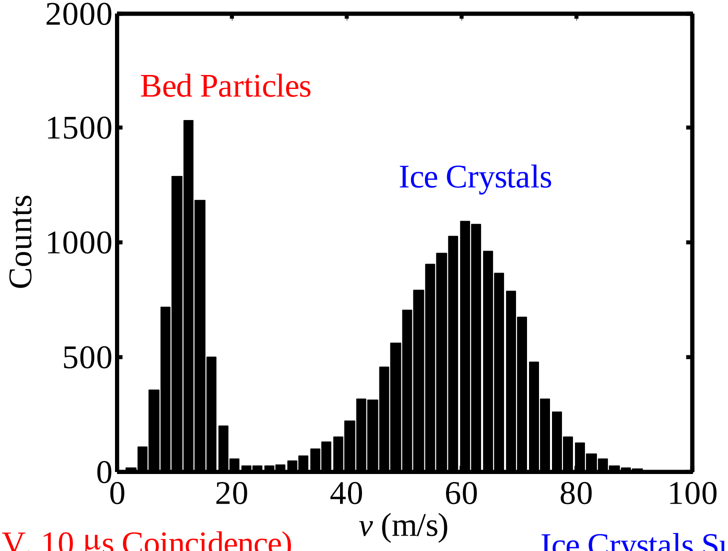




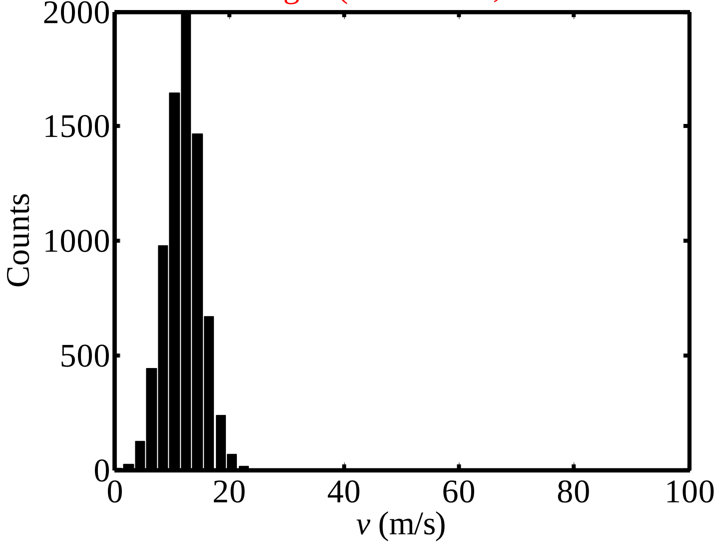
R. S. Barlow & C. Q. Morrison. “Two-phase velocity measurements in dense particle-laden jets,” Exp. Fluids. 9 (1-2) 93-104 (1990)

Velocity Histogram Separation

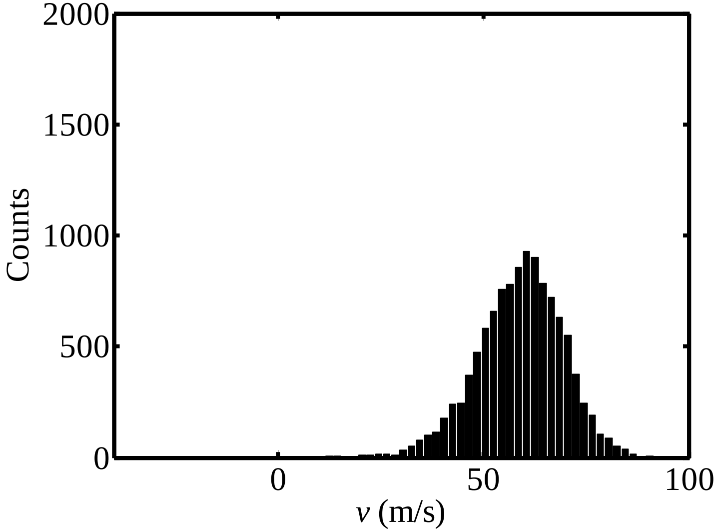
Bed Particles and Ice Crystals (0 μs Coincidence)



Bed Particles Subranged (*I* >500 mV, 10 μs Coincidence)



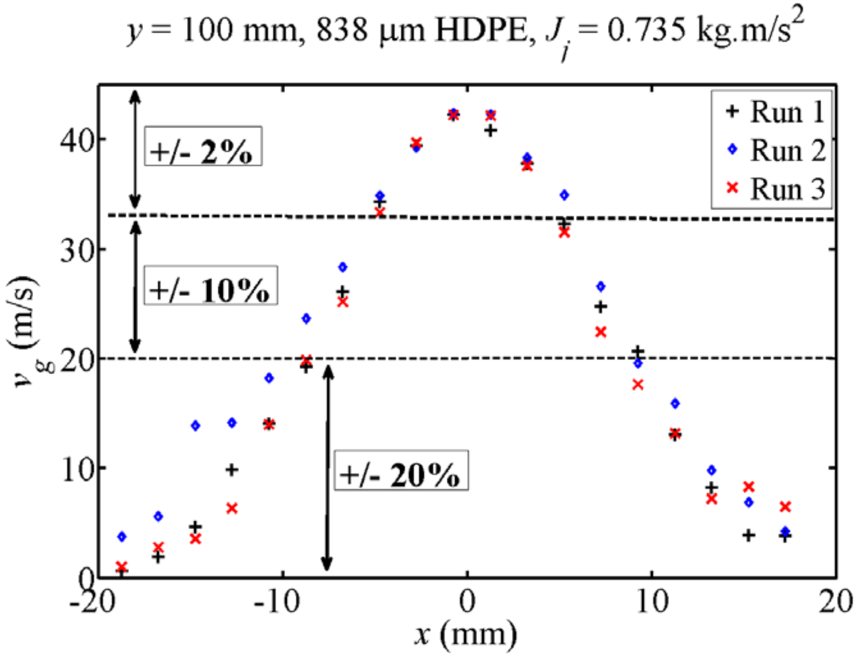
Ice Crystals Subranged (*I* < 200 mV, 0 μs Coincidence)



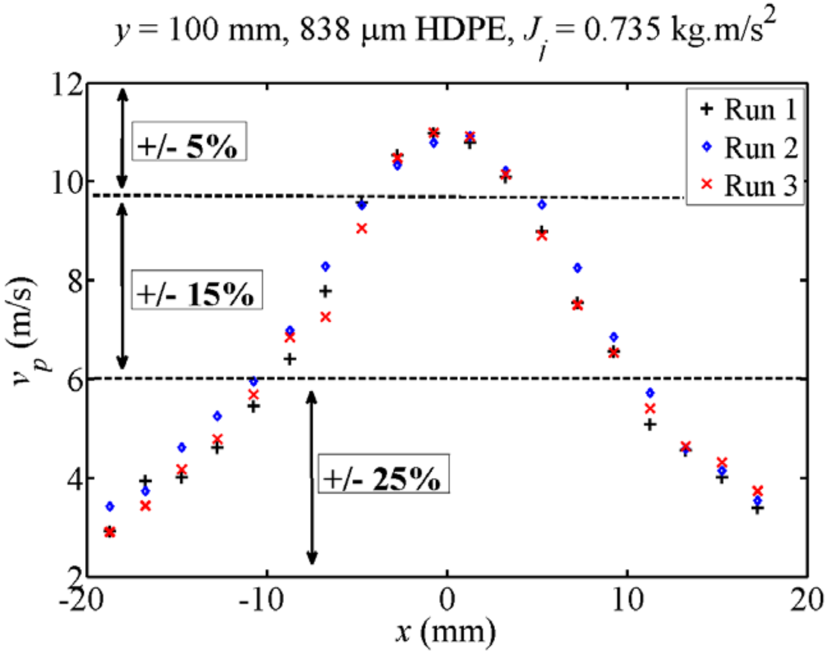
Measurement Uncertainty

- Low at the center, increasing towards the plume boundary
    - Higher burst count in the jet core for both phases
    - Unsteady bed dynamics (particle variation, plume fluctuations)
    - ***Majority of mass and momentum transport occurs in the core region***
- Calculated mass and momentum transport values within 5%

Gas Velocity Profiles



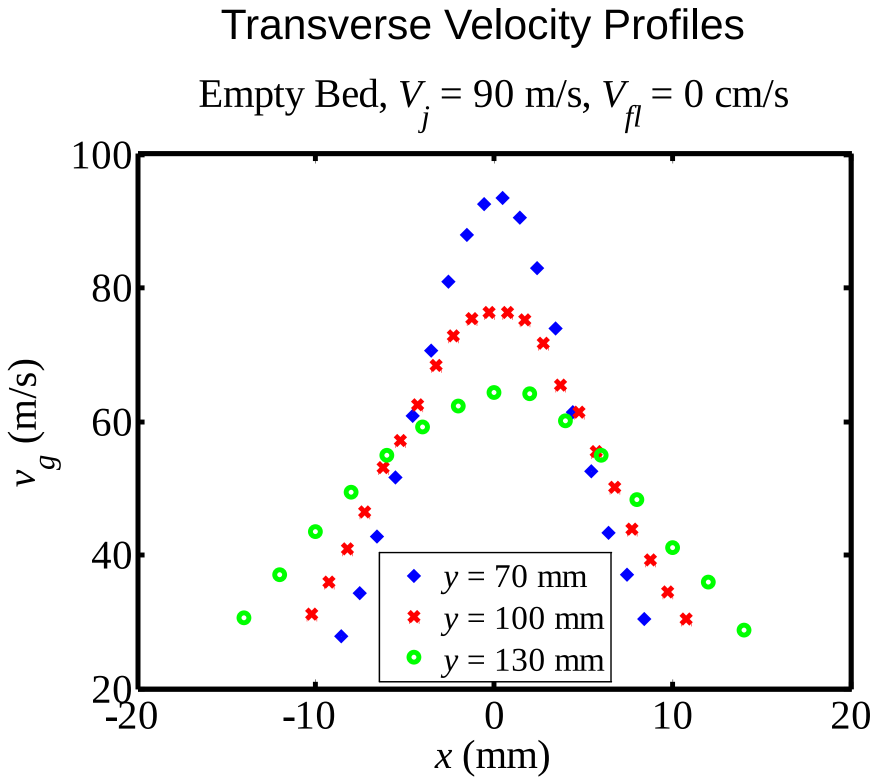
Particle Velocity Profiles

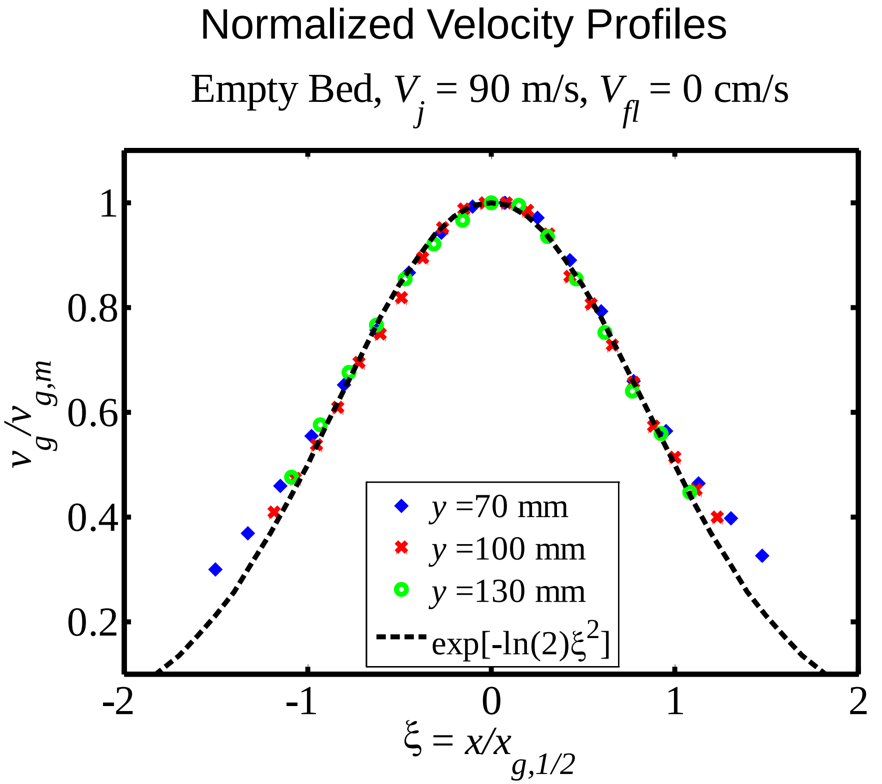


Single Phase Gas Jet

Empty Bed Transverse Velocity Profiles

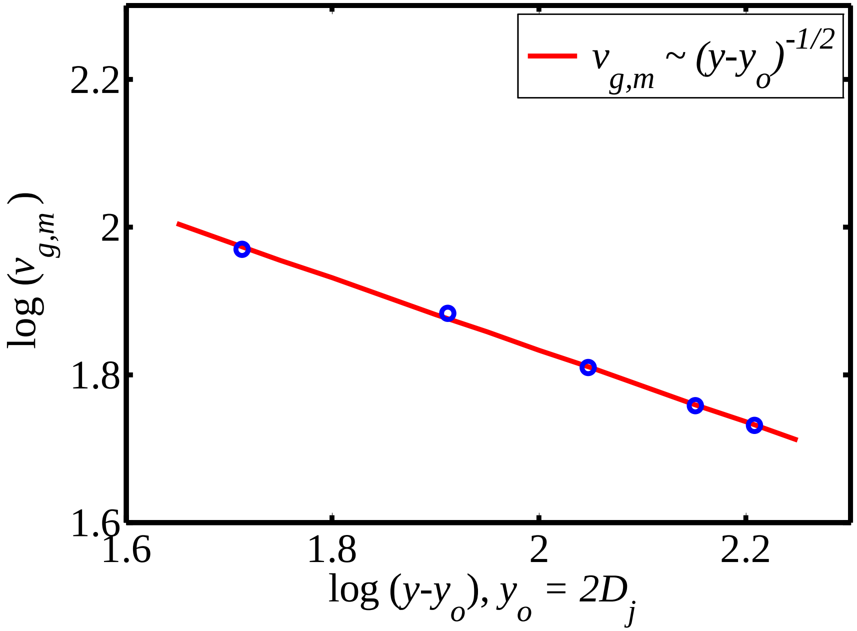
- Single phase gas jet plume velocity profiles are self-similar with a Gaussian bell-curve shape





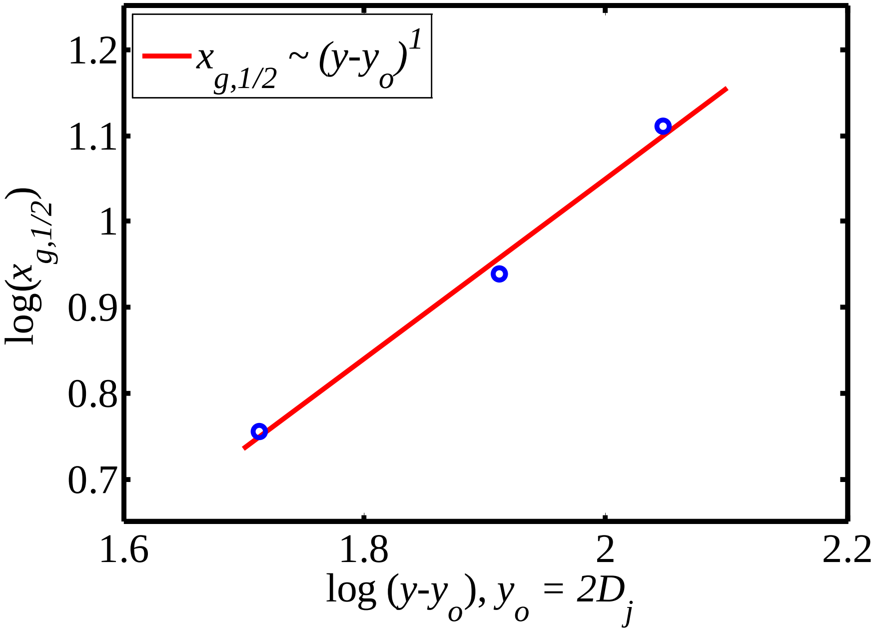
Empty Bed Axial Velocity Profiles

- Single phase gas jet plume centerline axial velocity decay and velocity profile width expansion are consistent with a free 2D turbulent jet



Axial Velocity Profile

Empty Bed, V_j = 90 m/s, V_{fl} = 0 cm/s



Velocity Profile Expansion

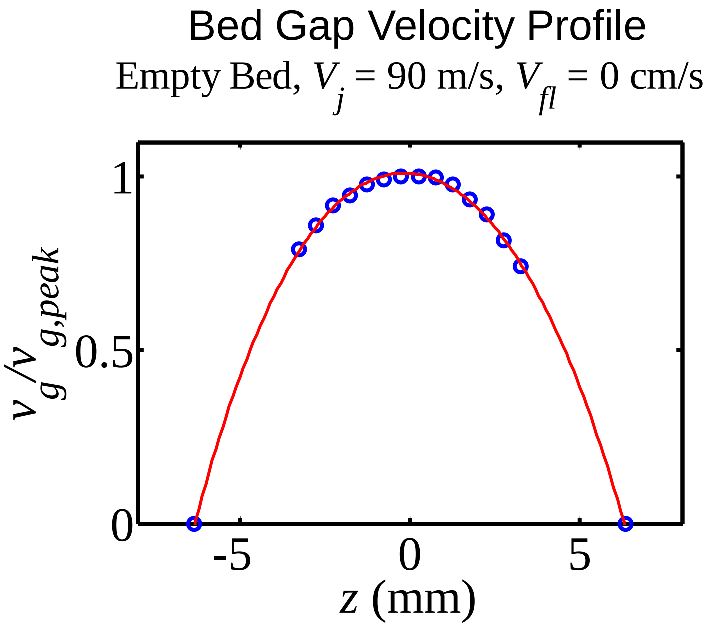
Empty Bed, V_j = 90 m/s, V_{fl} = 0 cm/s

Empty Bed Momentum Transport

- Axial momentum transport
  - Conserved in free jets
  - Calculated by numerically integrating LDV data points or analytically integrating Gaussian profiles

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

….Downstream calculated values nearly double the inlet value! (This has been noted in the literature but not properly considered)



Bed Gap Velocity Profile

Empty Bed, $V_j = 90$ m/s, $V_{fl} = 0$ cm/s

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

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

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)

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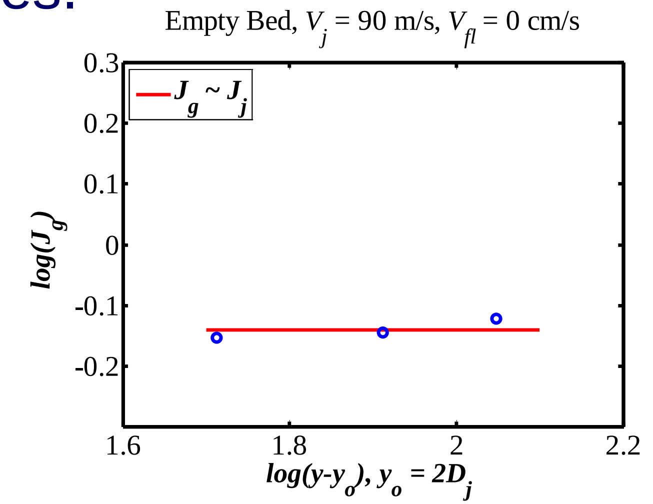
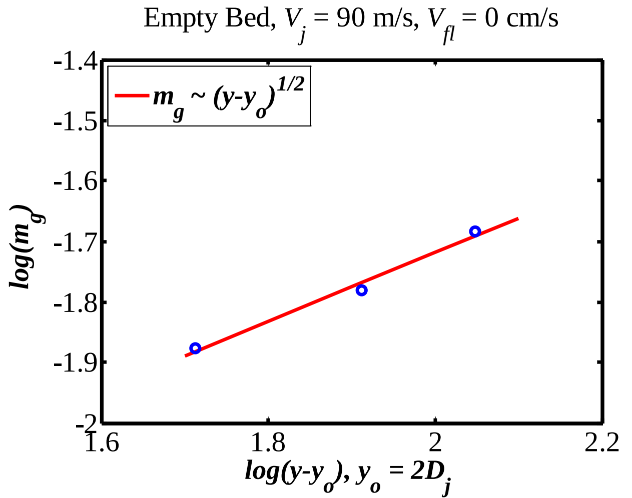
Mass and Momentum Transport Calculations

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



  - ❑ **Axial momentum transport**

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



  - ❑ **Axial mass transport**

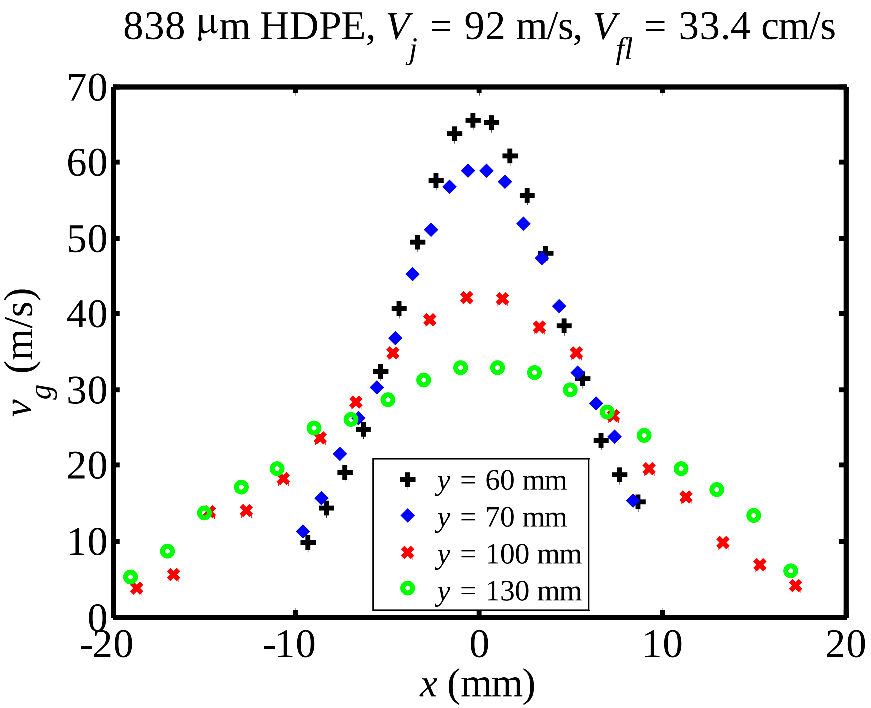
$$\dot{m}_g = C_1 \rho_g w \int_{-b}^{b} v_g \, dx = 2.09\, C_1 \rho_g w \left(v_{g,m} x_{g,1/2}\right)$$

Gas Jets in a Bubbling Bed

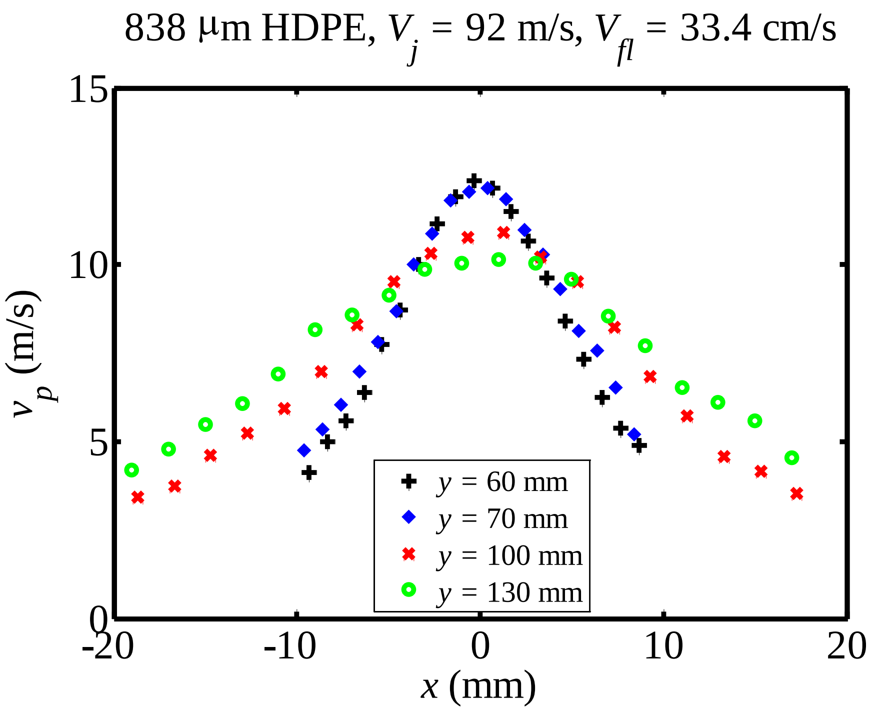
Bubbling Bed Vertical Jet Velocity Profiles

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

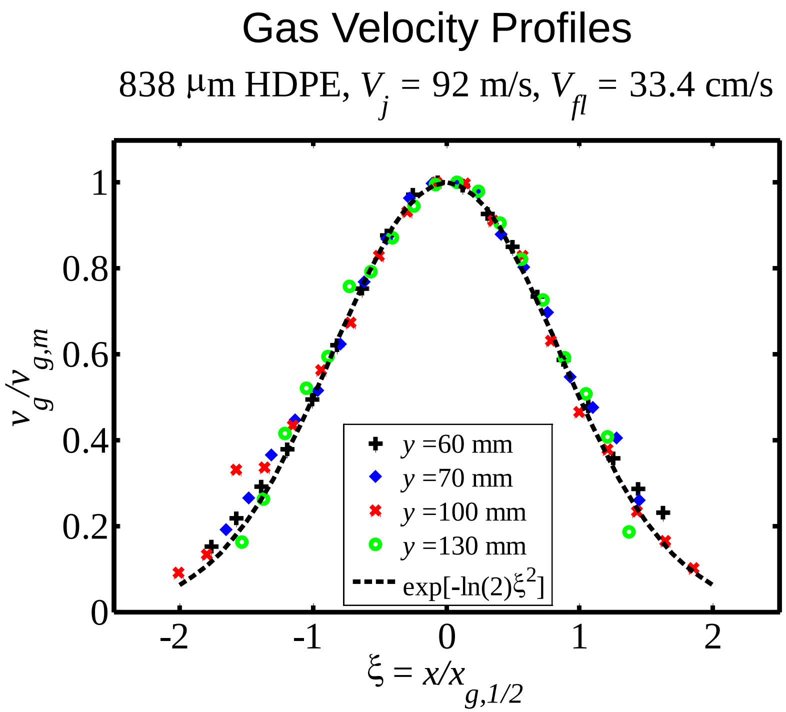
Gas Velocity Profiles



Particle Velocity Profiles

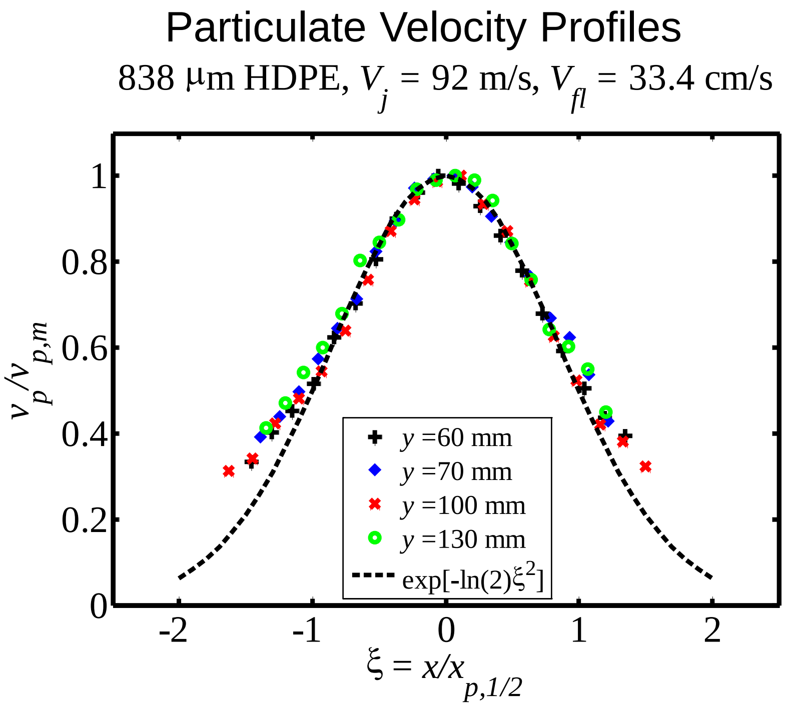


Transverse Velocity Profile Self-Similarity



Gas Velocity Profiles

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



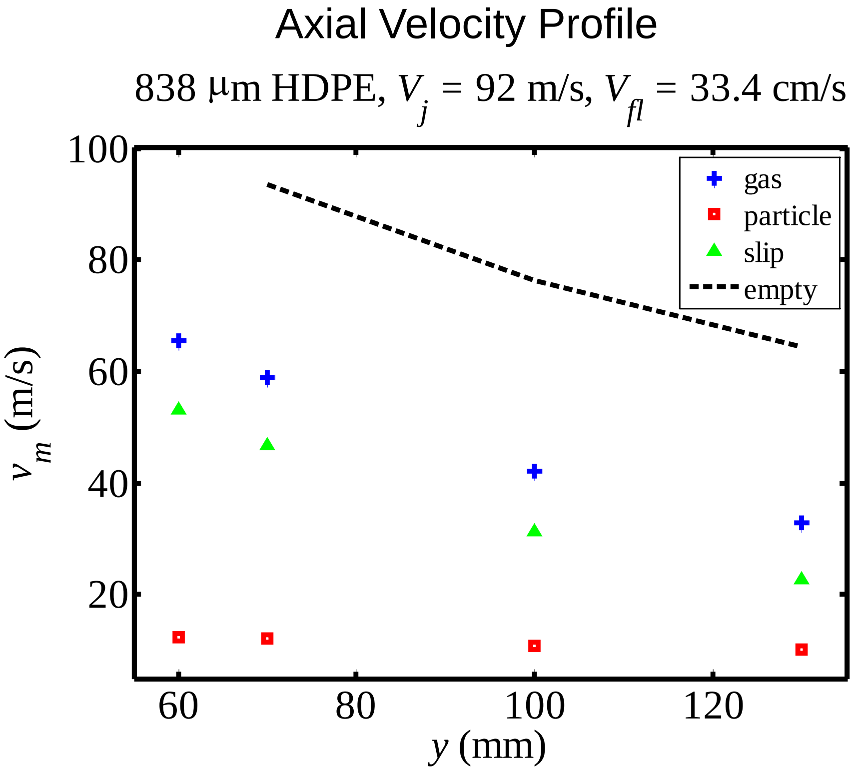
Particulate Velocity Profiles

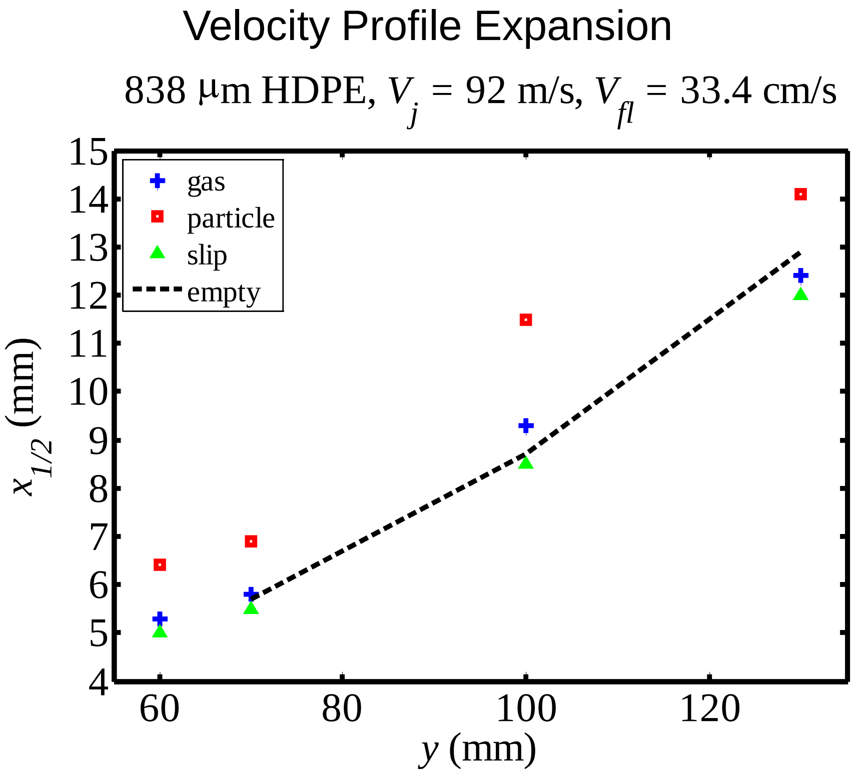
838 μm HDPE, V_j = 92 m/s, V_{fl} = 33.4 cm/s

- The gas and particulate phase velocity profiles appear self-similar, thus they can be fully characterized by
  - Consistent profile shape: $f(x/x_{1/2})$
  - 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





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Volumetric Void Fraction (*ε*)

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

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

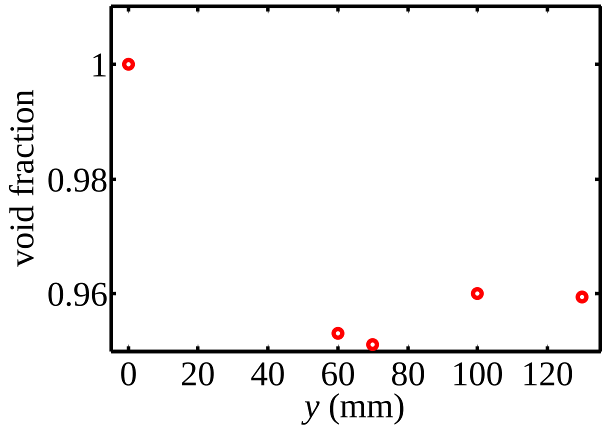
$$\dot{J}_p = (1-\varepsilon) C_2 \rho_p w \int_{-b}^{b} v_p^2 dx$$

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

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

- Void Fraction > 95% in the dilute jet plume

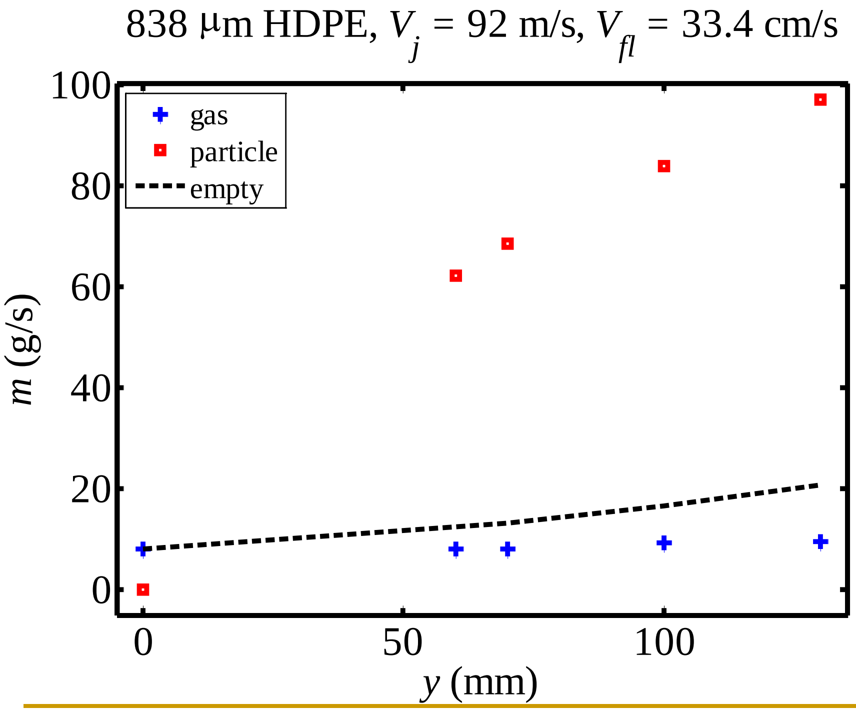
838 μm HDPE, V_j = 92 m/s, V_{fl} = 33.4 cm/s



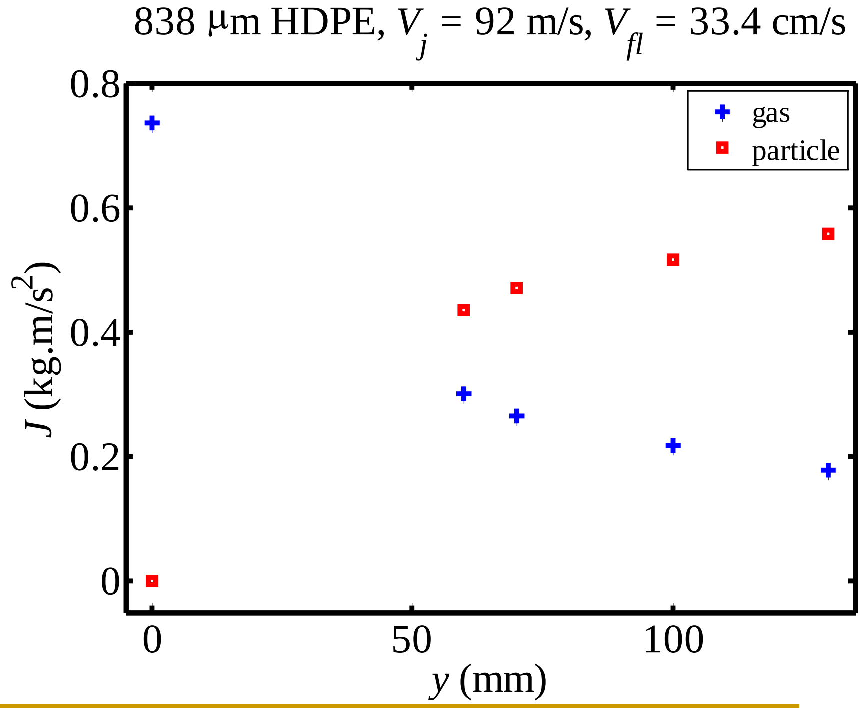
Mass Flow and Momentum Transfer

- 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



Coefficient of Drag

- LDV measures Eularian (field variable) not Lagrangian (particle tracking) velocity
- Decreasing particulate phase axial velocity due to particles entrained from rest
- Drag coefficient determined from the Equation of Motio phase, treating pa

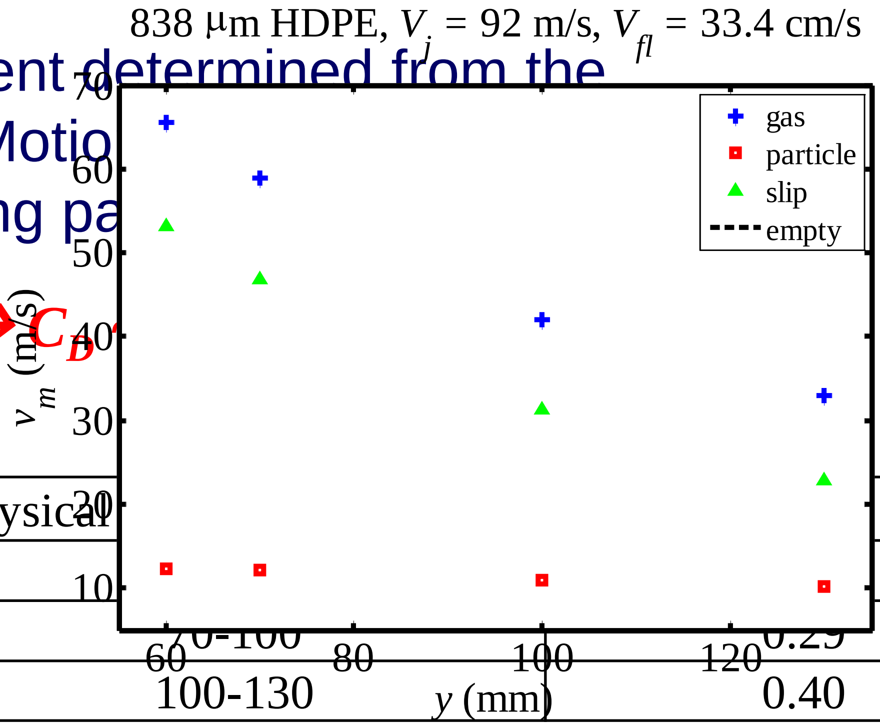
$Re_p > 1,000 \rightarrow C_D$

$$\dot{J}_p\big|_y - \dot{J}_p\big|_{y+\Delta y} + f_D - w_p = 0$$

$$f_D = N_p F_D = (1-\varepsilon)\frac{\Delta x \Delta y}{V_p} F_D$$

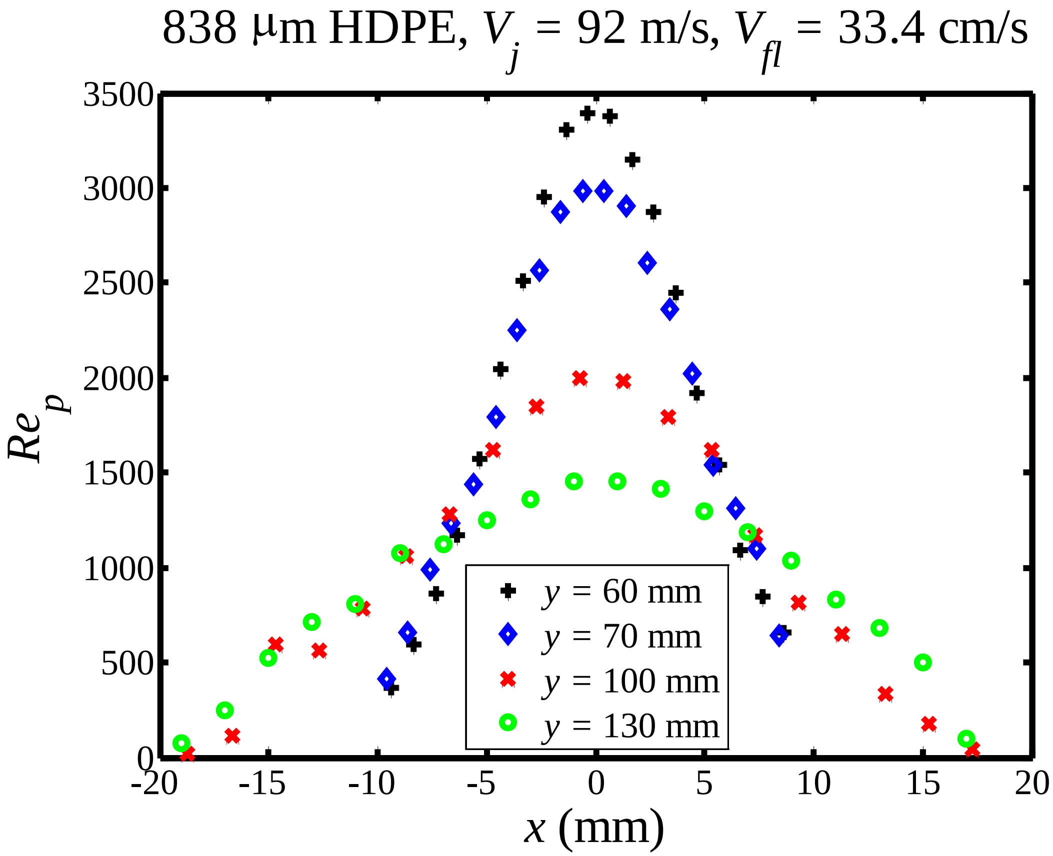
$$F_D = \frac{1}{2} C_D A_p \rho_g \left(v_g - v_p\right)^2$$

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

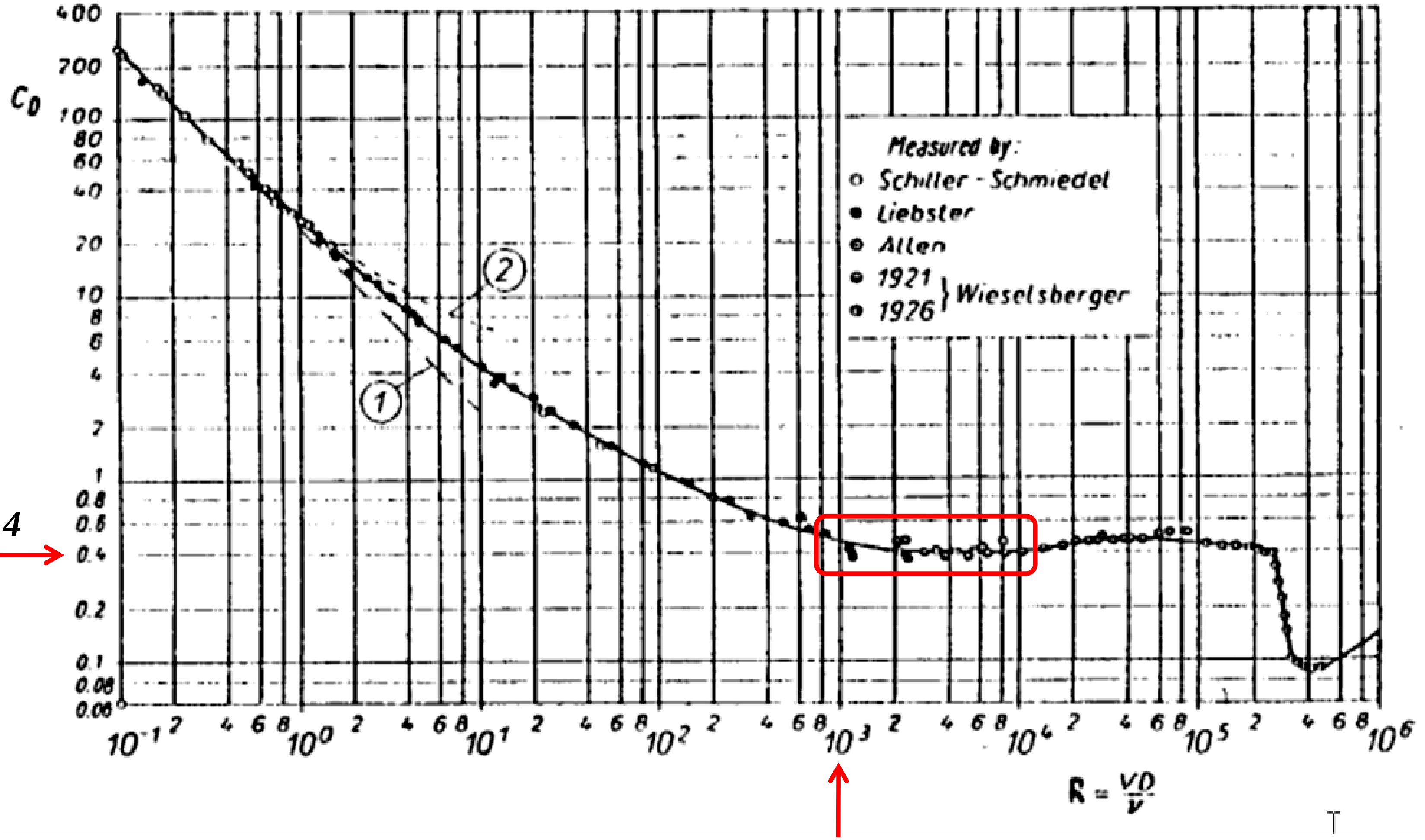


Physical	
70-100	0.29
100-130	0.40

Particle Reynold's Number Profiles



Coefficient of Drag for a Sphere



C_D = 0.4

Re_p = 1,000

Effect of Fluidization on Jet Dynamics

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

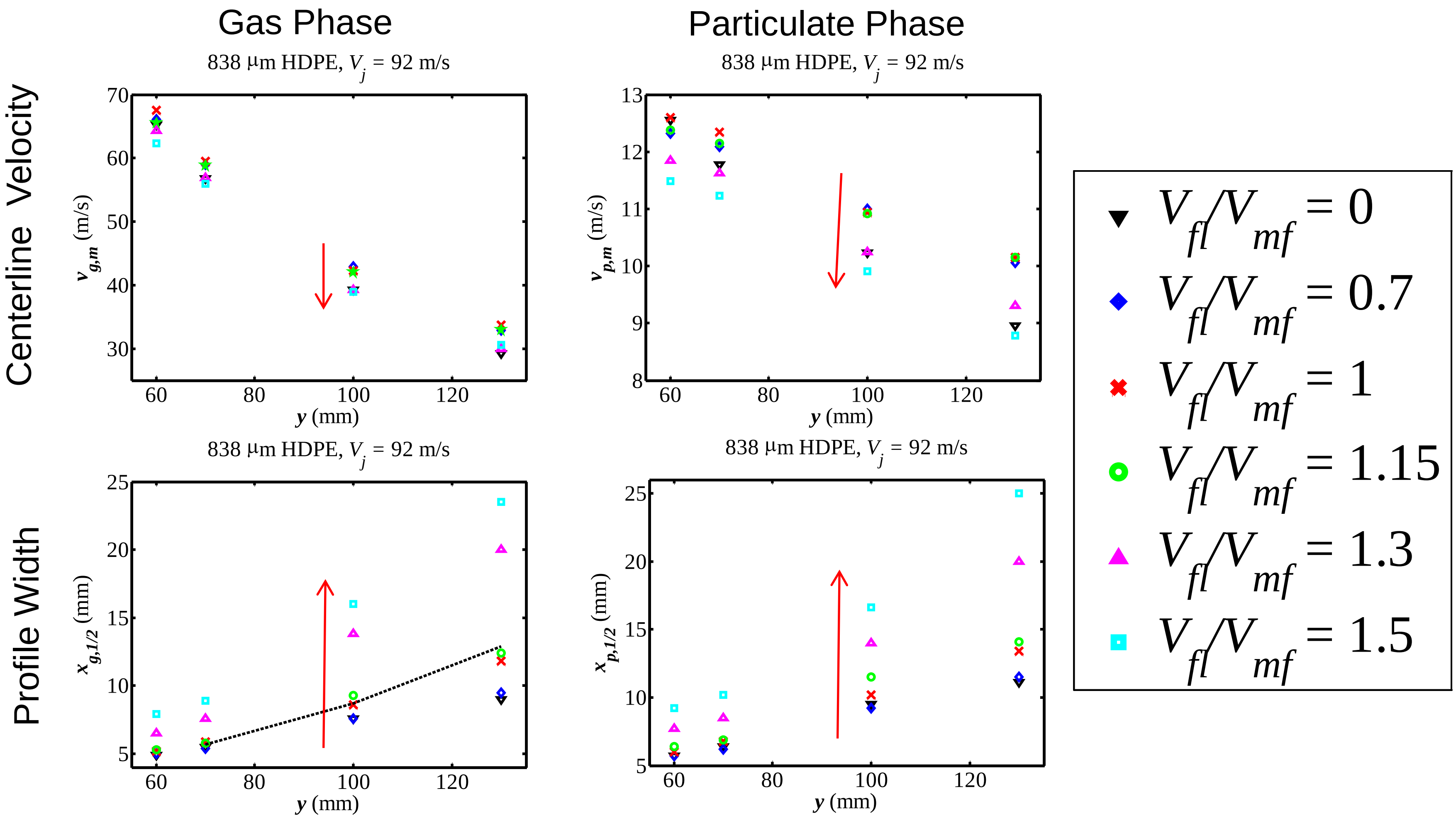
$V_{fl}/V_{mf} = 0$

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

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

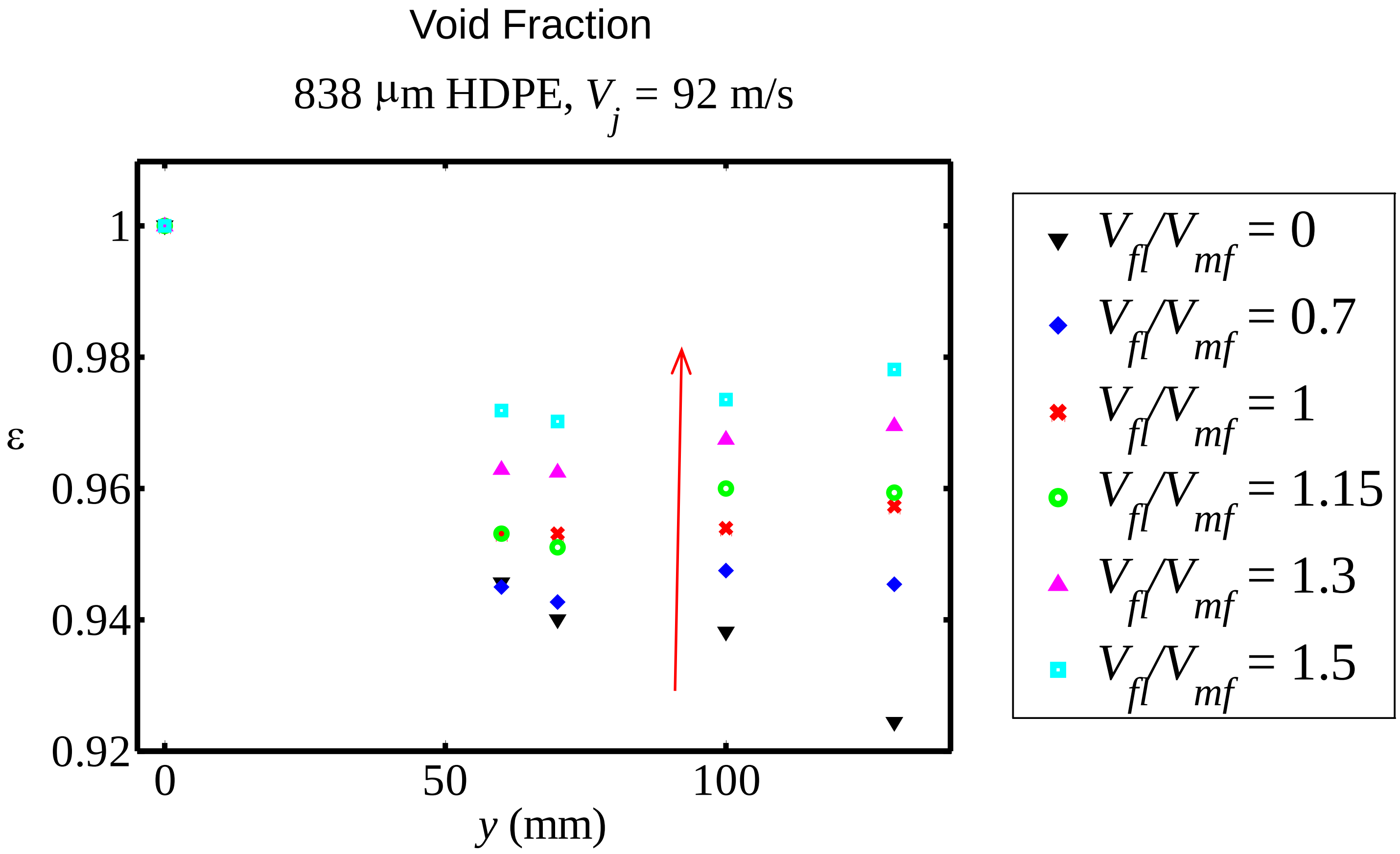
Effect of Fluidization on Velocity Profiles

- 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
- This effect is not mentioned in the literature



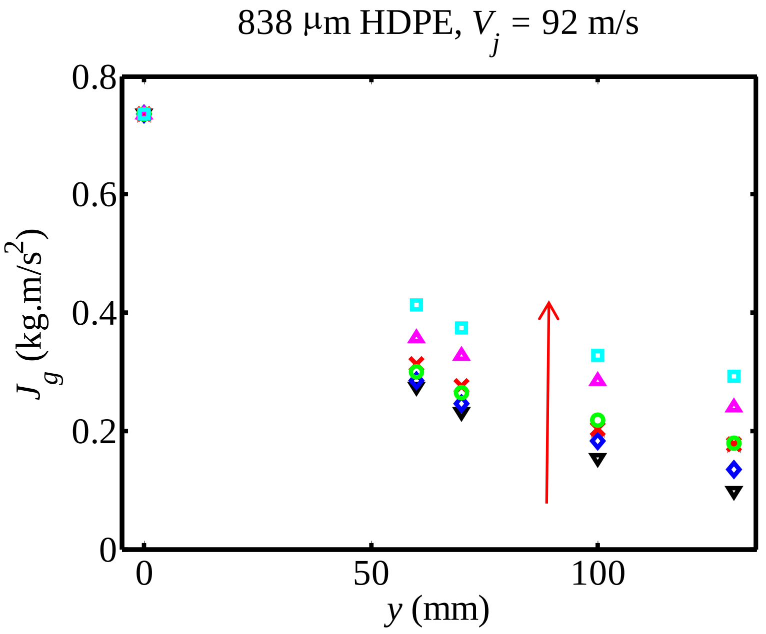
P.E. Roach. “The penetration of jets into fluidized beds,” Fluid. Dyna. Res. (11): 197-216, 1993.

Effect of Fluidization on Momentum Transport

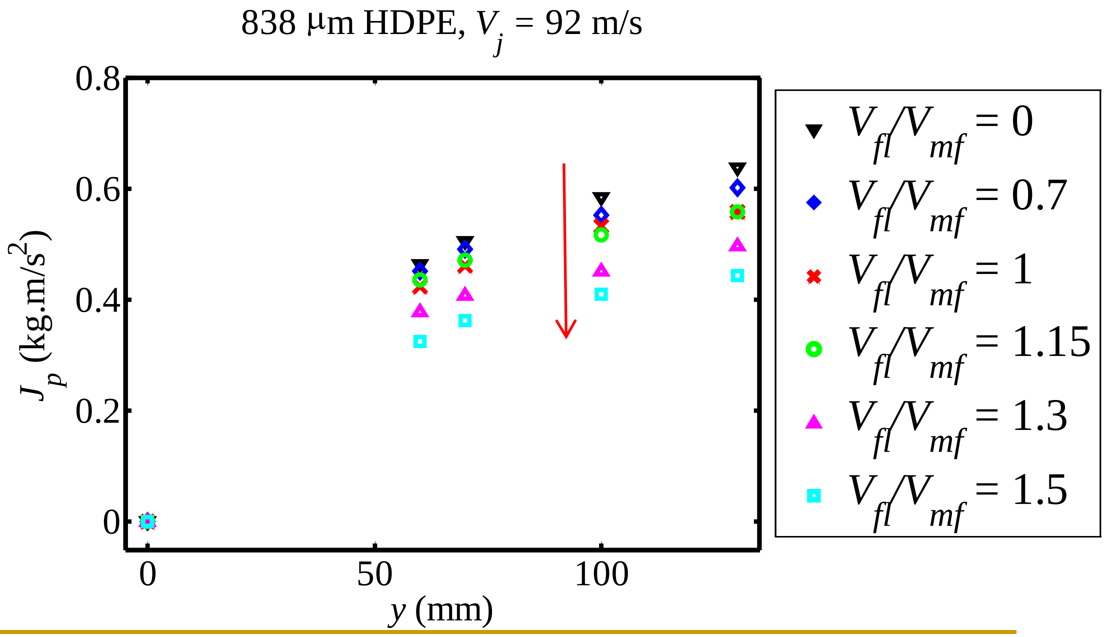
- As the fluidization rate increases, the gas phase momentum increases due to increased interstitial gas entrainment
- Particulate phase momentum decreases with increasing fluidization

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

Gas Phase Momentum

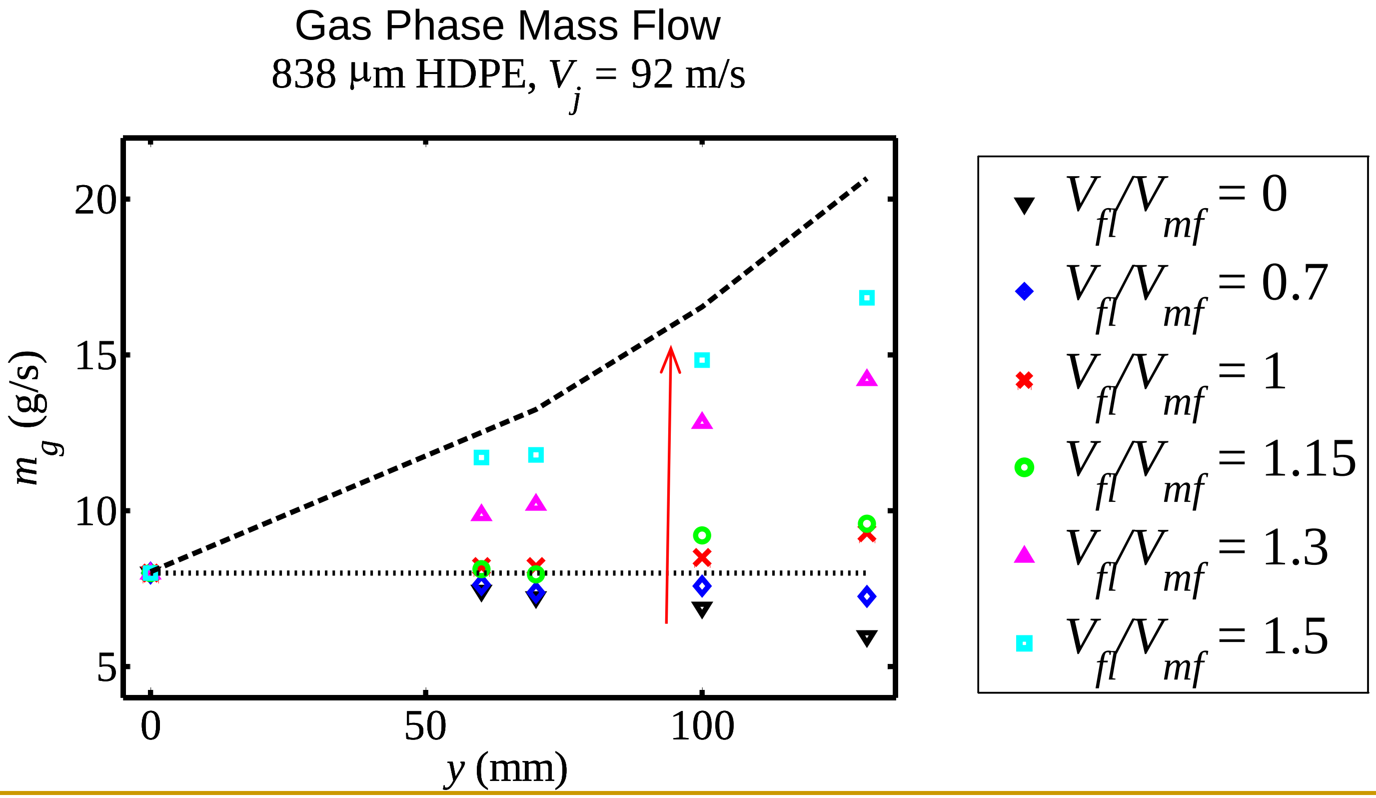


Particulate Phase Momentum



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*



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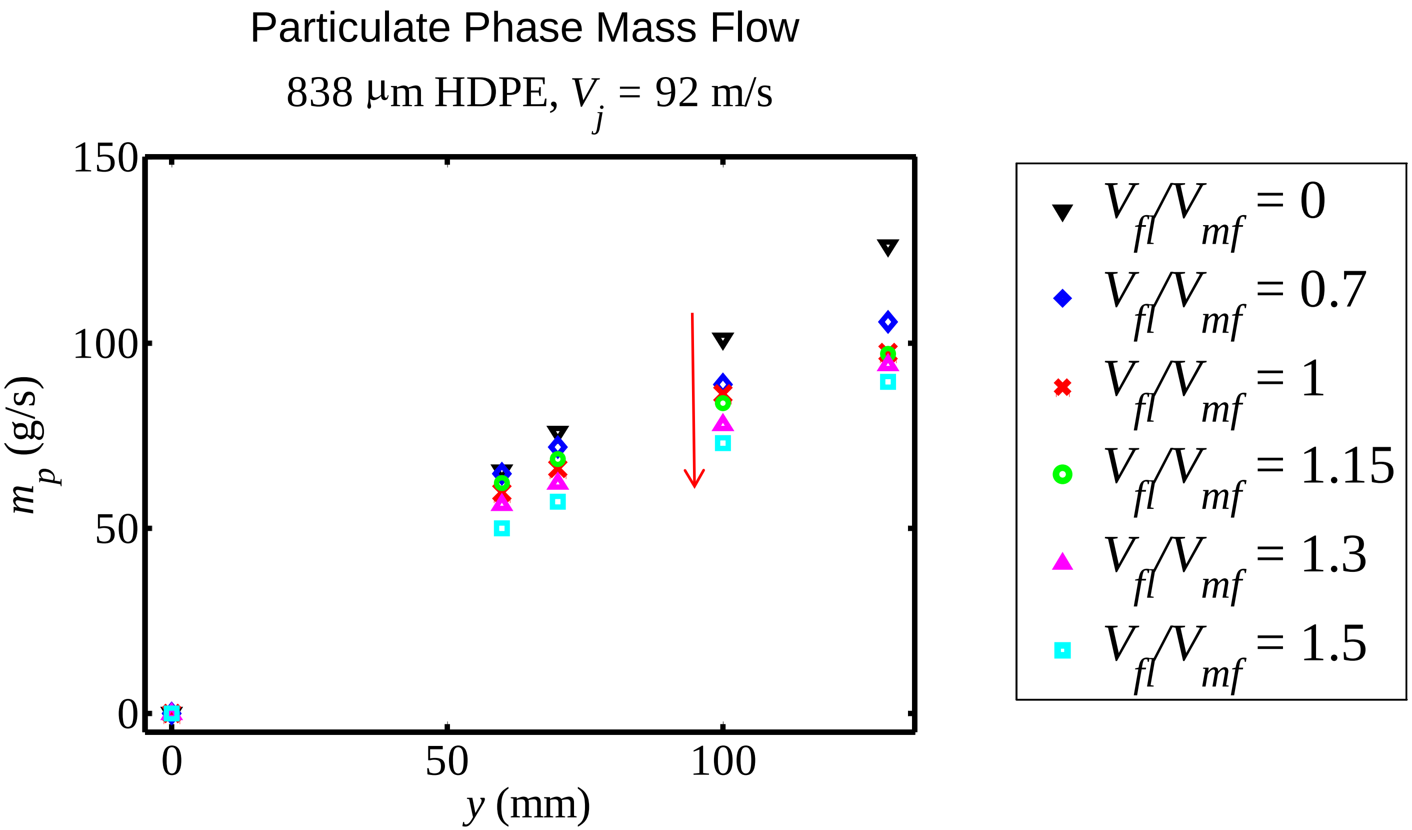
Effect of Fluidization on Mass Transport

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



Summary

- LDV technique was developed to simultaneously obtain gas and particulate phase velocity measurements, which are needed to quantify jet dynamics

- Bubbling Bed:
  - Measured self-similar velocity profiles which are Gaussian in shape
  - Quantified mass and momentum transport and particle drag coefficient
  - Examined the effect of fluidization level of the emulsion on the jet dynamics

Future Work

- Turbulence statistics profiles in the jet plume
  - Enhancement or suppression of turbulence by entrained bed particles
  - Only ‘initially loaded’ particle laden free jets reported in the literature

- Direct measurements of volume fraction profiles in the jet plume
  - X-ray densitometry
  - Imaging

M.A. Mergheni, J.C. Sautet, G. Godard, H. Ben Ticha, S. Ben Nasrallah.
“Experimental investigation of turbulence modulation in particle-laden coaxial jets by Phase Doppler Anemometry.” Exp. Therm Fluid Sci. **33** (3), 517-526 (2009)