NATIONAL ENERGY TECHNOLOGY LABORATORY

High Speed Imaging of Flow Phenomena in CFB Risers

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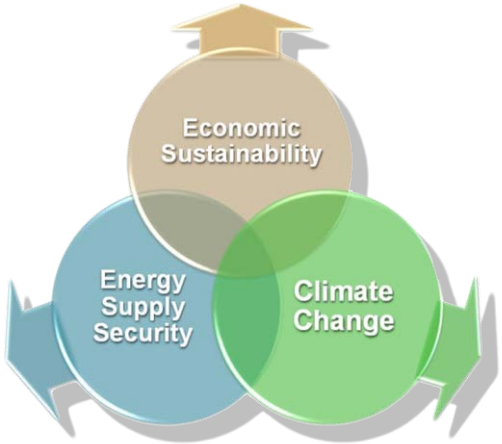
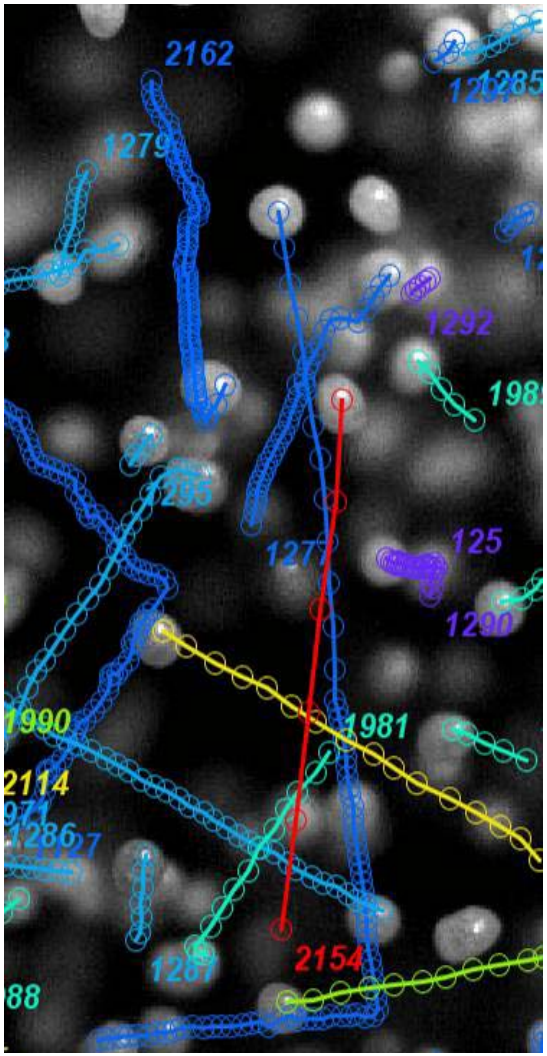


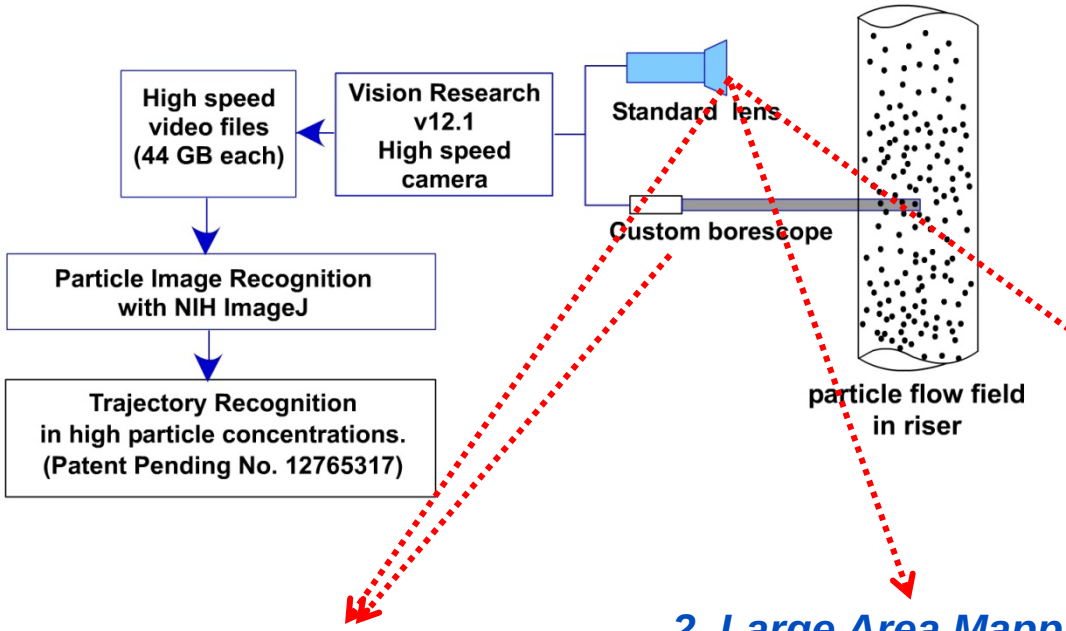


U.S. DEPARTMENT OF ENERGY

Motivation & Goals

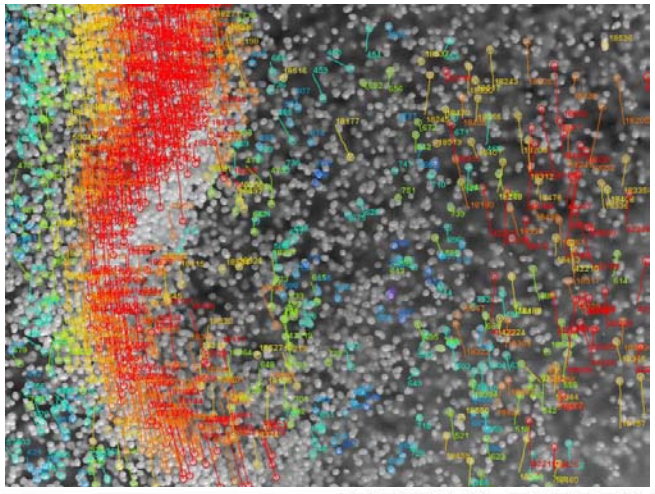
- **Develop a better understanding of gas and particle flow phenomena at high particle concentration conditions**
- **The main application is the riser section of circulating fluidized bed (CFB) systems**
- **Generate new data for evaluation and improvement of CFD models of high concentration particle flows**
- **The Grand Challenge is to develop comprehensive integrated models for the design and operation of advanced fossil fuel conversion systems with carbon capture and sequestration**

Types of High Speed Imaging Measurements

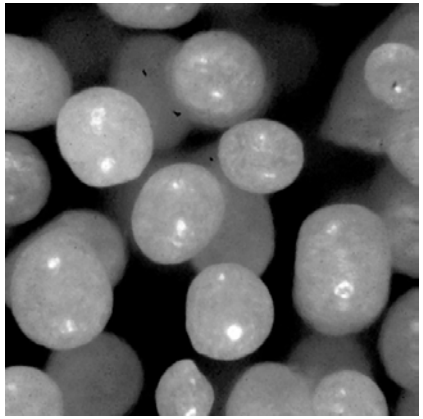


3. Qualitative Flow Visualization

2. Large Area Mapping



1.Small "Point" Measurement



Outline of Results

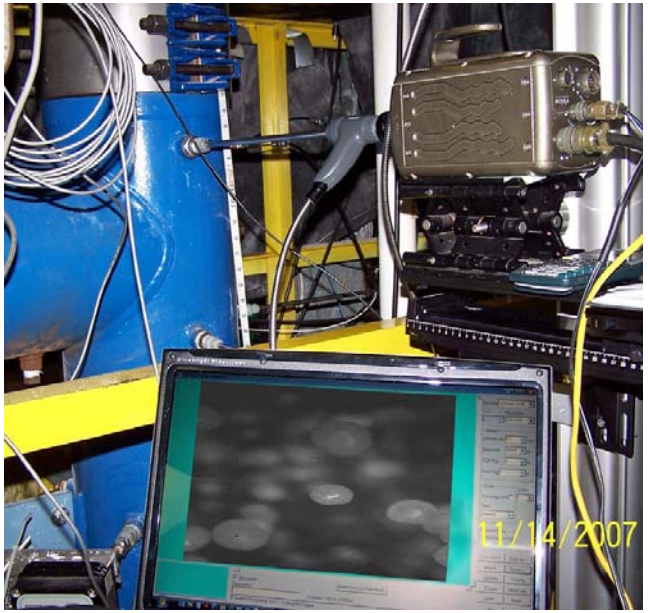
- **Small Field-of-View "Point" Measurement**
  - **Field-of-View is smaller than gradients of time-averaged properties**
  - **Produces a time series of 2D particle velocity and concentration**
  - **Very high data rates in the range of 100,000 to 1,000,000 vectors/sec**
  - **Scan CFB risers to generate radial profiles of mean and fluctuating components of velocity particle**
  - **High data rates allow examination of higher order statistics: velocity distributions, granular temperature, etc**

- **Large Field-of-View**
  - **2D maps of particle velocity and concentration**
  - **Measurement of large flow structures: jets, clusters, etc.**

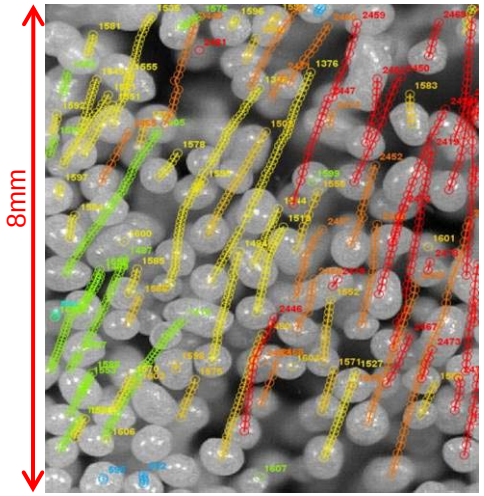
Outline of Results

- **Large Field-of-View measurements can be used to study the effect the size of measurement area on calculated results**
- **For comparison with CFD data, does the measurement area need to be the same size as grid cells?**
- **Are measured parameters defined in the same way as parameters in CFD models?**
- **Preliminary results will be presented for the effect of measurement area on shear rate and granular temperature**

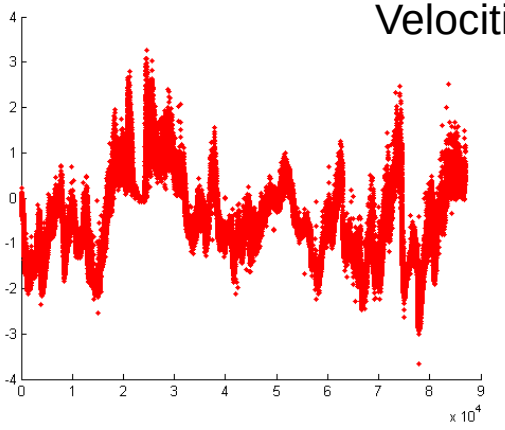
HSPIV Measurements for Small Field-of-View



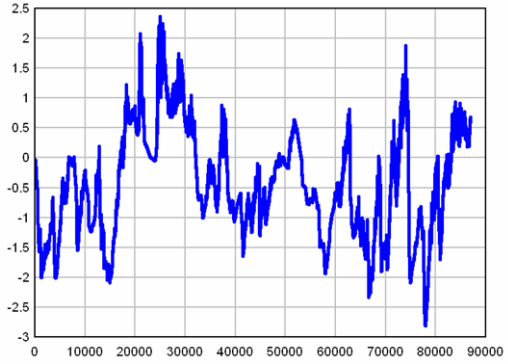
Tracked Particles



Individual Particle Velocities



Local Mean Velocity/Eulerian Velocity



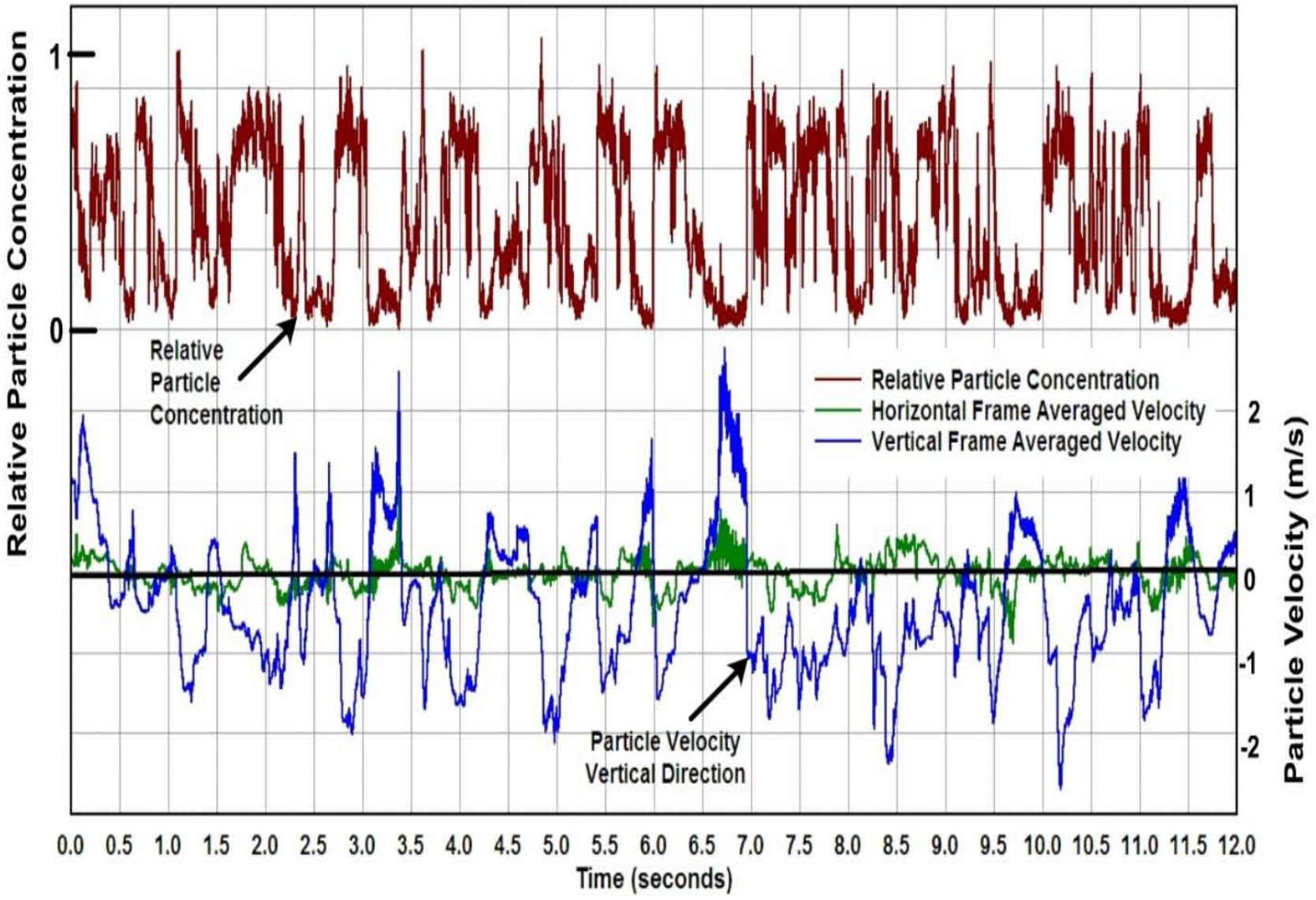
Local mean velocity measured with HSPIV is comparable to Eulerian particle velocity in CFD simulations

F. Shaffer (2010), B. Gopalan & F. Shaffer (2010, 2012)

Measurement Uncertainty of Individual Particle Velocity:
<1% at wall
~ 5% inside flow

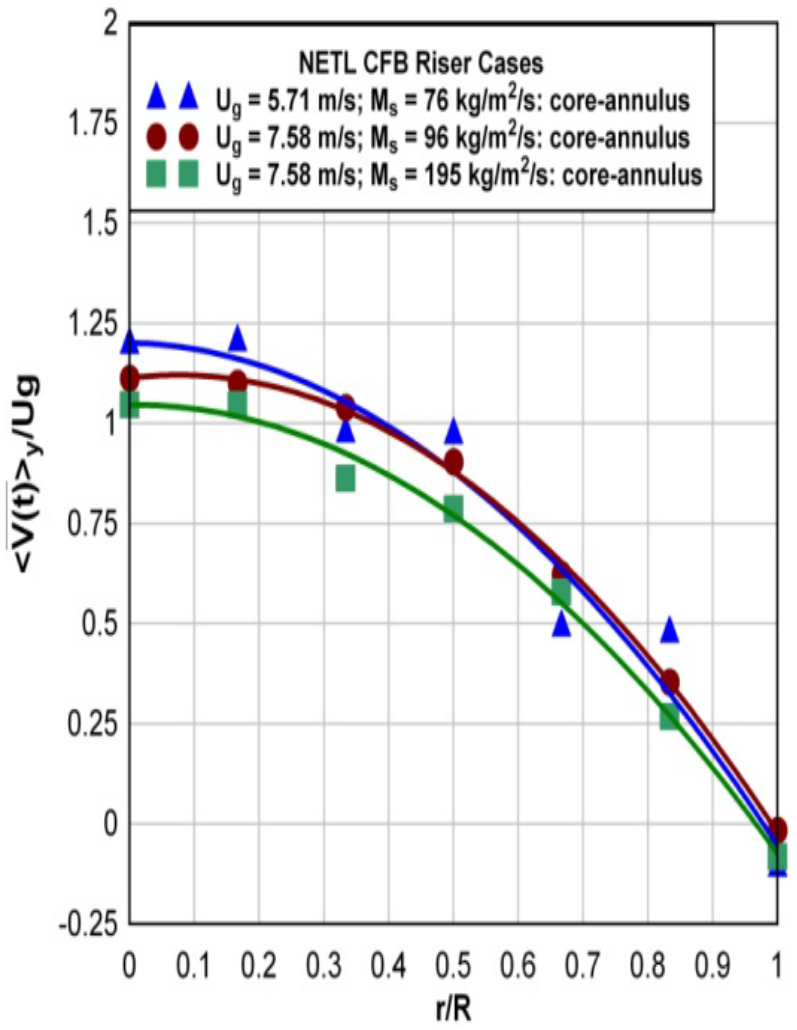
High Speed PIV "Point" Measurement in NETL 12" Riser

NETL SN9: Superficial Gas Velocity = 21.5 fps, solids flux = 20 kg/m^2/s

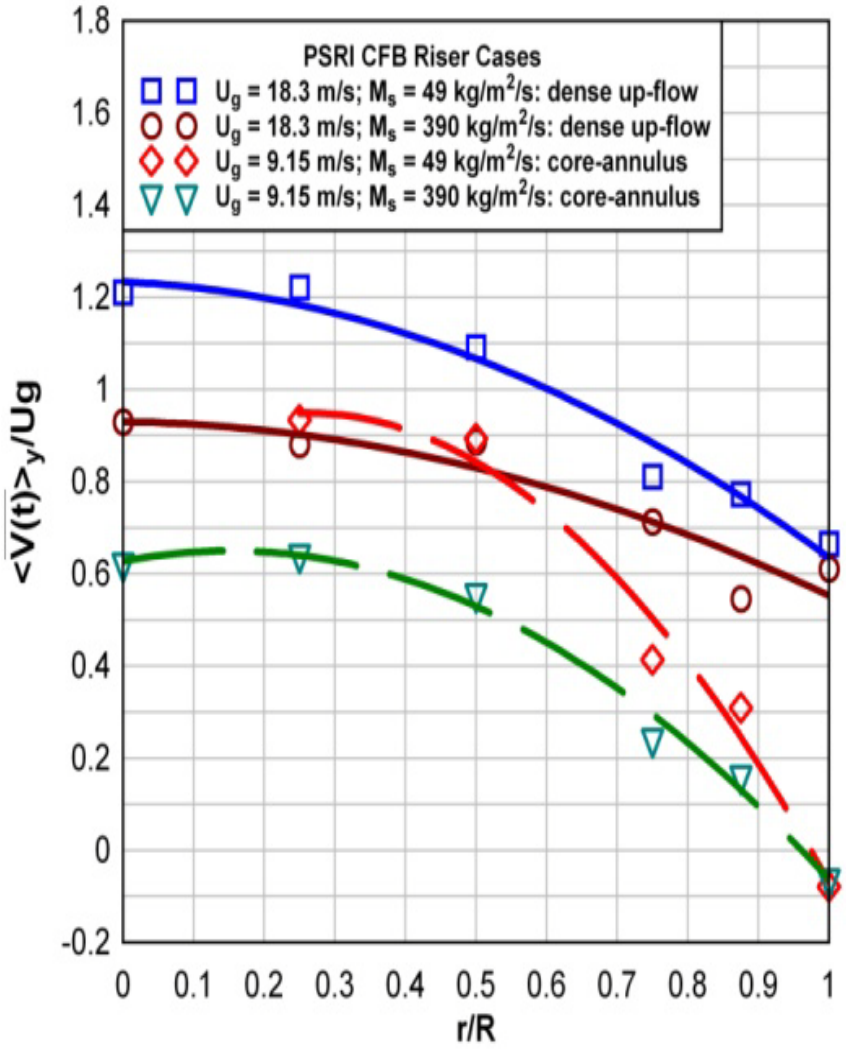


Radial distribution of Total Mean Particle Velocity

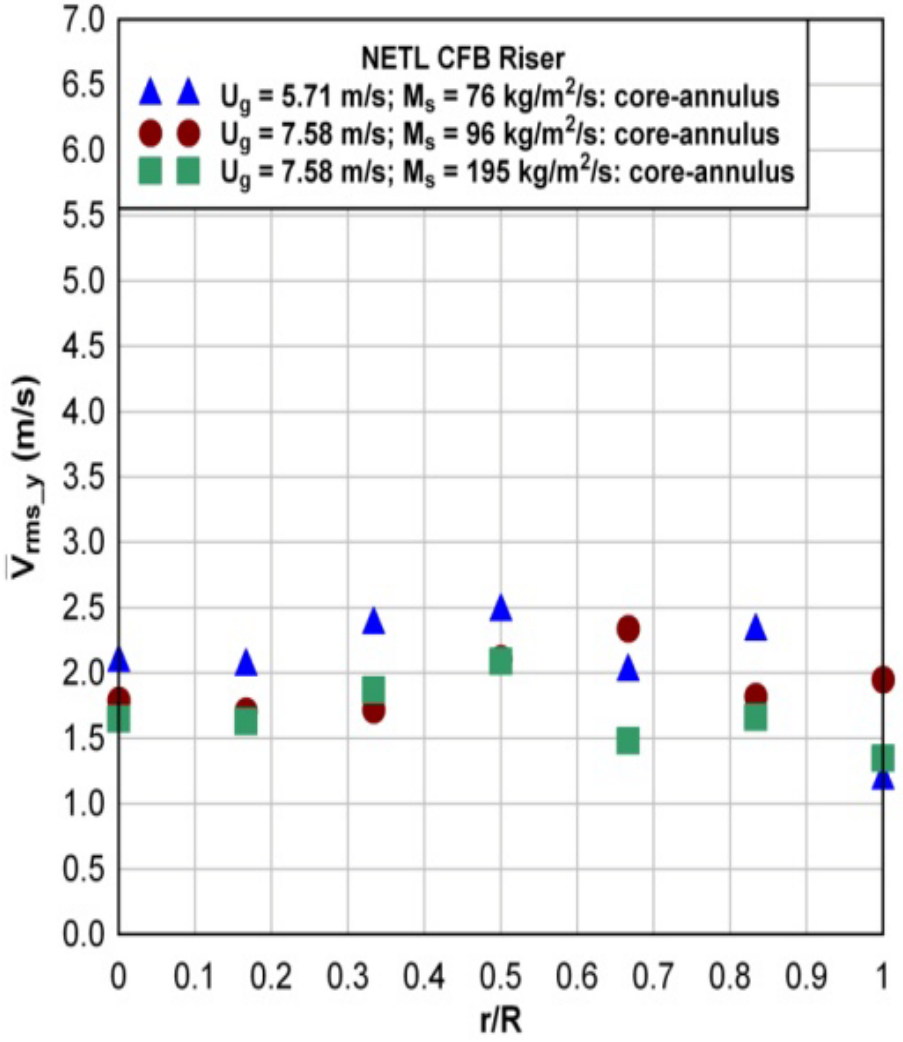
NETL riser with 800 micron HDPE

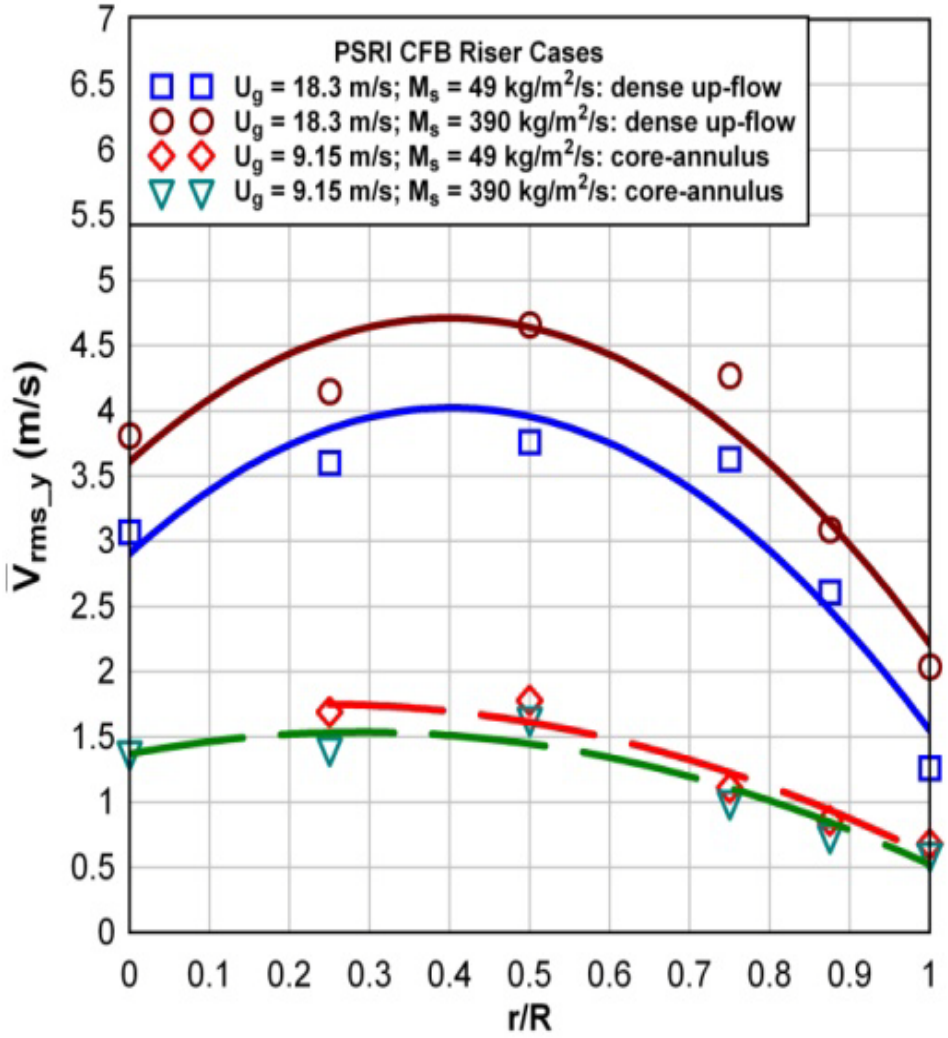


PSRI riser with 70 micron FCC

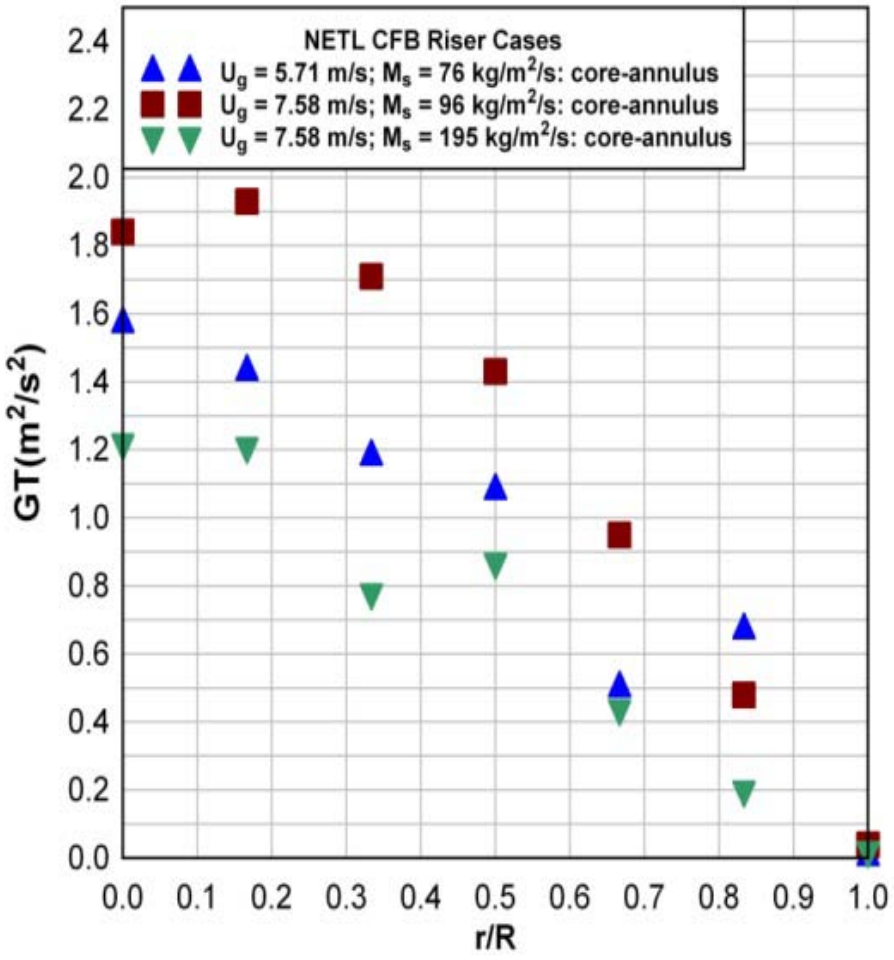


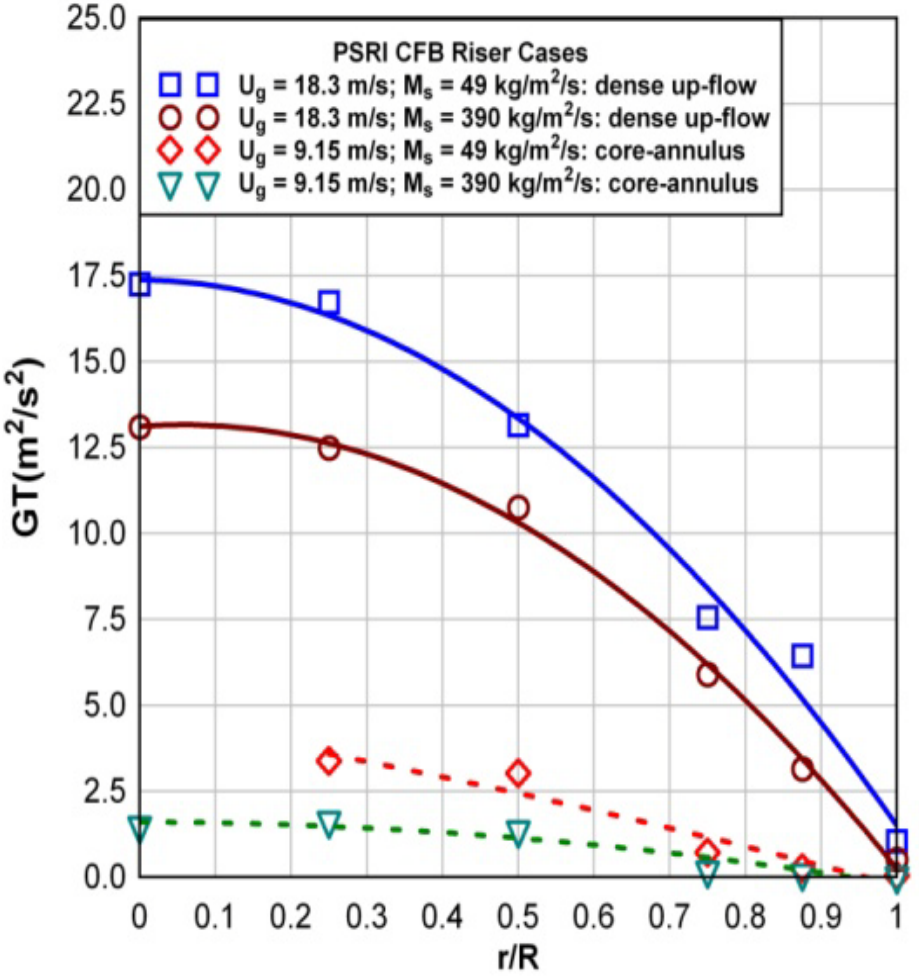
Radial Profile of RMS of Eulerian Velocity





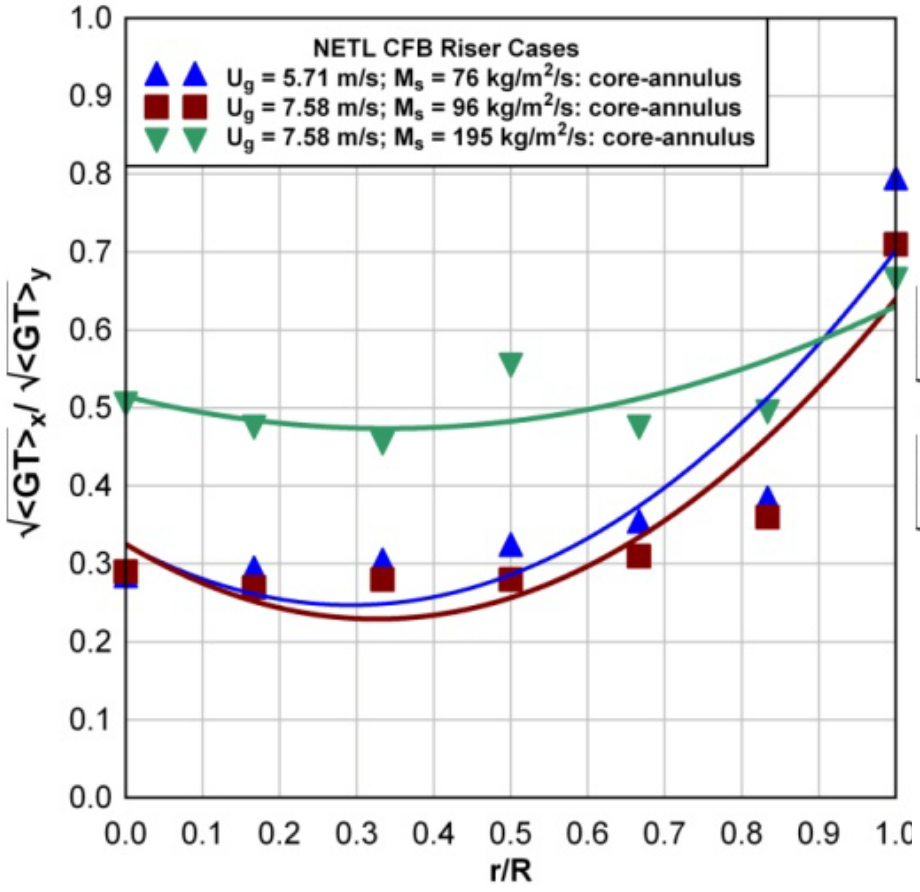
Radial distribution of Granular Temperature

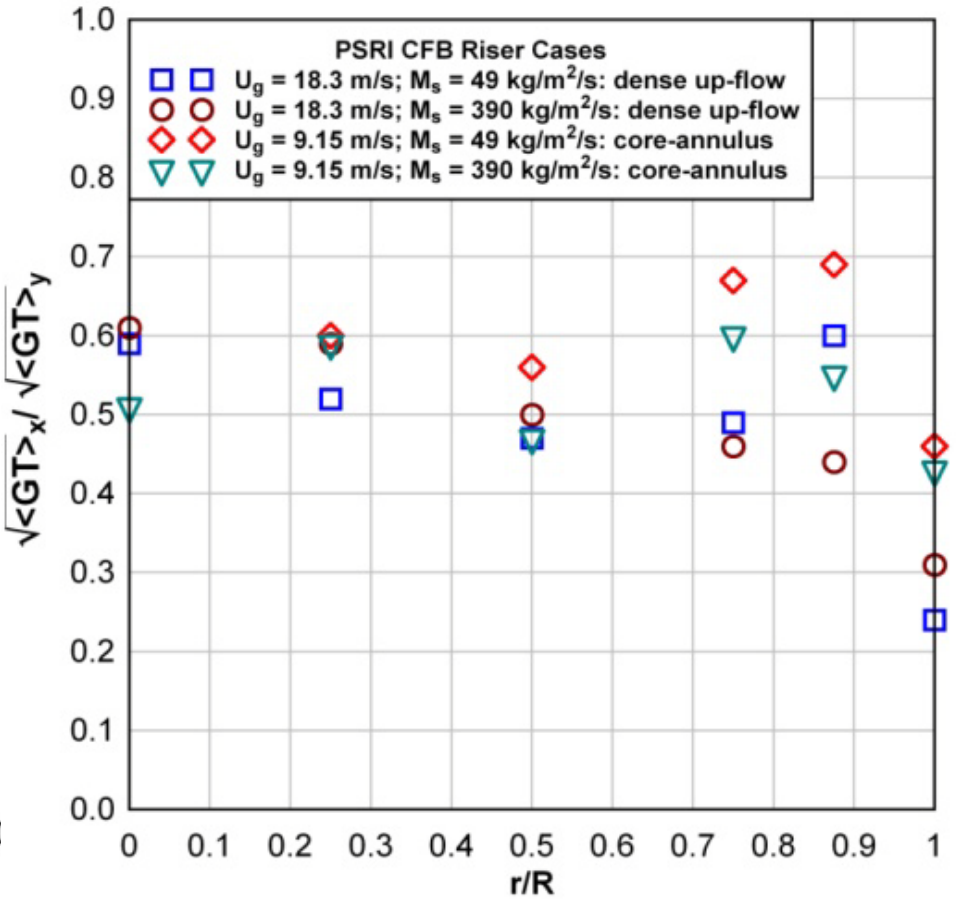




Granular temperature increases with increasing superficial gas velocity at a constant solids flux, and decreases with increasing mass flux at a constant gas velocity.

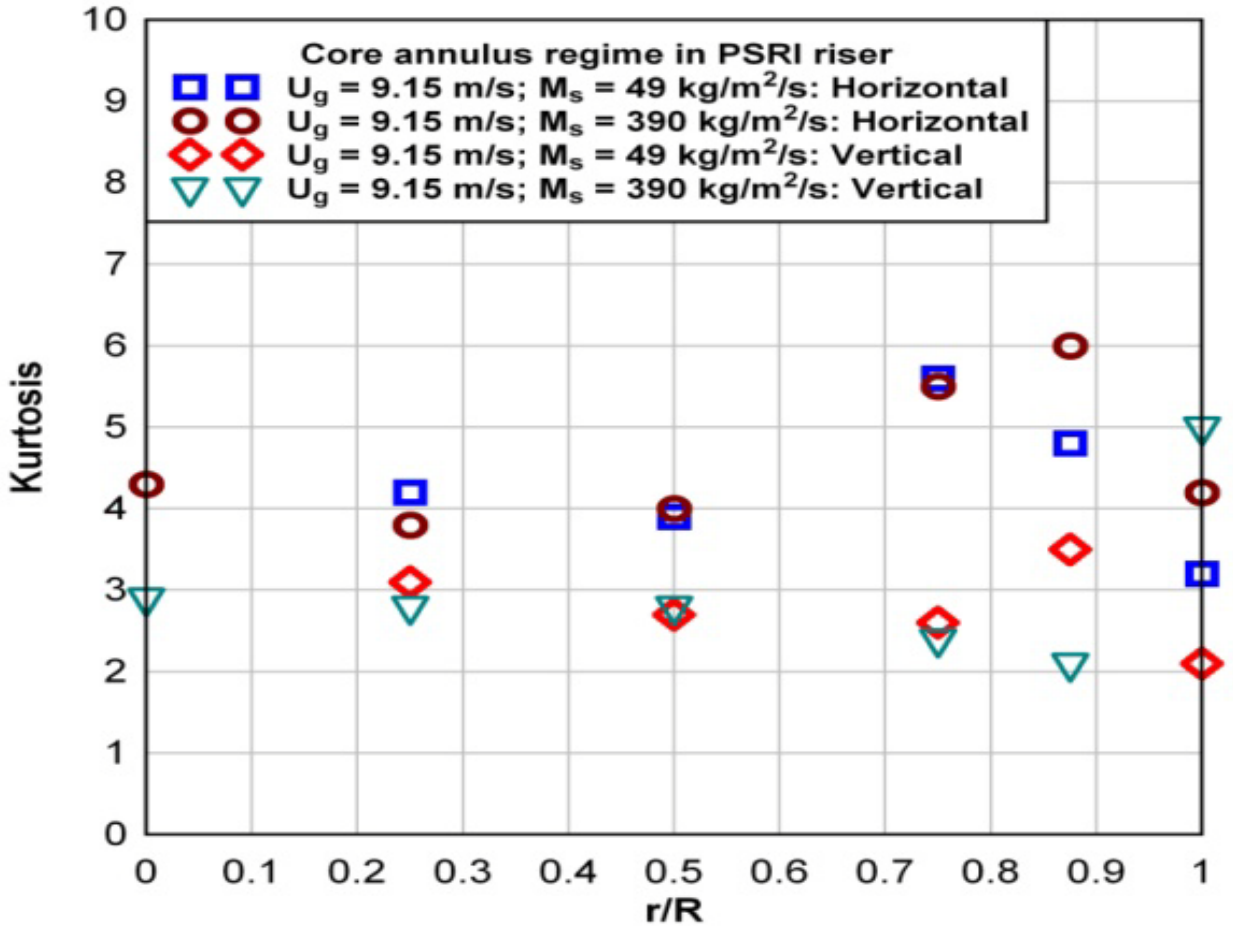
Anisotropy of Granular Temperature





Anisotropy decreases near the wall of the NETL riser, but increases near the wall of the PSRI riser.

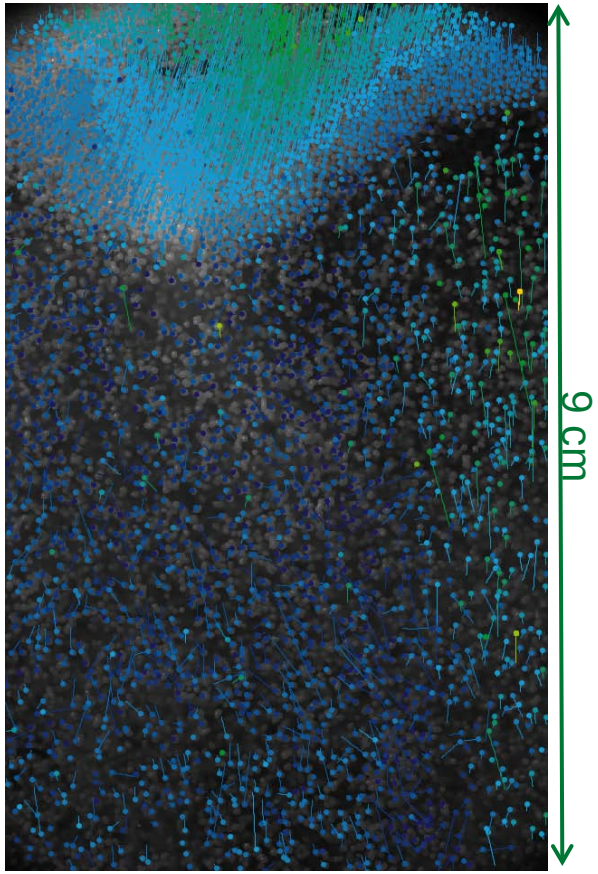
Kurtosis of Eulerian Velocity



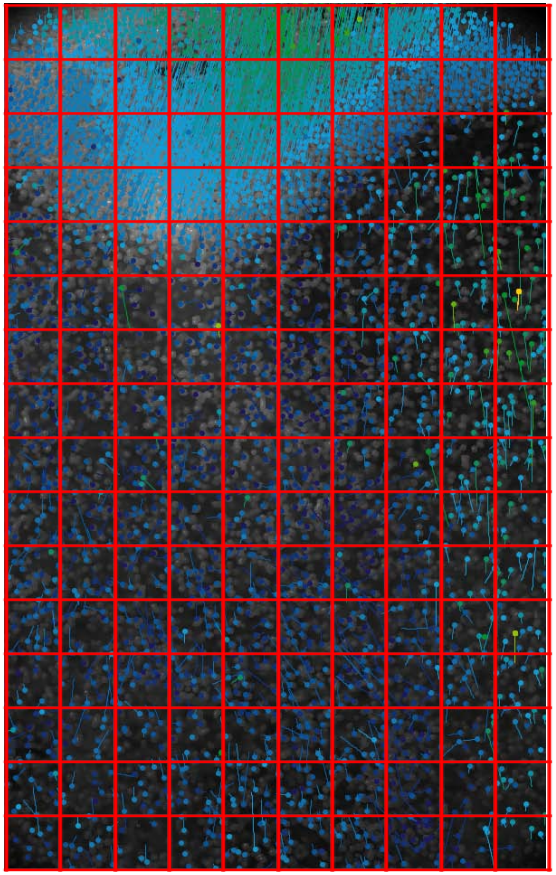
The kurtosis of the Eulerian particle velocity for the horizontal direction is always higher than that in the vertical direction.

HSPIV Measurements for Large Field-of-View

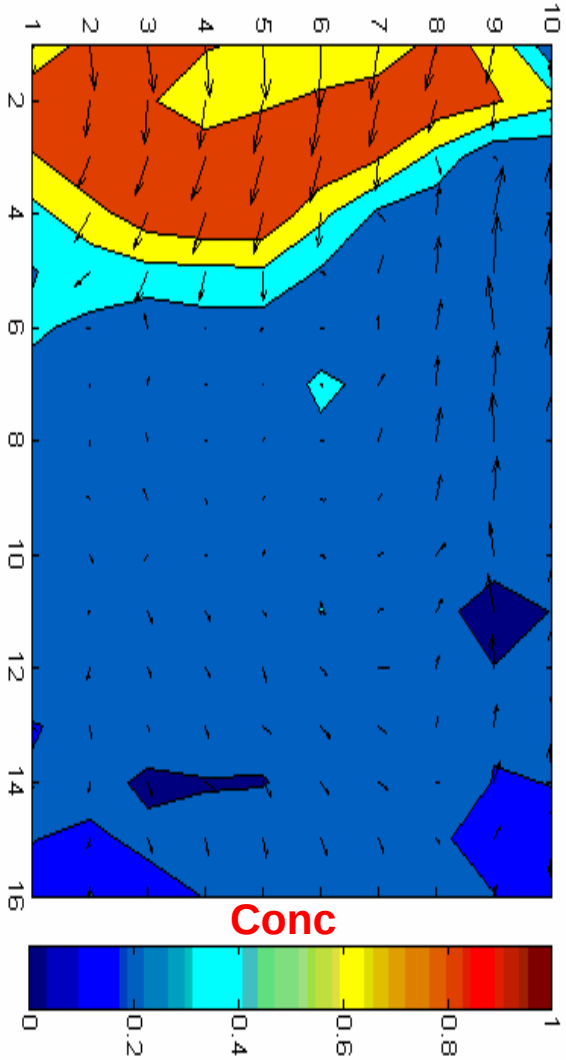
U_g = 7.58 m/s; M_s = 96 kg/m^2/s; Location at the wall;
Sample Area = 7 * Particle Diameter



Tracking



Averaging

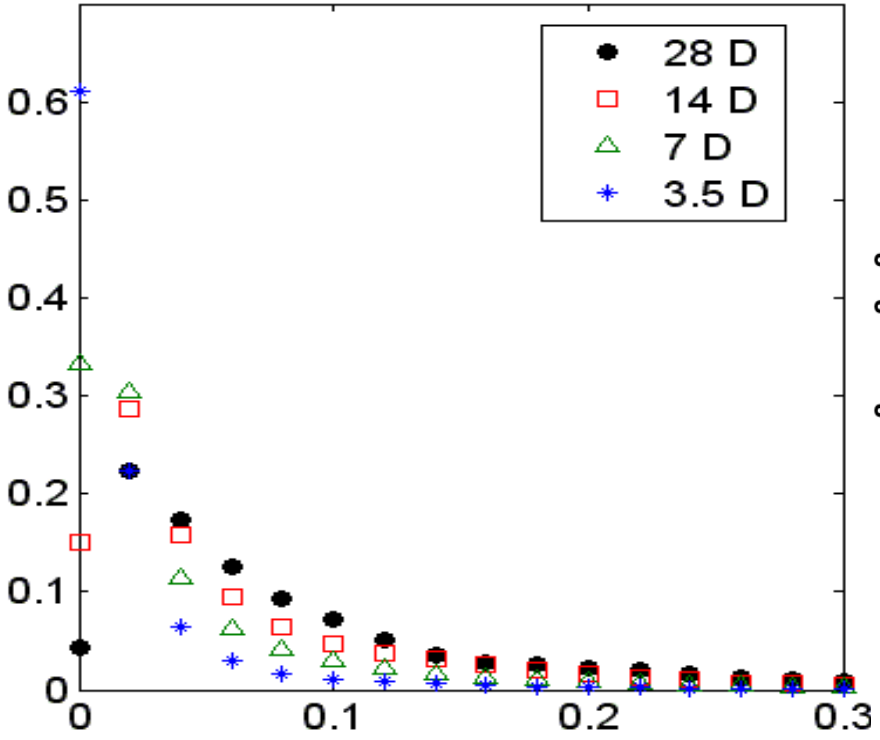


Analysis

Gas Flow

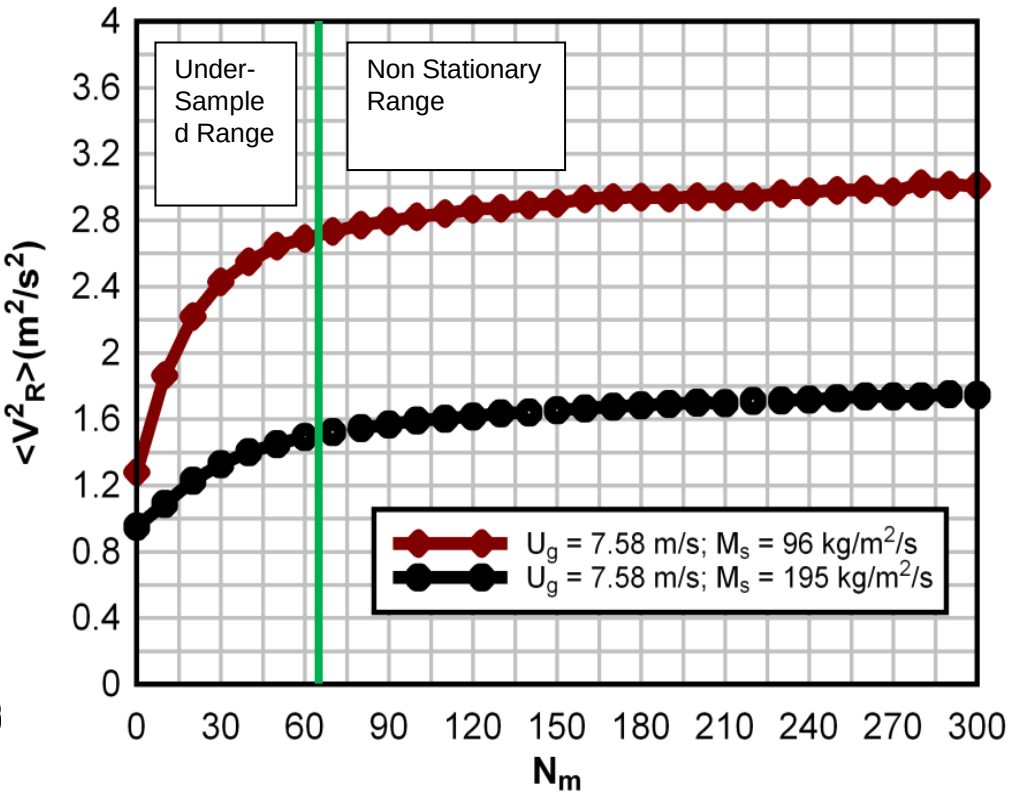
Effect of Sample Area on Calculated GT

PDF of GT at the wall



U_g = 7.58 m/s; M_s = 96 kg/m^2/s;
D is the Particle Diameter

Centre of the NETL 12" riser



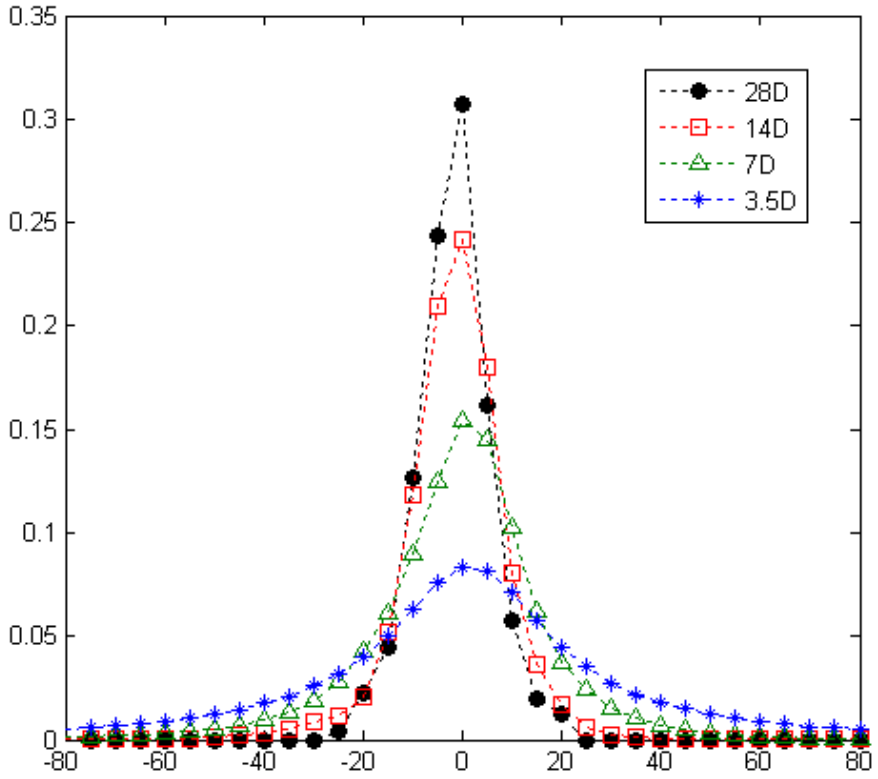
Gopalan & Shaffer 2012

Increasing the sample area increases the magnitude of the granular temperature

Effect of Sample area on Shear and Strain rate distribution

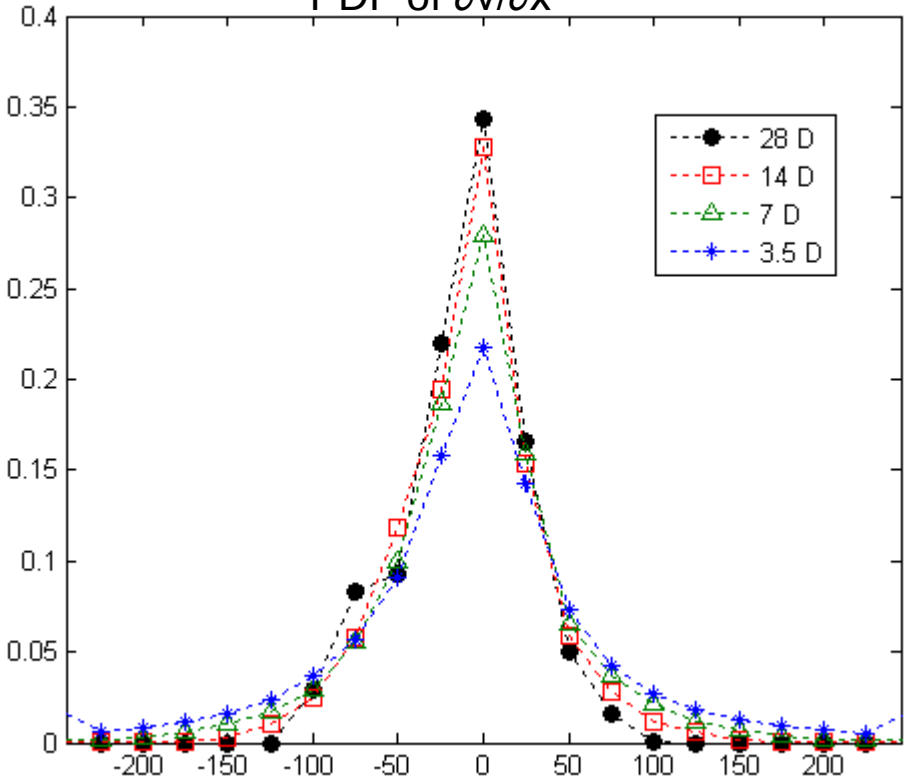
U_g = 7.58 m/s; M_s = 96 kg/m²/s; Location at the wall

PDF of ∂u/∂x



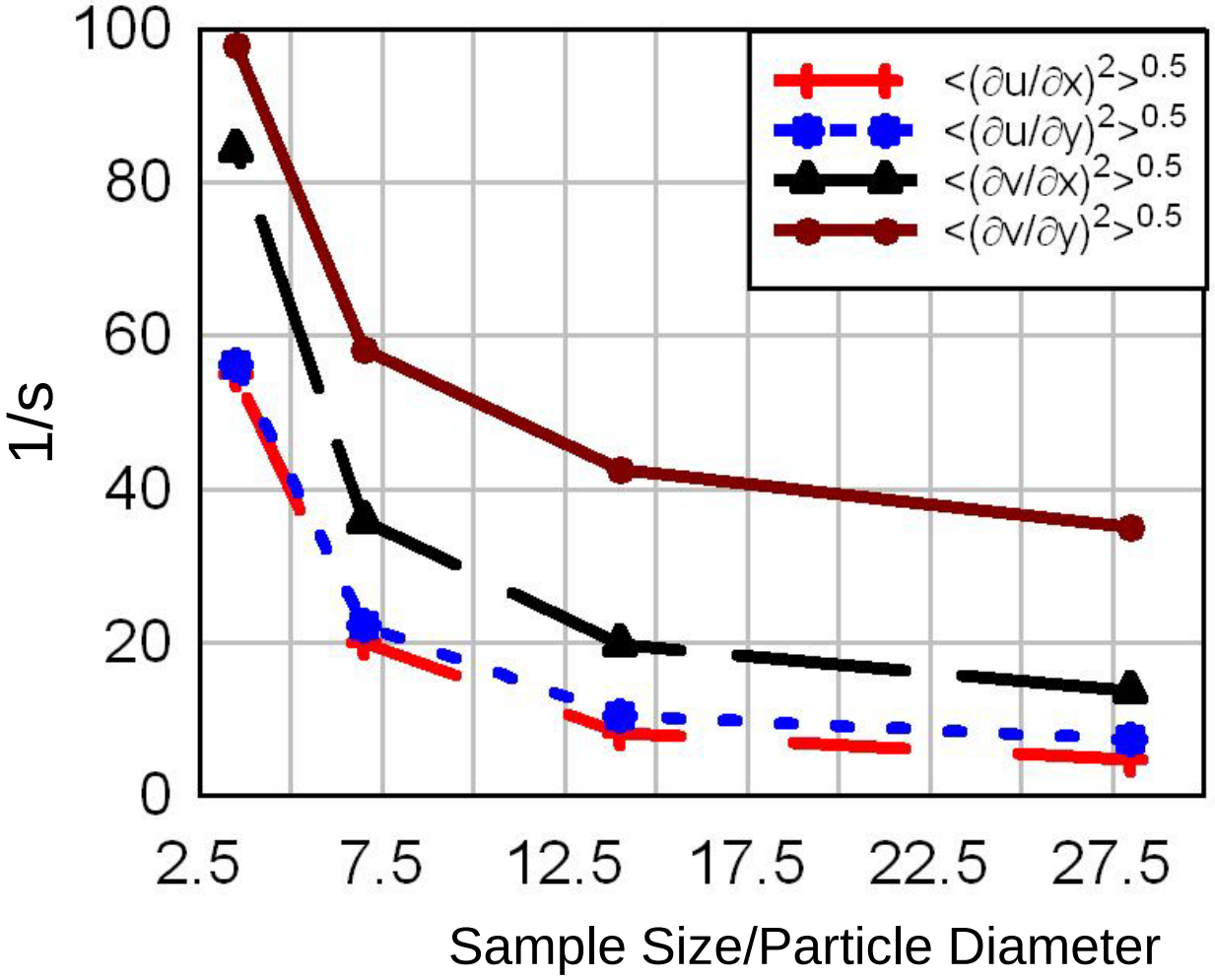
1/s

PDF of ∂v/∂x



1/s

Effect of Sample area on Shear and Strain rate magnitude



Increasing the sample area decreases the magnitude of the shear and strain rate **(opposite to granular temperature)**

Comparison of HsPIV with MFIX Simulations

U_g = 7.58 m/s; M_s = 96 kg/m^2/s; Location at the wall

Mean Strain rate	Exp_Wall (~2-3D)	Exp_Wall (~10 D FOV)	Exp_Wall (~20 D FOV)	Sim_Wall (20D FOV)
$\left\|\frac{\partial u}{\partial x}\right\|$	32	6.9	4.4	5.3
$\left\|\frac{\partial u}{\partial y}\right\|$	17	4.9	3.3	2.0
$\left\|\frac{\partial v}{\partial x}\right\|$	59	27.8	19.2	39
$\left\|\frac{\partial v}{\partial y}\right\|$	25	13.1	10.3	9.6

MFIX simulation
- Particle diameter: 802 µm
- Solid density: 863 kg/m^3
- Superficial gas velocity: 7.58 m/s
- Solid circulation rate: 7.03 kg/s
- Grid size: 1.6 cm
- Restitution coefficient: 0.8
- Gas-solid drag: Gidaspow
- Numerical scheme: superbee
- Simulation time: 60 s
- Sample frequency: 10 KHz
- Cut-cell

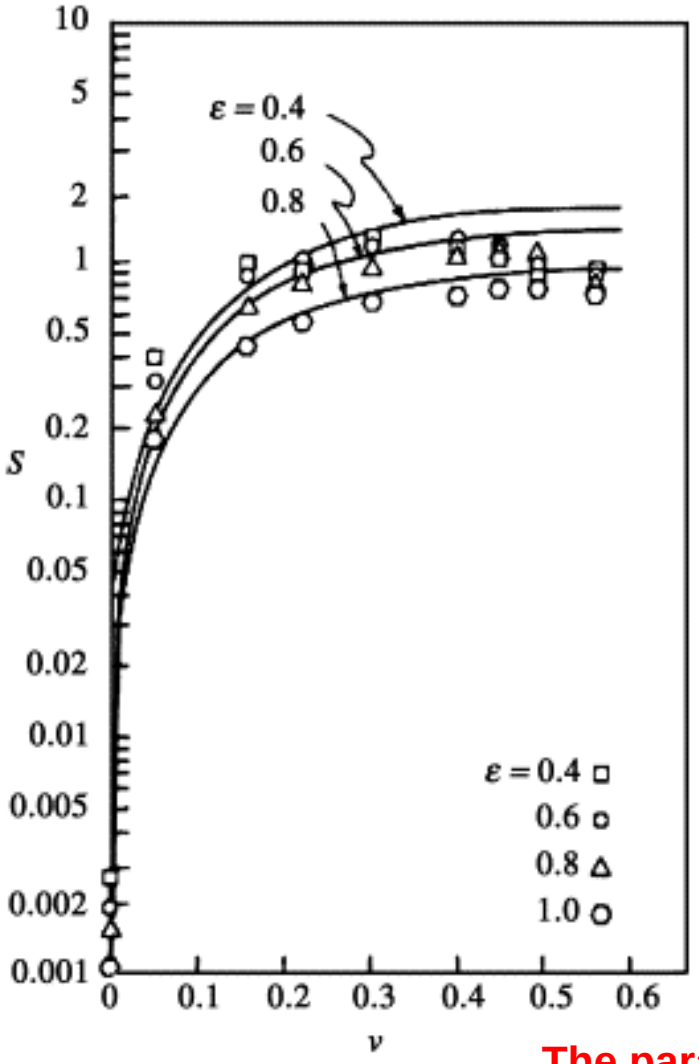
By T Li, M Shahnam at NETL

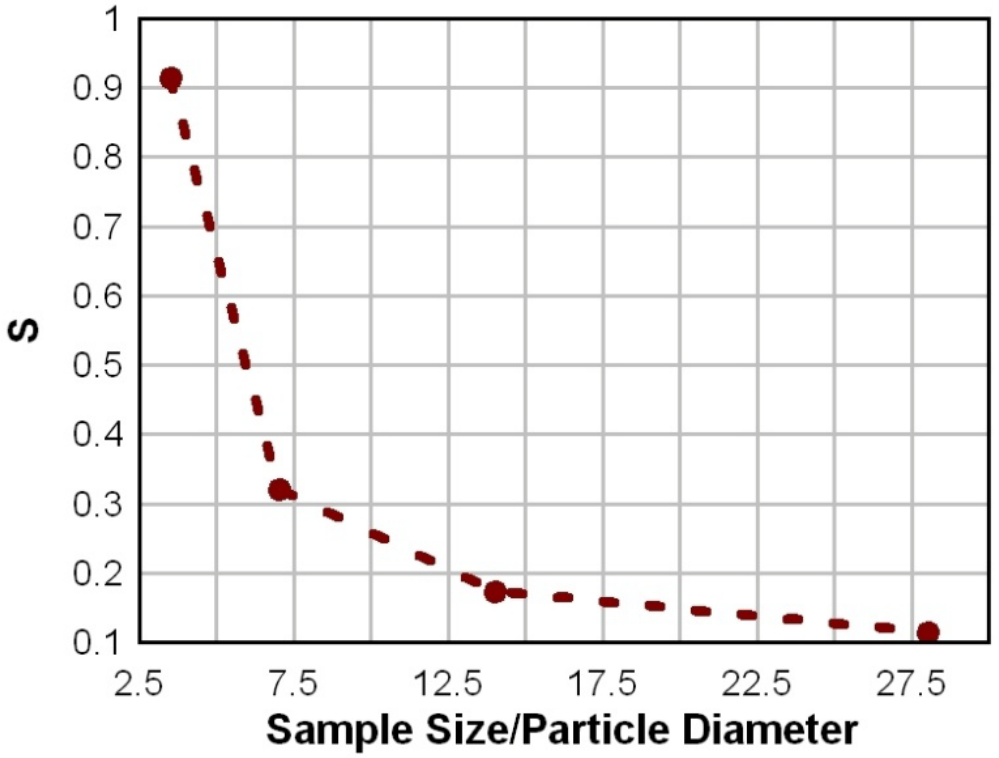
- Preliminary comparisons with the small sample area **showed an order of magnitude difference** between measured shear and strain rates of the MFIX and HsPIV data

- An **appropriate sample area comparison** shows a much better match

Scaling of Shear Rate

Savage and Jeffrey (1981), Lun et al., (1984), Campbell (1989)





$S = d\gamma/GT^{0.5}$

where γ is the shear rate
d is the particle size

The parameter 'S' increases with decreasing on sample area

Conclusions

- **HSPIV measures particle velocity at very high sample rates. This enables calculation of higher order statistics**
- **Large FOV mapping allows us to study the effect of the sample area on calculated results**
- **Comparisons between measurements and simulation should account for the effect of sample areas**
- **Accurate HSPIV data are currently available for comparison with simulations**

R. Cocco, F. Shaffer, R. Hays, S.B.R. Karri, T.M. Knowlton, “Particle clusters in fluidized beds,” Powder Technology, 203 (2010), pp. 3–11

B. Gopalan and F. Shaffer, “A new method for decomposition of high speed particle image velocimetry data,” Powder Technology, Volume 220, April 2012, Pages 164–171.

B. Gopalan and F. Shaffer, “Higher Order Statistical Analysis of Eulerian Particle Velocity Data in CFB Risers as Measured with High Speed Particle Imaging,” Submitted to Powder Technology (2012).

Shaffer et al., “High Speed Imaging of Particle Flow Fields in CFB Risers,” Submitted to Powder Technology (2012)