A New Approach to Decomposition of Particle Velocity and Calculation of Granular Temperature Using High Speed PIV Data

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Motivation

- Develop better analysis techniques for new data being generated with NETL's high speed particle imaging system

- Develop a better understanding of particle flows of high particle concentration through analysis of particle velocity and concentration statistics

Decomposition of Particle Velocity

- Experimental data and kinetic energy theory suggest that there is a random component of particle velocity, mainly caused by particle-particle collisions and gas turbulence

- The random component of particle velocity can be thought of as analogous to the random component of velocity in turbulent single phase flows, and similar velocity decomposition techniques can be applied

- We have new data for particle velocity at much higher sampling rates than achieved before (100,000 to 1,000,000 particle velocities/sec)

- We need to develop analysis techniques to accurately extract the random fluctuating component of velocity

- Modeling parameters such as granular temperature are derived directly from values of random fluctuating components of velocity

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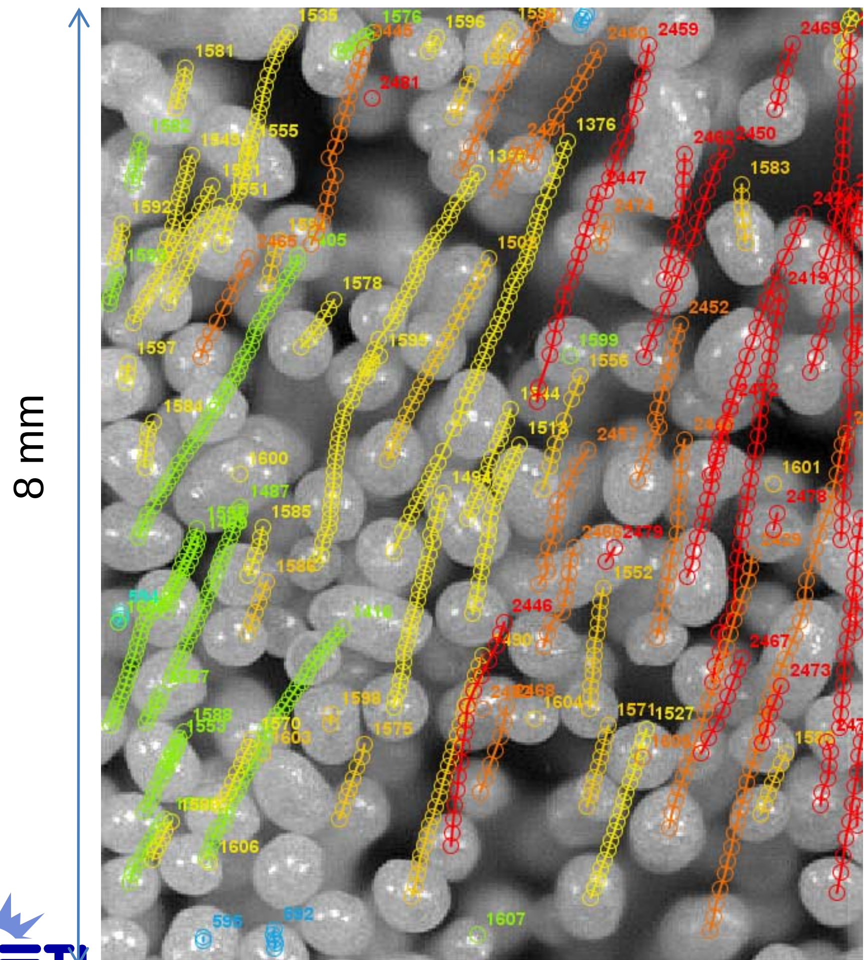
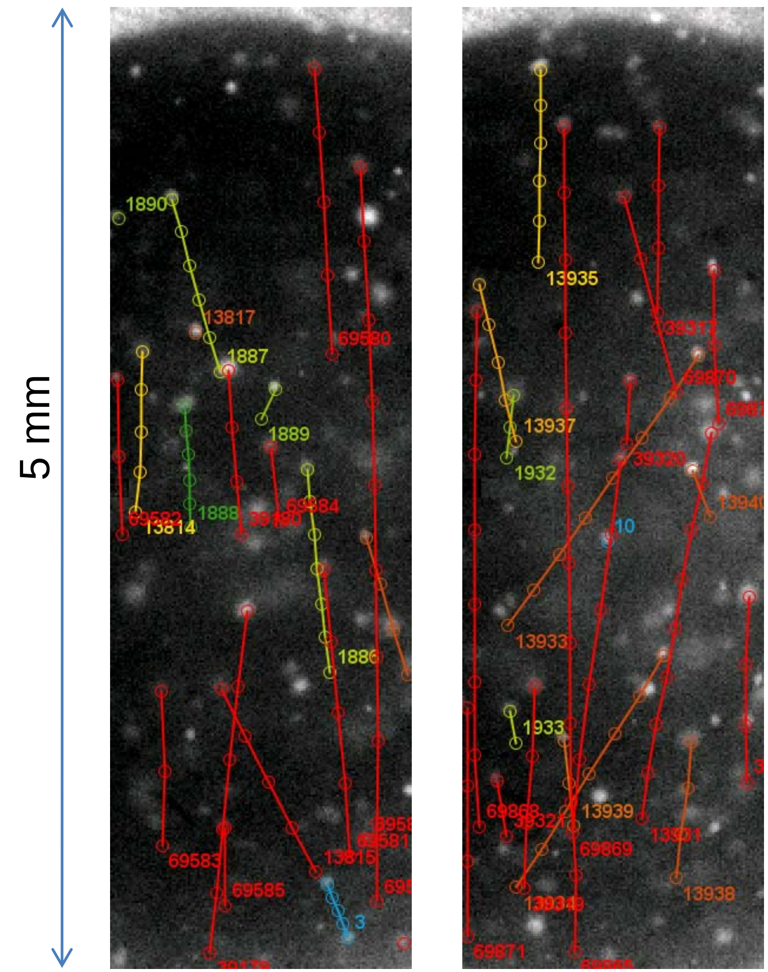
Examples of HSPIV Measurements:
Many velocity measurements at each sample time (1)

HDPE particles on wall of NETL 12 in dia riser
Mean particle diameter is 750 microns

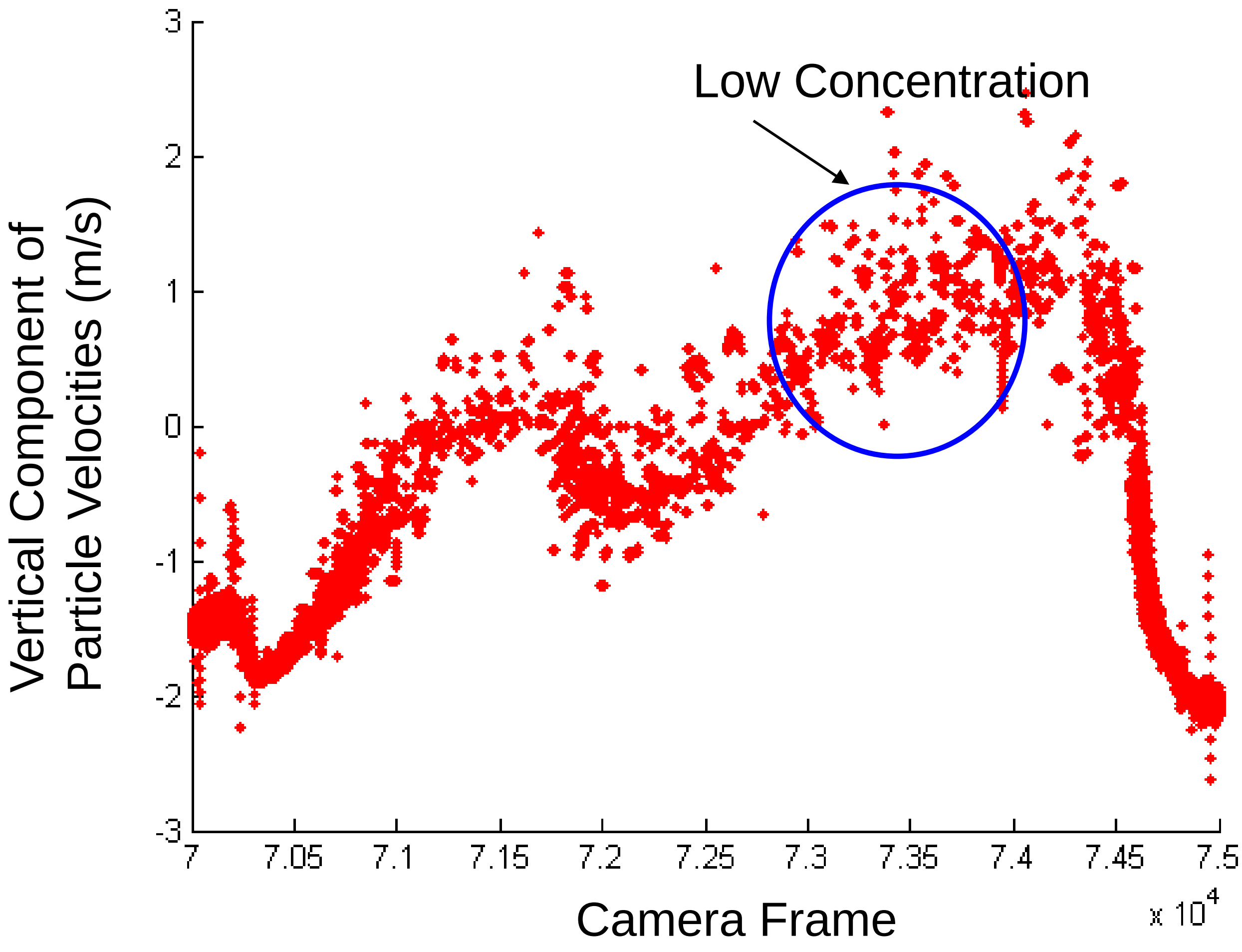


FCC particles inside a PSRI 8 inch riser
Particle diameter is 70 microns



Examples of HSPIV Measurements:
Many velocity measurements at each sample time (2)

NETL 12" Riser with 750 micron HDPE**;** Flux = 5 kg/m²/s; Superficial Velocity = 6.55 m/s
Measurement at wall of riser



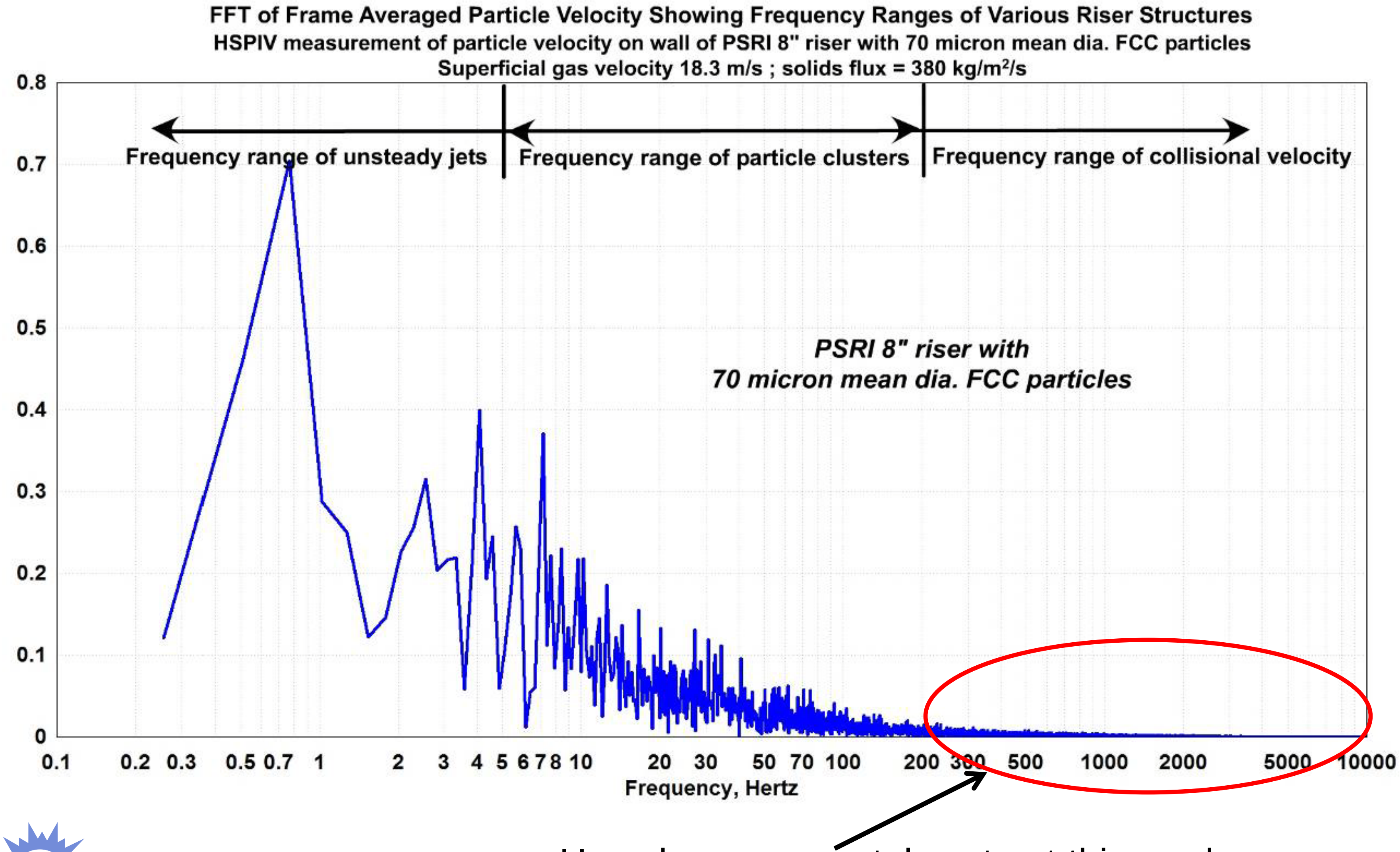
Decomposition of Particle Velocity (2)

- Issue: At each time instant we have multiple particle velocities

- How do we resolve a random component of velocity from such data?

- How to decompose velocity signal into other components that represent various flow structures: unsteady jets, clusters, random fluctuating component?

Ranges of Flow Structures in Velocity Signal



How do we accurately extract this random fluctuating component of velocity?

Decomposition of Particle Velocity (3)

Previous Decomposition Techniques:

- Standard Reynolds Decomposition: The overall mean is subtracted from the particle velocity at each instant of time. The overall mean might be a single value or vary over the spatial domain
- Decomposition using Frame Average Velocity: Particle velocities are averaged over a frame. The random component of velocity is calculated by subtracting individual particle velocities from the frame averaged value [Tartan & Gidaspow (2004)]

$$\bar{v}_{frame} = \frac{\sum_{i=1}^{n_{vectors\_in\_frame}} v_i}{n_{vectors\_in\_frame}} \Longrightarrow v = \left(v - \bar{v}_{frame}\right) + \bar{v}_{frame}$$

Random Component or Peculiar Velocity: $\left(v - \bar{v}_{frame}\right)$

Hydrodynamic Velocity: $\bar{v}_{frame}$

Decomposition of Particle Velocity (4)

Our Approach:

- Particle concentration varies from zero to the maximum concentration
- So some frames have no particle images, one particle image, or only a few – not enough to calculate an accurate frame averages of velocity
- We calculate a "local average velocity" over a small window of frames by requiring a minimum number of velocity vectors for an accurate local average velocity.
- The local averaging window must be large enough to yield an accurate local average, but small enough so as not to include parts of the velocity signal caused by other lower frequency flow structures.

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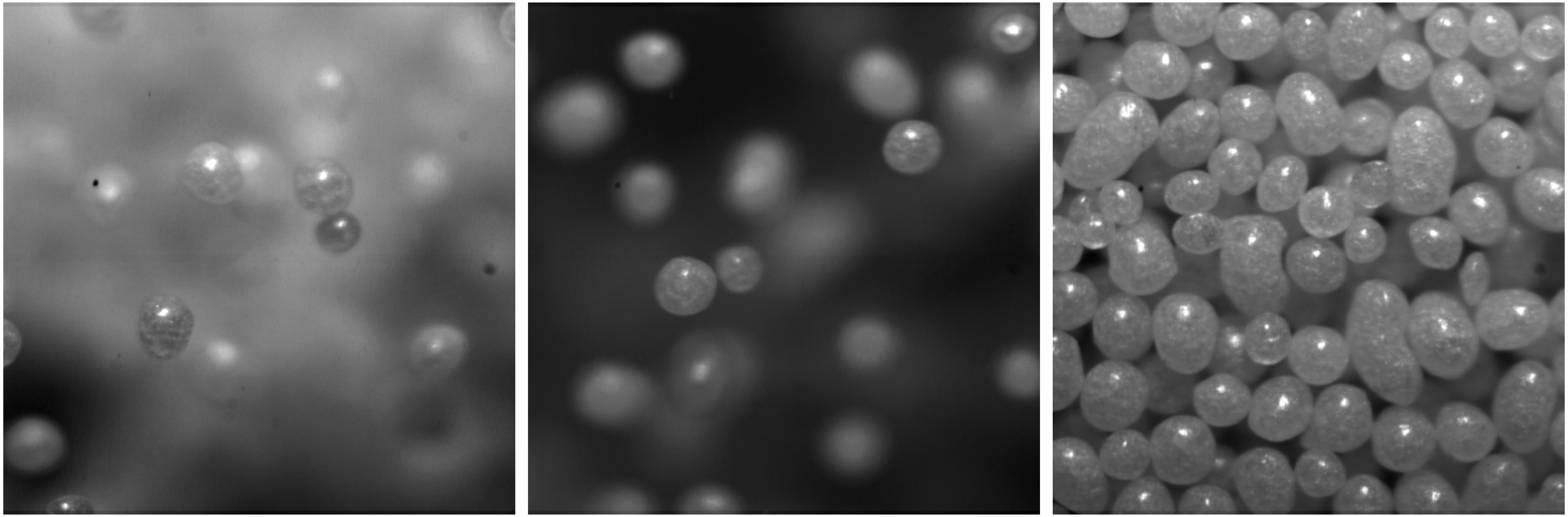
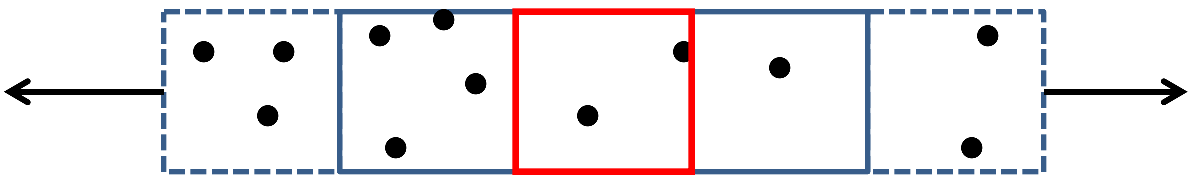
Decomposition of Particle Velocity (5)

HDPE particles on wall of NETL 12 in dia riser



Sample Low Concentration Images

High Concentration



The Frame size is symmetrically expanded in either direction to obtain enough velocity vectors.

Decomposition of Particle Velocity (6)

$$\bar{v}_{Local\_Mean} = \frac{1}{Total\_Vectors} \sum_{frame=1}^{N_{frames\_in\_window}} \bar{v}_{frame} \quad \textit{where} \quad \bar{v}_{frame} = \sum_{i=1}^{n_{vectors\_in\_frame}} v_i$$

$$v_{Particle} = (v_{Particle} - \bar{v}_{Local\_Mean}) + \bar{v}_{Local\_Mean}$$

$$v_{Particle} = v_{Random} + \bar{v}_{Local\_Mean}$$

where $N_{frames\_in\_window}$ is chosen so that the number of velocity vectors in the local averaging window is greater than the required minimum number, M_p , for an accurate local average.

➢ To determine the optimal value for M_p , it was varied over a wide range and the resulting magnitude of the random fluctuating energy, was calculated.

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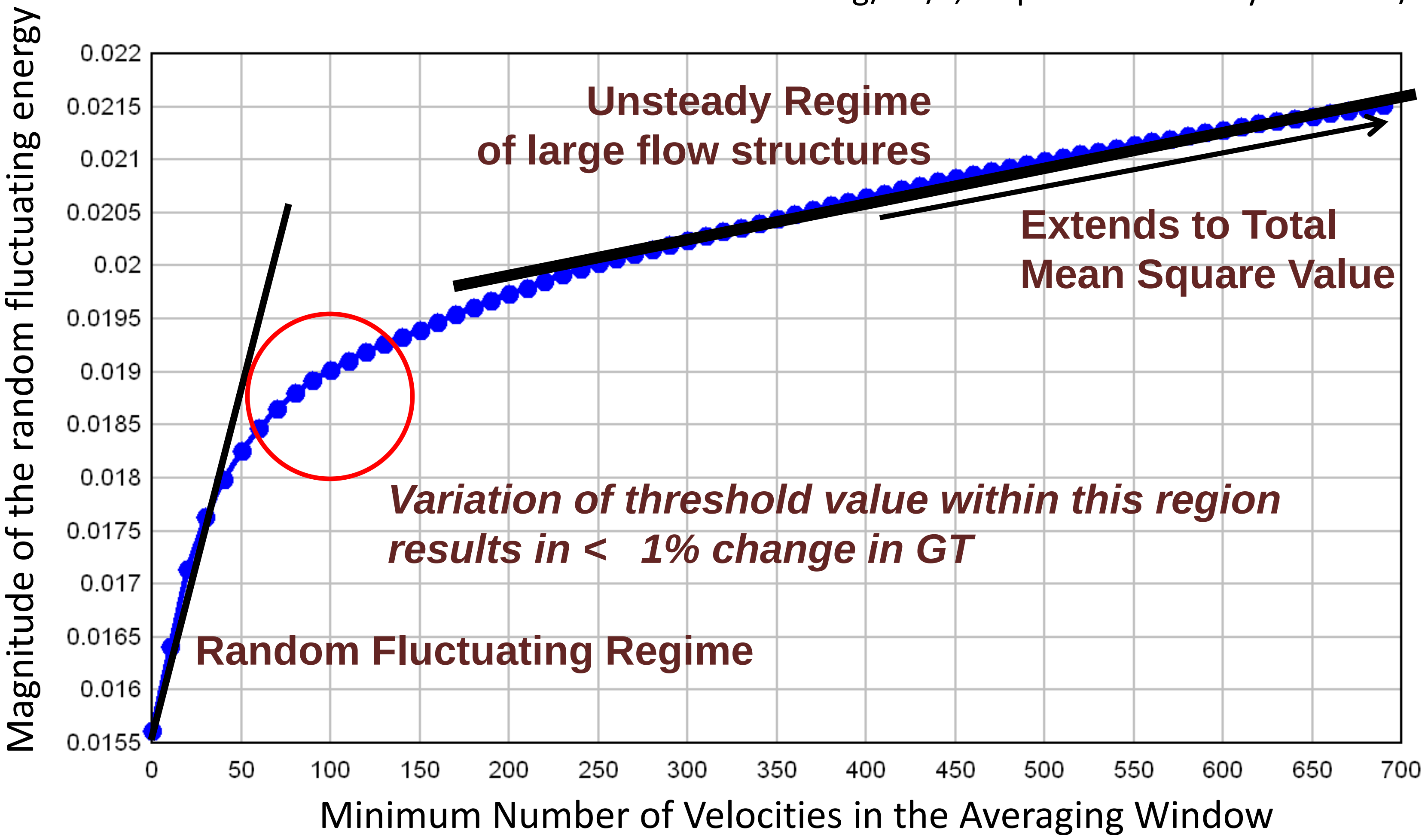
Selection of Optimum Size of Local Averaging Window for Extraction of Random Fluctuating Velocity

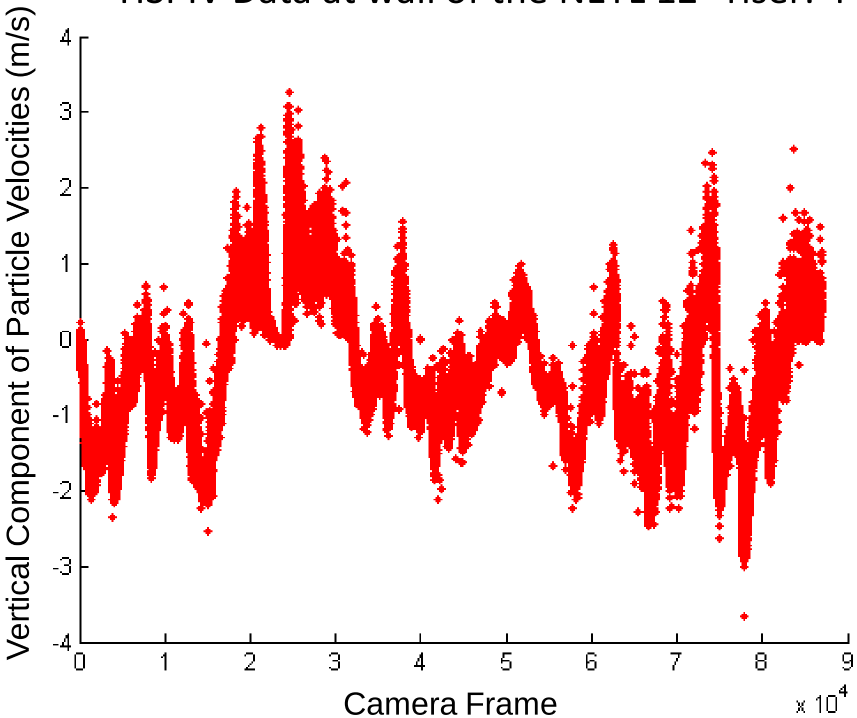
HSPIV Data at wall of the NETL 12” riser: Flux = 5 kg/m^2/s; Superficial Velocity = 6.55 m/s

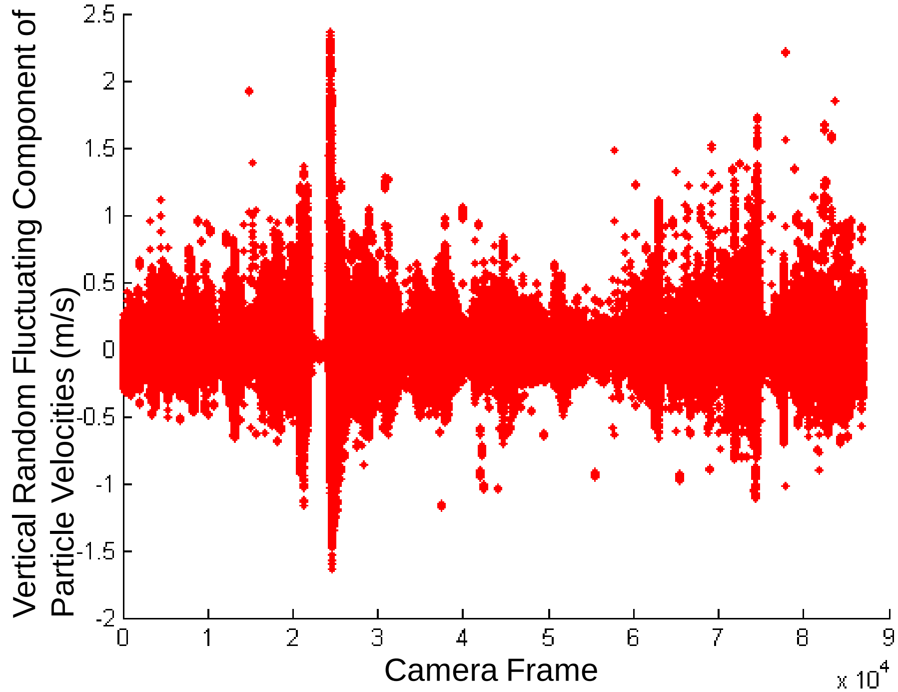


Change in slope indicating the presence of the Random Fluctuation regime is clearly seen.

Time Series of the Random Fluctuating Vertical Velocity

HSPIV Data at wall of the NETL 12” riser: Flux = 5 $kg/m^2/s$; Superficial Velocity = 6.55 m/s

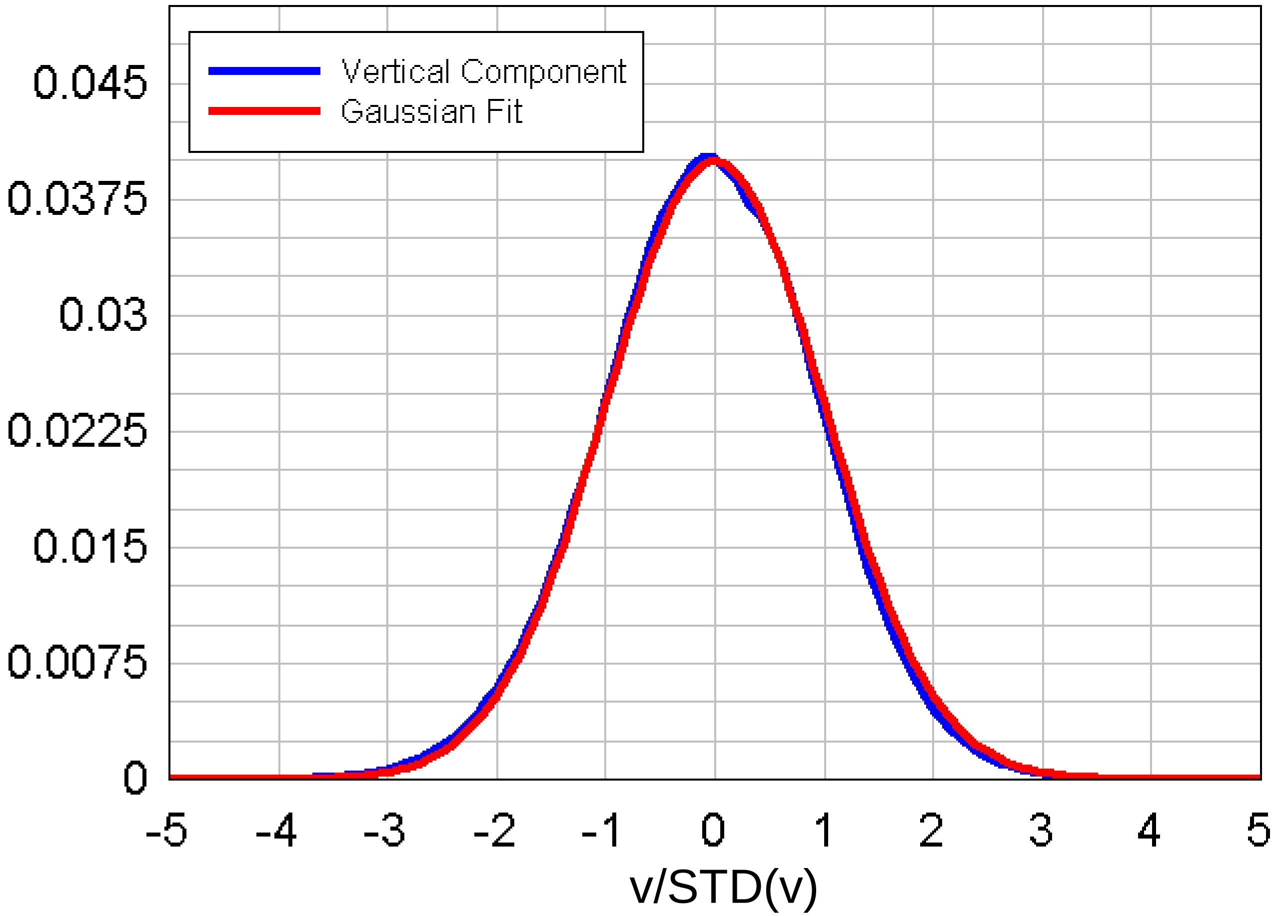




The local mean velocity subtraction successfully removed the mean cluster velocity variation and extracted the random fluctuating velocity

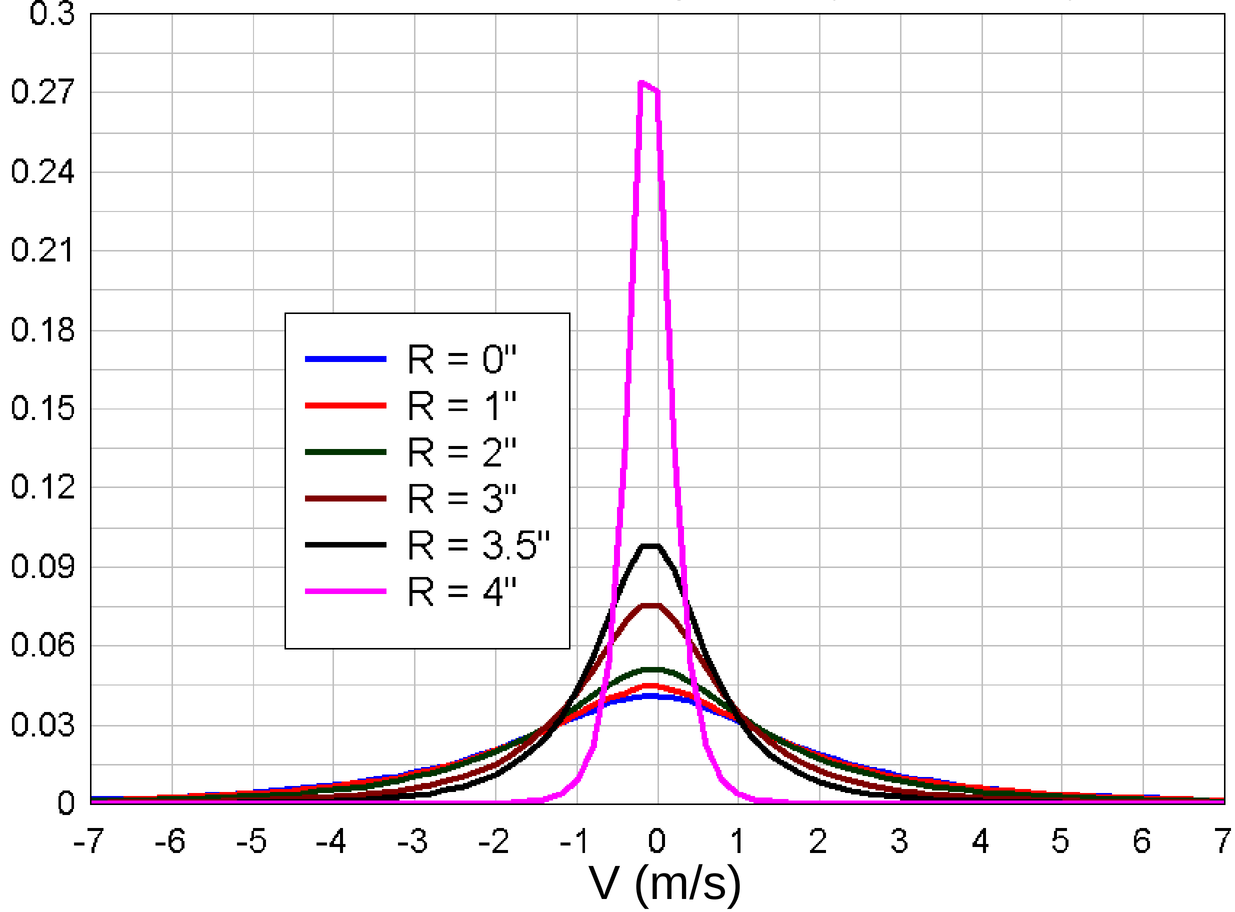
HSPIV Measurement of PDF of Random Fluctuating Velocity in Risers (1)

PSRI 8" Riser with 70 micron FCC; Flux = 48 kg/m²/s; Superficial Velocity = 18.3 m/s
Borescope measurement at R=2" from center of riser, with ~ 2 million velocity vectors



HSPIV Measurement of PDF of Random Fluctuating Velocity in Risers (2)

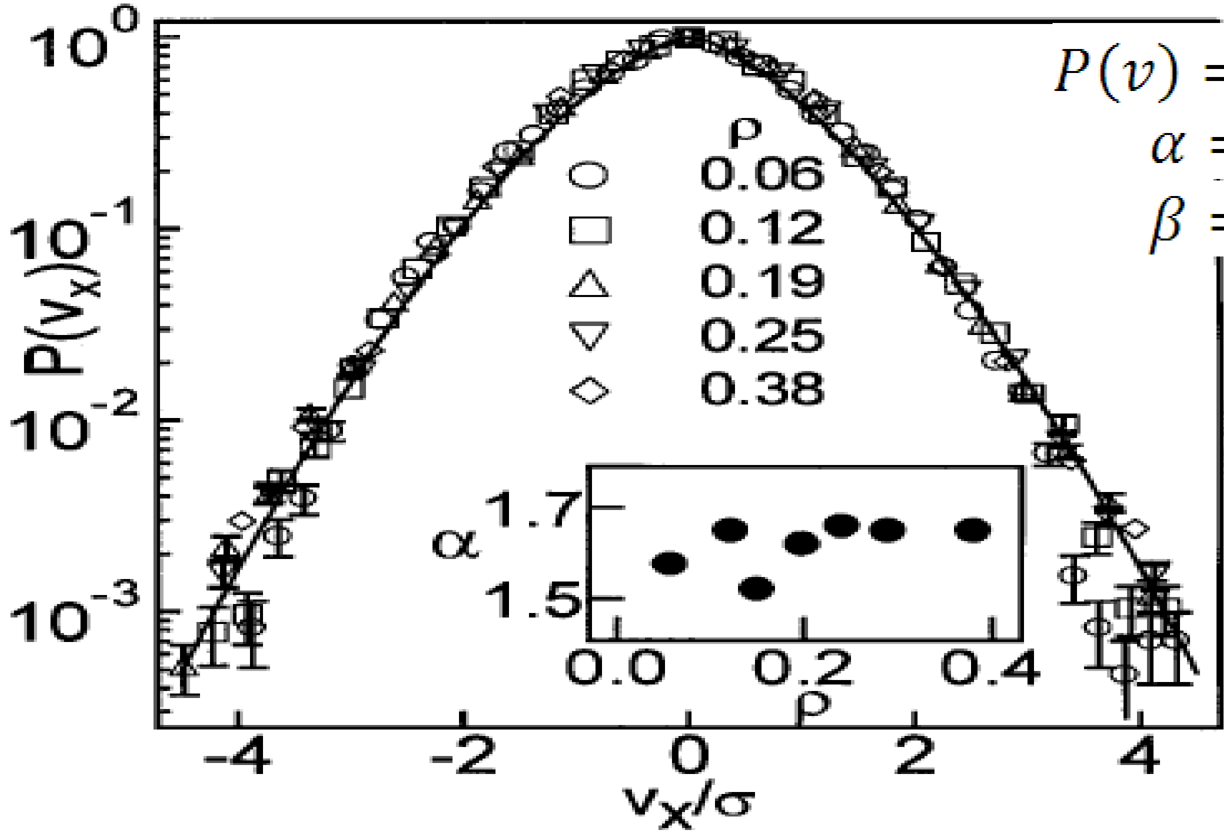
PSRI 8" Riser with 70 micron FCC; Flux = 380 kg/m²/s; Superficial Velocity = 18.3 m/s



The Horizontal PDF becomes narrower as we approach the wall due to lower RMS

Previous Data for PDF of Fluctuating Particle Velocity (1)

- Bench scale experiments [Rouyer & Menon (2000), Kohlstedt et al. (2005)] using shaker vibration to generate collisional random particle motion
- Revealed that the horizontal particle velocity distribution has an exponential “tail” and deviates from the Maxwell-Boltzmann distribution
- Rouyer & Menon (2000) measured an exponent of 1.5 for the horizontal direction.
- KE theory also predicts exponent of 1.5 [Noije & Ernst (1998)]

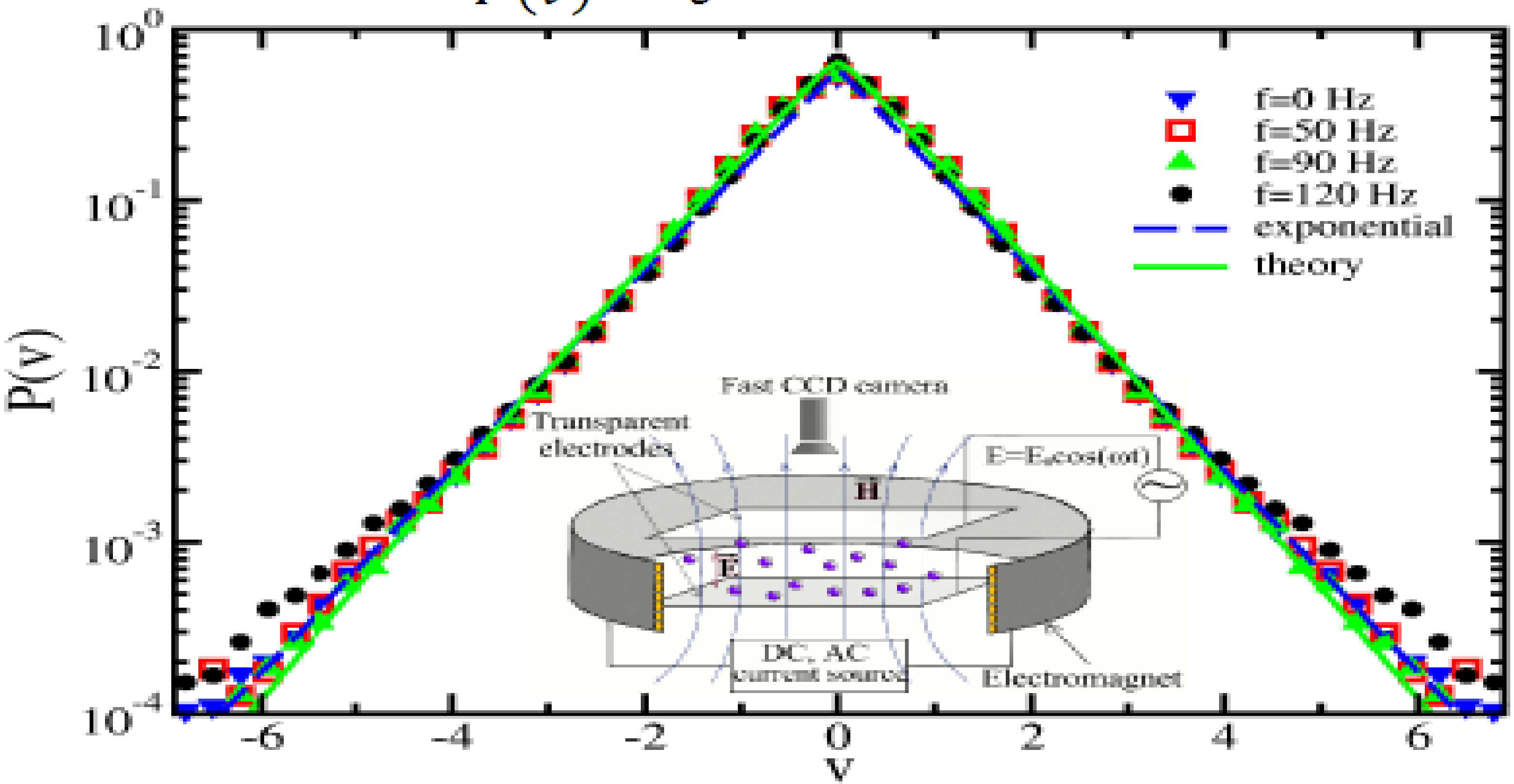


$$P(v) = e^{[-\beta|v|^{\alpha}]}$$
$$\alpha = 1.5$$
$$\beta = 0.8$$

Previous Data for PDF of Fluctuating Particle Velocity (2)

- Kohlstedt et al. (2005) measured an exponent of 1.0 for the horizontal direction
- Velocity statistics strongly depend on flow conditions
- Variation of the exponents based on flow condition suggests the need for experimental measurement of particle fluctuating velocity in a CFB riser

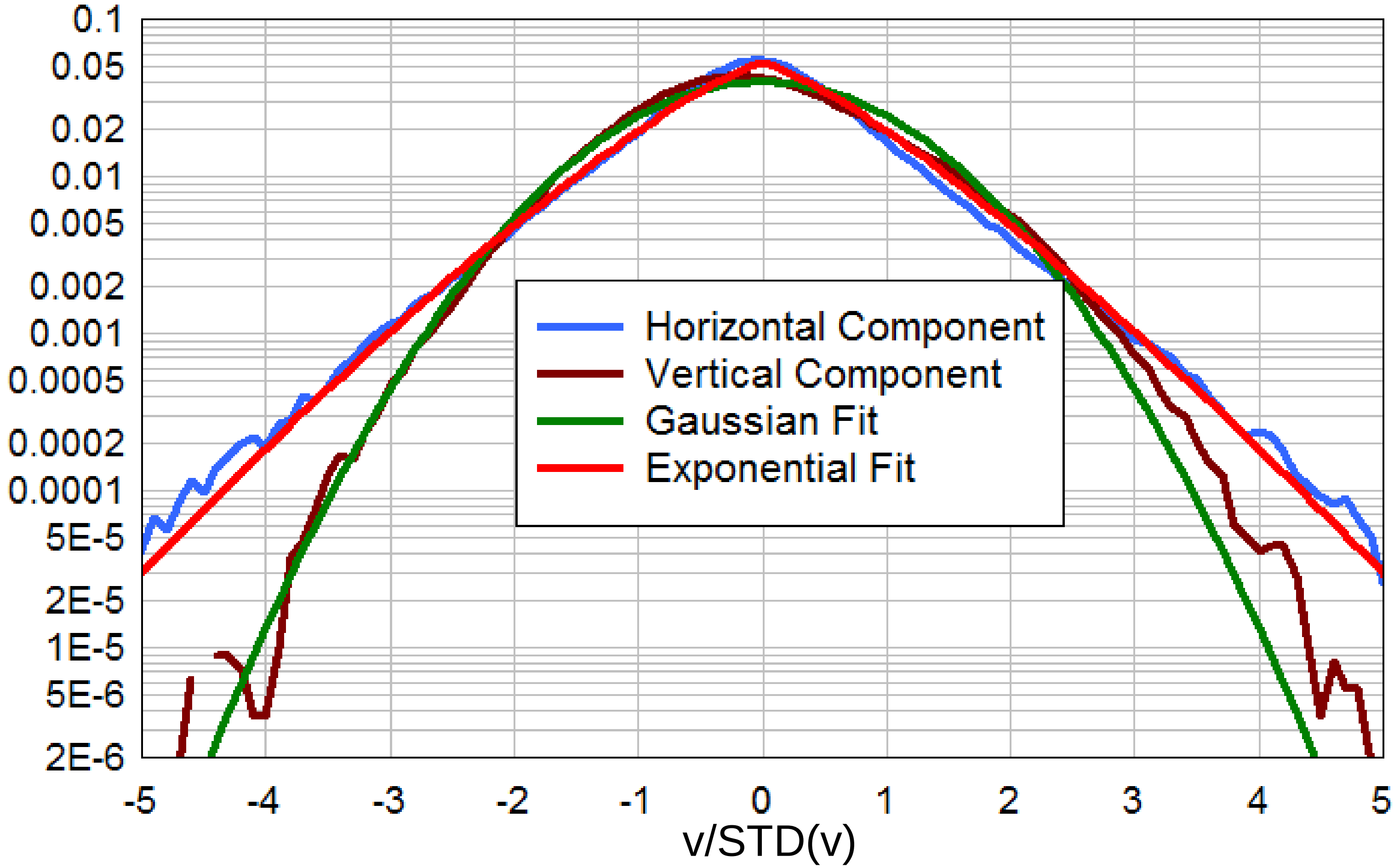
$$P(v) = e^{[-\beta|v|^{\alpha}]} \qquad \alpha = 1$$



Normalized PDF of Random Fluctuating Particle Velocity in PSRI Riser

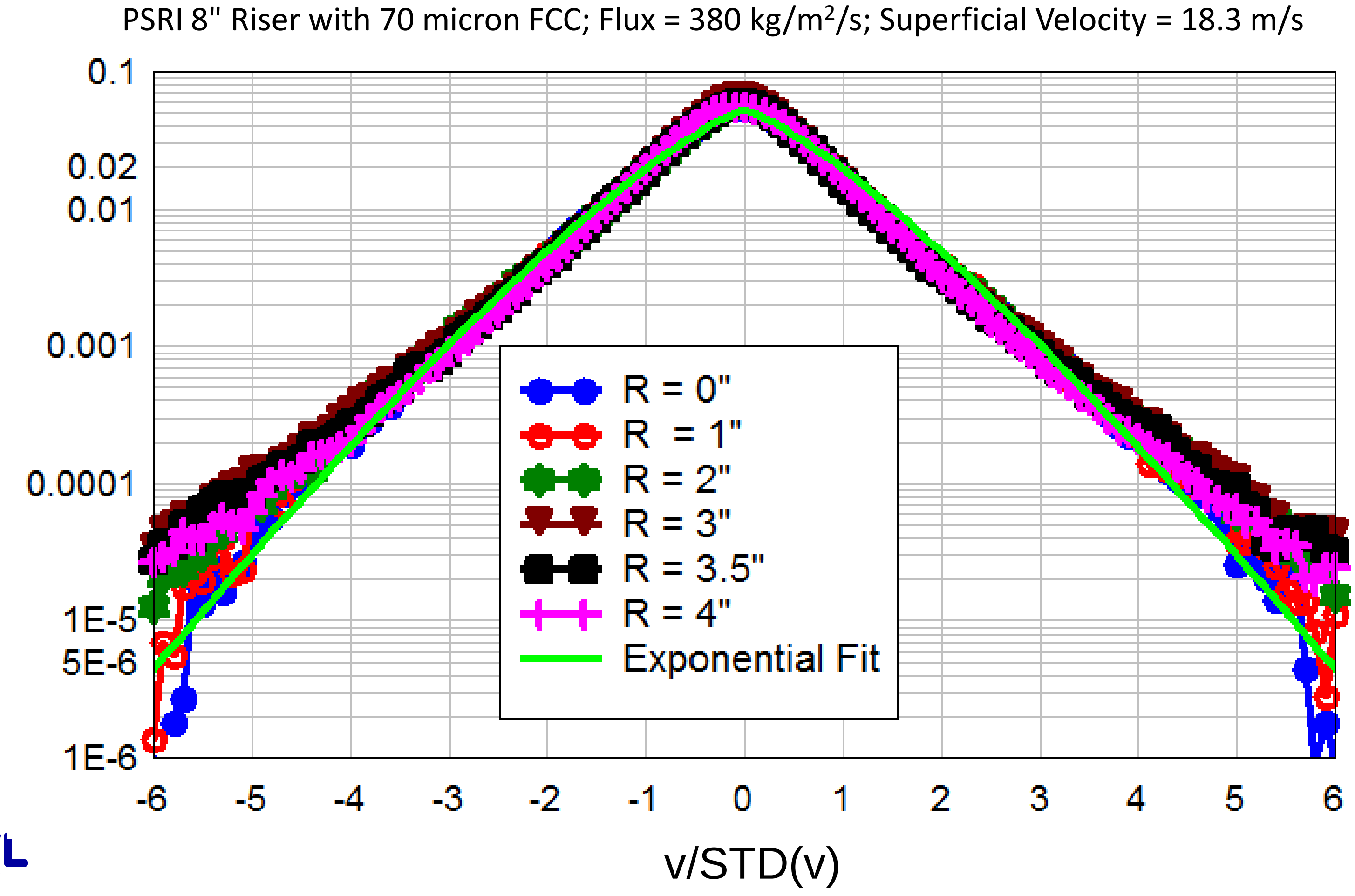
- Millions of velocity vectors enable us examine the shape of PDF in a log plot
- Exponential distribution fits the horizontal data with an exponent of 1.25
- Vertical PDF has a near Gaussian distribution with a slight skewness

PSRI 8" Riser with 70 micron FCC; Flux = 380 $kg/m^2/s$; Superficial Velocity = 18.3 m/s
Borescope measurement at R=0, center of riser, with ~ 1.1 million velocity vectors



Normalized PDF of Horizontal Random Fluctuating Particle Velocity for different Radial Locations (Higher Flux)

- Exponential distribution fits the horizontal random velocity data with an exponent of 1.25 up to a radial location of 2" from the centre of the riser
- For near wall measurements the tails of the distribution is more wider



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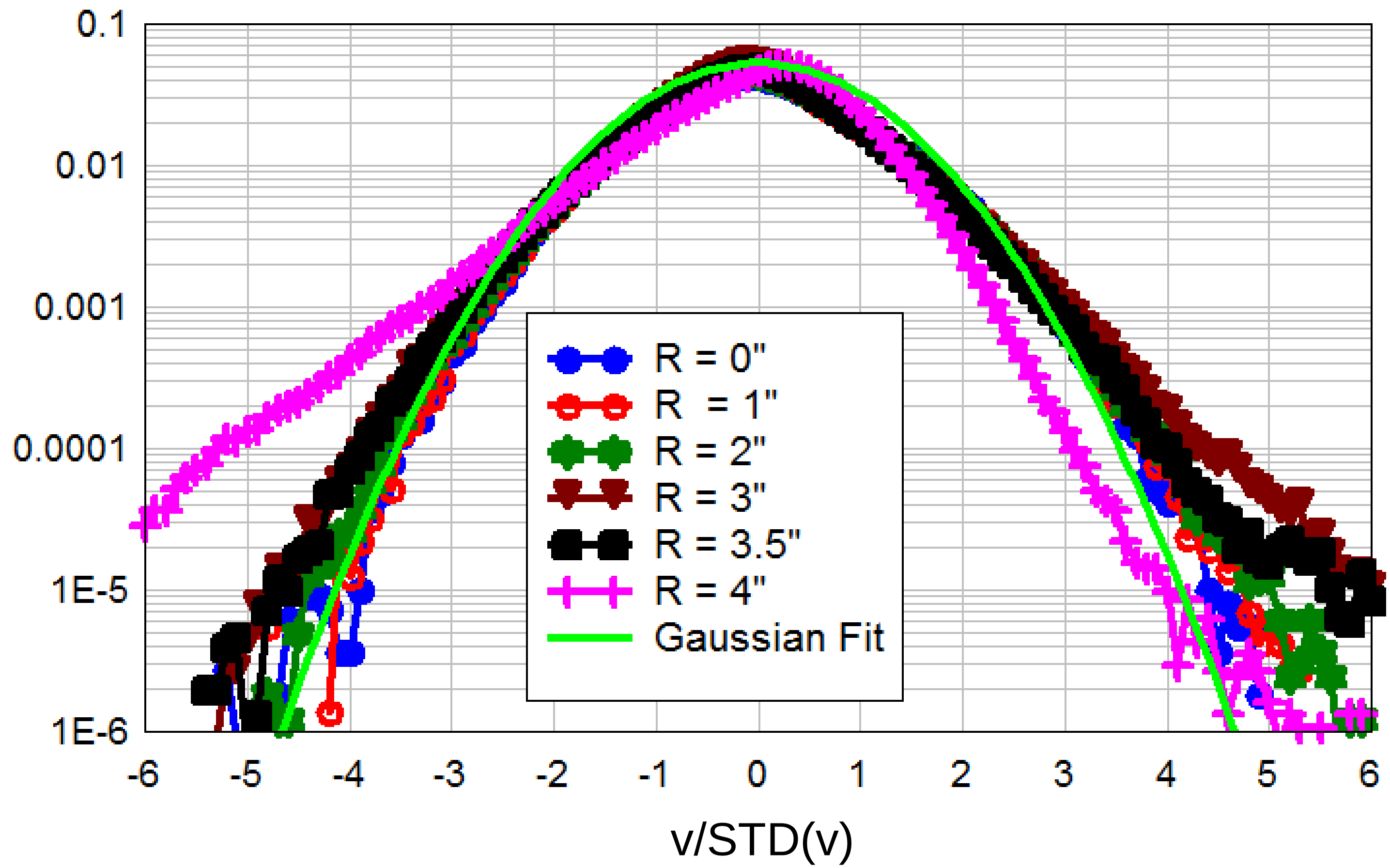
Normalized PDF of Vertical Random Fluctuating Particle Velocity for different Radial Locations (Higher Flux)

- The distribution of the vertical random velocity data is close to a Gaussian distribution with a small skewness.
- For wall measurements the tails of the distribution is skewed

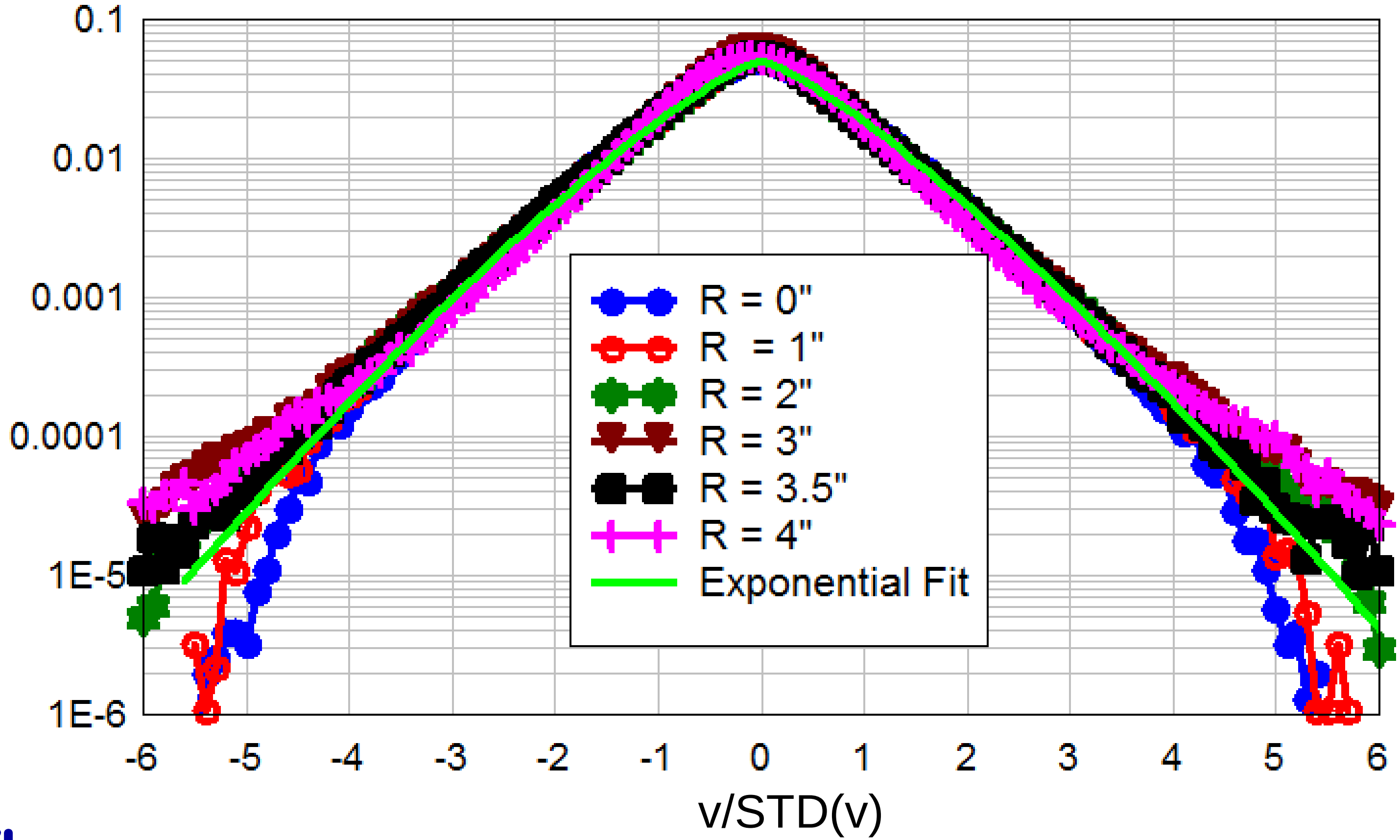
PSRI 8" Riser with 70 micron FCC; Flux = 380 kg/m^2/s; Superficial Velocity = 18.3 m/s



Normalized PDF of Horizontal Random Fluctuating Particle Velocity for different Radial Locations (Lower Flux)

- Exponential distribution fits the horizontal random velocity data with an exponent of 1.25 up to a radial location of 2” from the centre of the riser
- For near wall measurements the tails of the distribution is more wider

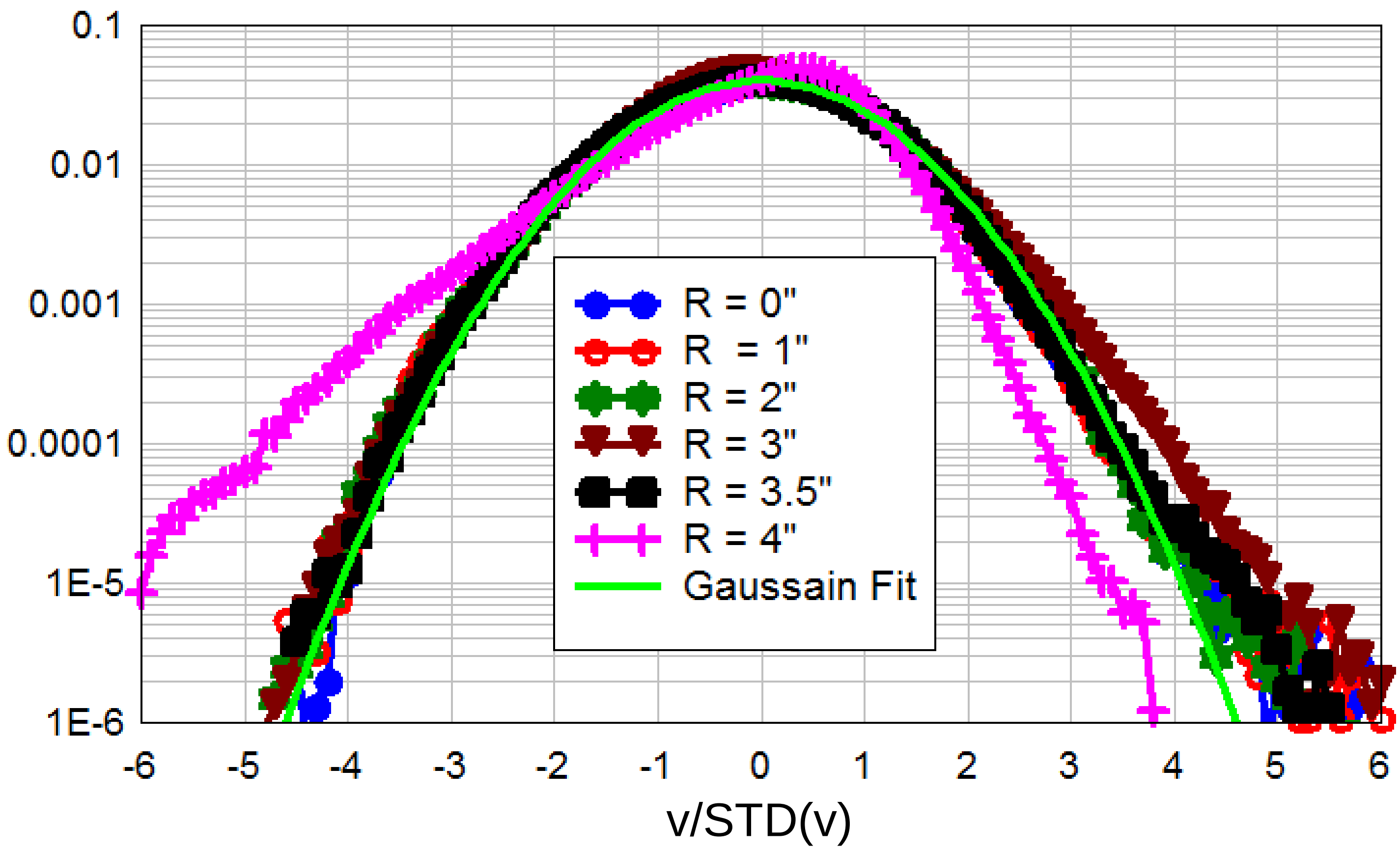
PSRI 8" Riser with 70 micron FCC; Flux = 48 kg/m²/s; Superficial Velocity = 18.3 m/s



Normalized PDF of Vertical Random Fluctuating Particle Velocity for different Radial Locations (Lower Flux)

- The distribution of the vertical random velocity data is close to a Gaussian distribution with a small skewness
- For wall measurements the skewness of tails of the distribution is high

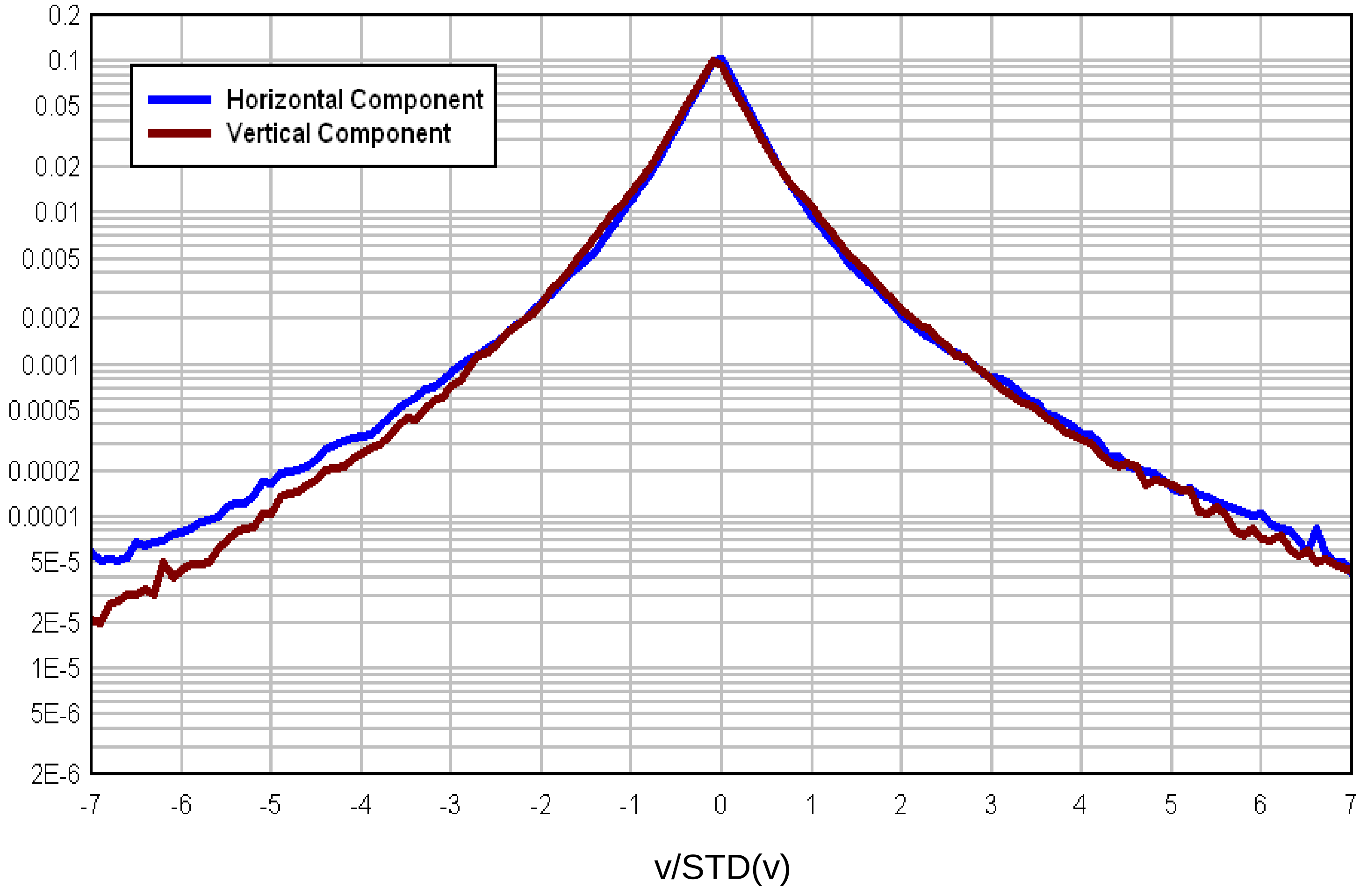
PSRI 8" Riser with 70 micron FCC; Flux = 48 kg/m²/s; Superficial Velocity = 18.3 m/s



Normalized PDF of Random Fluctuating Particle Velocity in NETL Riser

- The horizontal distribution is symmetric while the vertical one is skewed
- Both distribution deviate significantly from the exponential distribution

NETL 12" Riser with 750 micron HDPE; Flux = 5 $kg/m^2/s$; Superficial Velocity = 6.55 m/s
Measurement at the wall of riser with ~ 2.23 million velocity vectors



Summary

- HSPIV measurements enable us to measure particle velocities in a riser at high spatial and temporal resolution

- Using a borescope extends these measurements to all regions of a riser

- A new decomposition technique has been developed based on multi frame averaging to extract the random fluctuating component of velocity

- Measured data of millions of velocity vectors enable us to understand the shape of the PDF of random velocity

- The random horizontal velocity has an exponential distribution while the vertical one is close to Gaussian

- These data will help in the development/verification of riser models

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Thank You!!

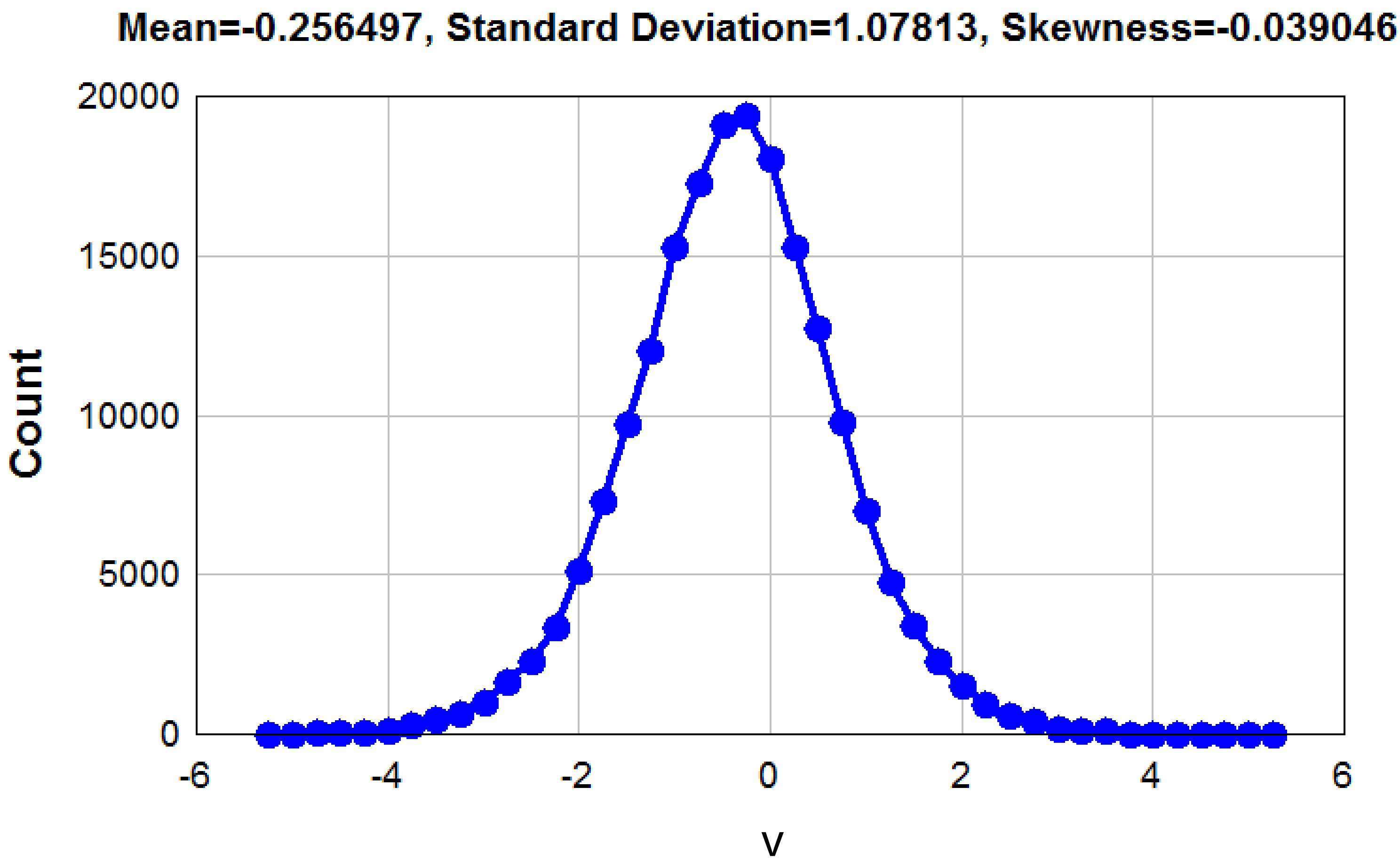
Snapshot of Range of Experimental Conditions

Probably don't need this slide because I will cover this in the first presentation.
Frank

- Particles: 70 μm mean dia. FCC and 750 μm mean dia. HDPE
- Superficial Gas Velocity: 5 - 20 m/s
- Mass Flux : 5 - 380 kg/m^2s
- Flow Regime: unsteady jet (core-annulus) and high speed dense upflow
- Experimental Measurement: Short particle trajectories using HSPIV over a small sample volume

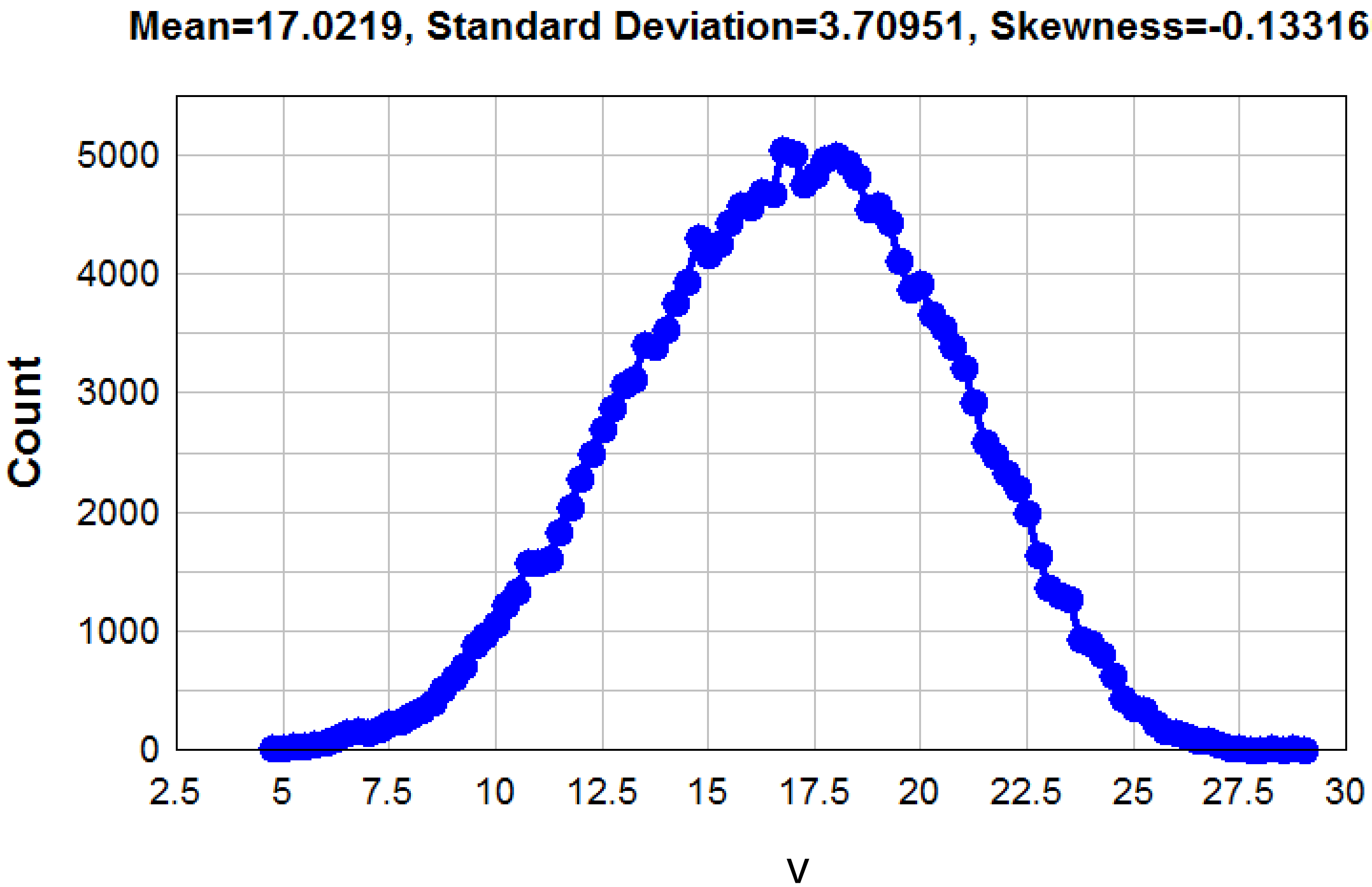
Sample Histogram of Local Mean Horizontal Velocity

PSRI 8" Riser with 70 micron FCC; Flux = 380 kg/m^2/s; Superficial Velocity = 18.3 m/s
Borescope measurement at center of riser

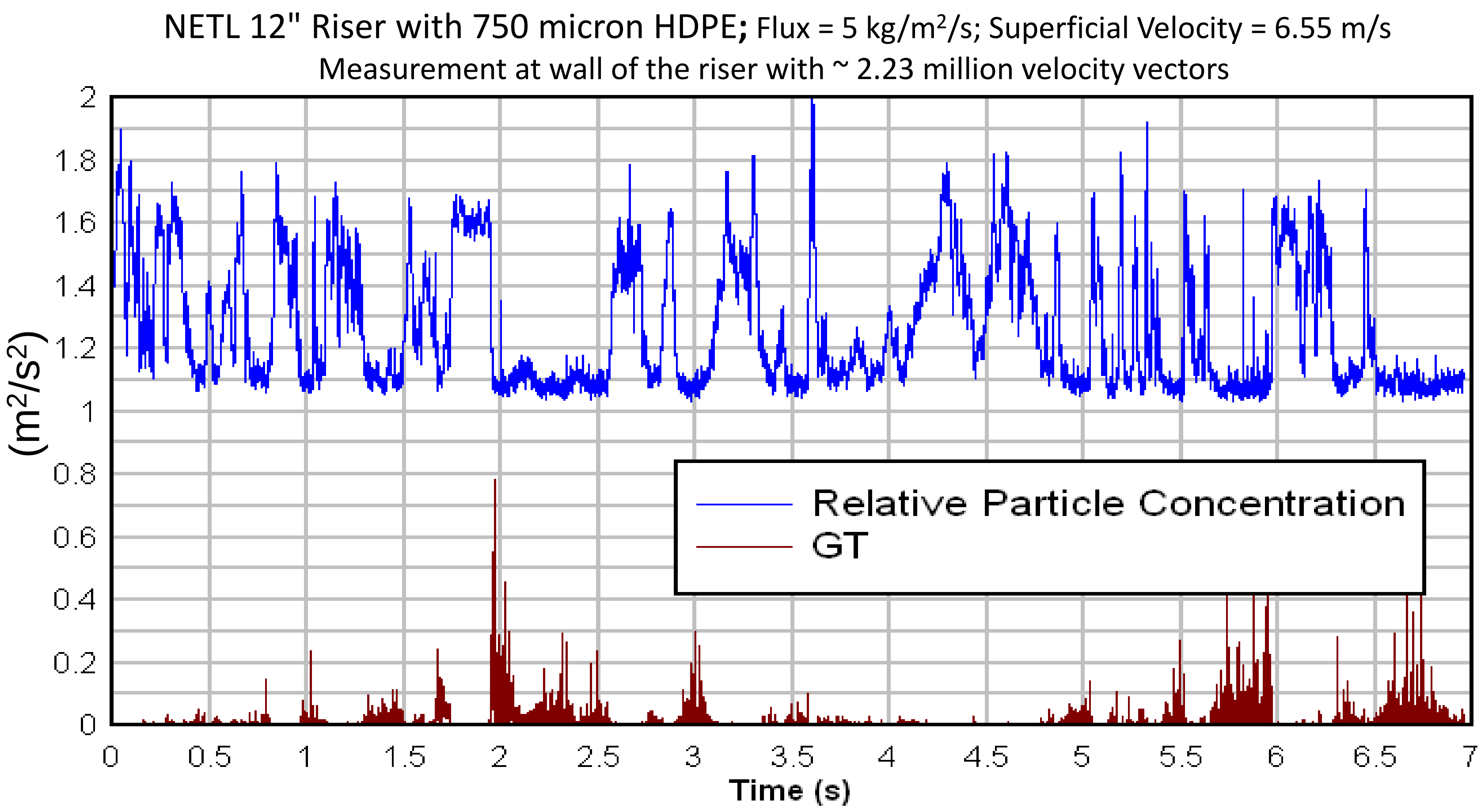


Sample Histogram of Local Mean Vertical Velocity

PSRI 8" Riser with 70 micron FCC; Flux = 380 kg/m²/s; Superficial Velocity = 18.3 m/s
Borescope measurement at center of riser



Time series of Granular Temperature for NETL 12" Riser (GT)



- Bulk of the flow has very small contribution from the random fluctuations
- Low particle concentration is accompanied by higher Granular Temperature