A new method for decomposition of high speed particle image velocimetry data

Balaji Gopalan*, Franklin Shaffer

U.S.D.O.E National Energy Technology Laboratory, Office of Research and Development, Computational Science Division, United States

Abstract

A high speed particle image velocimetry (high speed PIV) system developed by the National Energy Technology Laboratory (NETL) is being applied to measure individual particle motion in flow fields of high particle concentration. Particle flow fields were measured in two risers of circulating fluidized bed (CFB) systems, one riser of 0.203 m (8 in.) diameter with 80 μm mean diameter FCC particles flowing at velocities up to 30 m/s and one riser of 0.305 m (12 in.) diameter with 800 μm mean diameter HDPE particles at velocities up to 15 m/s. Particle concentrations ranged from zero to maximum packing in particle clusters. In these risers the high speed PIV system achieves sustained data rates of 0.1 to 1.0 million velocity vectors per second. This produces time series data for particle velocity that measures the full temporal range of velocity fluctuations. For comparison with CFD models that decompose particle velocity into a mean and a random fluctuating component of particle velocity in a manner similar to Reynolds Decomposition of single phase flows, the particle velocity data must be decomposed into a non-stationary mean component and a random component. The standard Reynolds decomposition method, which utilizes ensemble averaging, is inadequate for this application because particle velocity is under-sampled when particle concentration is low. We present a local window averaging method that decomposes the particle velocity time series even when particle velocity is being under-sampled due to periods of low particle concentration. This method decomposes particle velocity accurately and without loss of high frequency components of the velocity signal. Implementation of this method has led to the first measurements of the random component of particle velocity (and parameters derived from it, such as granular temperature) in a CFB riser that detects the entire temporal range of the particle velocity time series.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

An understanding of the factors governing the high concentration particle flows is needed for several applications, such as mineral and oil extraction and other chemical processing applications. Modeling of these processes poses an enormous computational challenge due to the complexities of the flow system. Hence, experimental data of high concentration particle flows at high spatial and temporal resolution is needed both for the advancement of the models being developed and for verification of existing models. The current unavailability of these experimental data has been a significant factor in the lack of accurate models for dense particulate flows as compared to single phase flows [6].

Over the last few decades, particle image velocimetry (PIV) systems using small tracer particles to measure single phase flows have matured to the point that they are available commercially from several companies. The new experimental data produced by PIV has led to advances in modeling of single phase turbulent flows [1]. For comparison with CFD models, velocity data produced by PIV of single phase flows is often decomposed into a mean and a fluctuating component [14]. In a flow with a stationary mean, such as turbulent flow in a pipe with a steady mean velocity, the mean velocity is calculated by an ensemble average of velocity data taken over a long period of time [17]. If the mean is non-stationary, for example on the downstream side of a cylinder in cross flow where vortex shedding occurs or with oceanic waves, then further modifications of the decomposition method must be made to separate the frequency components of the non-stationary mean from the fluctuating component of velocity.

Similar decomposition methods are employed in the modeling of particle flow fields of high particle concentration [18,22,13,4]. Many experimental techniques to measure particle flow fields are unable to measure several instantaneous individual particle velocities [3,7,16], and therefore the random component of velocity is not accurately measured. If a flow is non-stationary, such as the dense particle flow in a circulating fluidized bed riser, individual particle velocities must be measured with sample rates high enough for full resolution of temporal and spatial variations before a velocity decomposition can be executed. Such experimental data has been previously unavailable for particle flows of high particle concentration. Decomposition of a non-stationary, non periodic, unsteady flow is difficult or impossible if the frequency range of the unsteady mean overlaps the frequency range of the random component.

* Corresponding author.
E-mail address: gopalanb@netl.doe.gov (B. Gopalan).

0032-5910/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.powtec.2011.09.001

In particle flow fields, a random relative motion between particles is generated by particle collisions, particle-wall collisions, and gas turbulence. In many CFD models of high concentration particle flow fields, the random components of velocity are very important because they not only generate particle stresses, but other important “state” properties such as particle “temperature” (often called granular temperature). Owing to the inability to measure individual particle velocities or to inadequate sample rates, many measurement techniques calculate a random component of velocity, and parameters derived from it, as fluctuations in mean particle velocity [7,16]; however, fluctuations in the mean component of a flow field are, by definition, not granular temperature [9,10,23]. Granular temperature is derived from the relative motion between particles flowing at a mean velocity. For example, high speed videos [20] have shown that a large fraction of particles in a high concentration particle flow field move en masse in large clusters. In such clusters, there is little or no relative motion between particles. Because relative motion goes to zero in large packed clusters, granular temperature, by definition, goes to zero inside large packed clusters. Therefore the velocity of particles inside clusters must not be included in a calculation of the fluctuating component of velocity. To properly measure the random component of velocity, and to properly calculate parameters like granular temperature from it, a decomposition method is needed that separates an unsteady mean from the random component of velocity. Our goal is to determine the optimum method to decompose the measured individual particle velocity into a non-stationary mean velocity, which is an Eulerian field property, and a random component of velocity.

The high speed particle imaging velocimetry (high speed PIV) system developed by the NETL [21,20,2] is producing the first measurements of individual particle velocity with sample rates high enough (in the range of 0.1–1 million velocity vectors per second) to resolve the full range of temporal scales in gas-particle flows encountered in many fossil energy conversion processes, such as the risers of circulating fluidized beds. The high speed PIV system measures the trajectories of individual particles, velocity along each particle trajectory, and relative particle concentration for millions of particles in a thin two-dimensional field-of-view. To achieve a point measurement, the size of the measurement volume (or the camera field-of-view) is chosen to be small enough that gradients in the time averaged flow are negligible over the field-of-view. However, the field-of-view is chosen to be large enough to detect numerous particles in each camera frame, and to resolve short lengths of particle trajectories. Detecting numerous particles in each camera frame leads to very high sample rates for particle velocity. The size of the two-dimensional measurement window is close to the size of the smallest grid cells used in CFD models of particle flow fields, and the same hydrodynamic data predicted by CFD models is measured. Hence the data generated from high speed PIV is ideal for CFD model validation and development.

In this paper we examine the high speed PIV data recorded in the riser flows at the National Energy Technology Laboratory (NETL) and Particle Solid Research Inc. (PSRI), Chicago, where the mean particle velocity is unsteady because of natural variations in CFB units and the nature of a riser flow. In the NETL riser with high density polyethylene (HDPE) particles of 800 μm mean diameter, we have measured frequencies above 500 Hz for the mean velocity, and in the PSRI riser with 80 μm particles we have measured frequencies above 5000 Hz [20]. Viewing high speed videos of riser flow behavior shows that the fluctuations in mean velocity are caused by several factors, including unsteady high speed gas jets, large packed clusters (often with length scales of thousands of particle diameters), and variations in the solids circulation rate of the CFB itself.

Because the concentration of particles is not controlled and can at times approach zero, decomposing the particle velocity time series measured with high speed PIV is significantly more complicated than the Reynolds Decomposition method for single phase flows where particle concentration is controlled. In the measurement of single phase flows with conventional PIV, the minimum concentration of particles in the PIV measurement volume can be controlled to achieve adequate sample rates, but in particle flow fields, concentration can vary independently from zero to a maximum packing limit. In many particle flow fields, particle concentration is often low enough to cause inadequate sample rates for particle velocity. A decomposition method is needed that detects and compensates for such periods of under-sampling. The decomposition method must detect both the mean and random components of particle velocity without losing high frequency components of the velocity signal during periods of low particle concentration. This paper presents a decomposition method that overcomes the under-sampling problem. Results are presented showing decomposed mean and random components as well as other important modeling parameters derived from the velocity data. To the best of our knowledge, the results we show are the first accurate measurements of the random component of particle velocity and of derived parameters, such as granular temperature, inside large scale CFB riser flows.

2. Experimental

2.1. Facility description

The experiments were performed in a 0.305 m (12 in.) circulating fluidized bed (CFB) riser at NETL, Morgantown, and a 0.203 m (8 in.) CFB riser at PSRI, Chicago. The NETL riser was charged with 800 μm High Density Poly Ethylene (HDPE) particles, while the PSRI riser was charged with 80 μm FCC particles. The fluidizing medium in both these facilities was air, and measurements were taken at superficial gas velocities that produce either a “core-annulus” or a “dense up-flow” regime. In this paper we consider the flow in the CFB regime as “core annulus” if the particles near the wall, the “annulus layer,” have a higher concentration and much lower velocity than a “core” flow upward in the center of the riser. A “dense up-flow” is when the bulk particle flow is upward at all radial locations. The flow conditions in both these facilities have been characterized using in-house measurement and control techniques, details of which are available [11,19,12]. Additional details about these facilities are available in previous literature [11,19]. The measured properties of the riser flow in the NETL and PSRI risers are available in Table 1, and the properties of the particles are available in Table 2. The high speed PIV measurements were recorded at 9.75 m (32 riser diameters) above the gas distributor at the NETL riser and 20 m (98 riser diameters) above the distributor for the PSRI riser.

2.2. Measurements with the NETL high speed PIV system

A high speed borescopic PIV system [20] developed by the NETL was utilized to acquire the data presented in this paper. The high speed PIV system uses a Vision Research v12.1 high speed camera with a pixel resolution of 1280 x 800 pixels and 12 bit gray scale resolution. At this resolution, 6300 frames per second can be continuously recorded. The data transfer rate from the image sensor to the internal memory of the v12.1 camera is fixed, so if the sensor is sampled at a lower resolution, the frame rate can be increased proportionally. The NETL’s version of the v12.1 can record at up to 500,000 frames/s, making it one of the fastest high speed video cameras available at the time the data in this paper was acquired. The camera frame rate was set high enough to detect the highest particle velocities occurring in each riser. For the NETL riser data presented in this paper, the frame rate of the v12.1 was in the range of 5000 to 15,000 frames/s, and the exposure time was 2–6 μs. For the PSRI riser, frame rates were in the range of 2000 to 50,000 frames/s with exposure times of 2–10 μs. These frame rates provided resolution of...
the complete temporal range of the particle velocity signal and adequate spatial resolution for low measurement uncertainty (high measurement accuracy). With a custom borescope developed by NETL and Gradient Lens Corporation for high speed PIV, high speed PIV measurements were taken at several radial locations inside the riser. The total sample period of a high speed PIV measurement is limited by the 32 GBytes of internal memory of the v12.1 high speed camera. Under the conditions of this study, the total sample period of continuous data acquisition ranged from 5 to 15 s, over which 50,000 to 200,000 camera frames were recorded. The length of the sampling period limits detection of frequencies lower than about 0.1 Hz. However, at the particle and gas velocities of this study, it is likely that frequencies less than about 0.1 Hz are characteristic of the entire CFB system rather than the particle flow field. The time averaged properties of the gas and particle flow rates in the CFBs studied are estimated by averaging data from pressure drops and spiral vane particle volume flowmeters over a period of 5 min. It is well known that CFBs do not stay at a constant total gas and particle flow rate, but have inherent instabilities in total gas and particle flow rate. Hence, we consider frequencies less than about 0.1 Hz in the particle velocity time series to be characteristic of the entire CFB, not characteristic of the particle flow field in the riser. The details of the parameters of the high speed PIV system used for each riser and flow condition are available in Table 2.

Fig. 1 shows examples of measurements of particle trajectory, velocity, and number concentration in the NETL riser. The measurement volume, which is the volume in which particles are detected, is simply the camera field-of-view multiplied by the camera depth-of-field. The camera optics and aperture are adjusted to produce a thin depth-of-field that is about 0.5 mm thick. The size of the field-of-view is set to be small enough to be a point measurement. By a "point measurement" we mean that there are no significant gradients in time-averaged flow parameters across the measurement volume. Yet to automatically recognize particle trajectories and to better understand the flow behavior, the measurement area must also be large enough to see the motion of particles along their trajectories. To ensure that there are not significant gradients in time-averaged parameters over the measurement volume, the analysis of particle velocity and concentration is repeated with the measurement volume divided into a number of smaller sub-regions.

### Table 1
The measured (a) test conditions and (b) properties of granular material.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Measurement facility</th>
<th>Measurement information dataset</th>
<th>Superficial gas velocity ($U_g$) (m/s)</th>
<th>Solids flux ($M_s$) (kg/m²s)</th>
<th>Flow regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td>12 in. NETL Riser</td>
<td>7 radial locations</td>
<td>7.58</td>
<td>96</td>
<td>Core-Annulus</td>
</tr>
<tr>
<td>Condition 2</td>
<td>12 in. NETL Riser</td>
<td>7 radial locations</td>
<td>7.58</td>
<td>195</td>
<td>Core-Annulus</td>
</tr>
<tr>
<td>Condition 3</td>
<td>8 in. PSRI Riser</td>
<td>6 radial locations</td>
<td>18.3</td>
<td>49</td>
<td>Dense Up-flow</td>
</tr>
<tr>
<td>Condition 4</td>
<td>8 in. PSRI Riser</td>
<td>6 radial locations</td>
<td>18.3</td>
<td>390</td>
<td>Dense Up-flow</td>
</tr>
</tbody>
</table>

### Table 2
Experimental parameters for the High speed PIV measurement at the NETL and PSRI riser.

<table>
<thead>
<tr>
<th>Measurement information</th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
<th>Condition 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera resolution</td>
<td>256 x 600</td>
<td>384 x 640</td>
<td>384 x 512</td>
<td>64 x 400</td>
</tr>
<tr>
<td>Field of view</td>
<td>1.74 x 4.08 mm²</td>
<td>3.37 x 6.28 mm²</td>
<td>2.87 x 3.55 mm²</td>
<td>1.7 x 10.6 mm²</td>
</tr>
<tr>
<td>Frame rate</td>
<td>15,000</td>
<td>5000</td>
<td>21,000</td>
<td>5000</td>
</tr>
<tr>
<td>Number of frames</td>
<td>120,000</td>
<td>90,000</td>
<td>115,000</td>
<td>90,000</td>
</tr>
</tbody>
</table>

used to calculate particle velocity. The standard root sum-of-squares method of combining uncertainties to estimate a total uncertainty is applied here. Velocity is calculated by measuring the distance a particle travels between camera frames, or

\[ V = \frac{S_2 - S_1}{n \cdot \Delta T} \]

where \( S_2 \) and \( S_1 \) are the particle centroid locations as the particle travels between a certain number (\( n \)) of camera frames camera frames and \( \Delta T \) is the time between camera frames.

The uncertainty in \( S_2 \) and \( S_1 \) arises from measurement uncertainties of several individual primary measurements, including the pixel resolution of the image sensor, the uncertainty of the rule used to calibrate the field-of-view size, the finite depth-of-field, and the image processing algorithm used to calculate the geometric center (centroid) of a particle image. The uncertainty in \( \Delta T \) is a characteristic of the internal clock of the high speed camera. The image processing routine used in this study can detect the centroid of the particle image with a measurement uncertainty of 0.5 pixels (using the public domain NIH Image program developed at the U.S. National Institutes of Health and available at http://rsb.info.nih.gov/nih-image/). Particle velocities are calculated over at least five camera frames (\( n \geq 5 \)), and typical particle displacements over which particle velocity is calculated are at least 100 pixels. This gives a measurement uncertainty caused by finite pixel resolution (\( U_{\text{centroid}}(fi) \)) of about 0.5%. The measurement uncertainty due to calibration of the field-of-view is simply the resolution of the rule used to calibrate the field-of-view. In this study a microscope calibration slide was used to calibrate the field-of-view. The calibration of the field-of-view (\( U_{\text{calibration}}(fi) \)) has an uncertainty on the order of 0.1%.

Another uncertainty in displacement also arises from the depth-of-field effect of the optical imaging system. Particles are “in-focus” over a certain range of object distance from the camera lens, and this distance is called the depth-of-focus. This causes an uncertainty in the object distance and hence an uncertainty in the magnification of the camera system. The custom borescope used in this study was designed to have a very thin depth-of-field, on the order of 0.5 mm under the imaging conditions used in this study. Image processing algorithms, such as Fast Fourier Transform (FFT) filters are applied to ensure detection of only in-focus particles. The magnification of an imaging system is defined as the ratio of the image distance (distance from the optical center of the imaging lens system to the image sensor) to the object distance (distance of particles from the optical center of the imaging lenses of the borescope). The object distance for the custom borescope is about 10 mm. This produces a measurement uncertainty due to depth-of-field (\( U_{\text{depth-of-field}}(fi) \)) of about 5%. The uncertainty in the time between camera frames is very low, on the order of 20 ns. Since particle velocity is calculated over at least five camera frames, or a total period of at least 20 \( \mu \)s, the uncertainty in time period (\( U_{\text{tr}}(fi) \)) is very low, less than 0.01%.

The well known root sum-of-squares method of combining individual measurement uncertainties of an instrument to estimate total measurement uncertainty is applied here. The resulting equation is

\[ U_{\text{total}} = \sqrt{U_{\text{centroid}}^2 + U_{\text{calibration}}^2 + U_{\text{depth-of-field}}^2 + U_{\text{tr}}^2} \]

\[ U_{\text{total}} = \sqrt{0.5^2 + 0.1^2 + 5^2 + 0.01^2} \]

\[ U_{\text{total}} = 5.025\% \]

This shows that the measurement uncertainty is about \( \pm 5\% \) and is mainly caused by the uncertainty in magnification caused by the finite depth-of-field.

### 3. Discussion on particle velocity decomposition

#### 3.1. Decomposition of particle velocity

We start with the standard assumption of the Reynolds Decomposition method that the particle velocity (\( v_i \)) can be represented by the sum of a mean and a random component. It is assumed that a mean velocity exists for particles present within a small measurement volume. Further, it is also assumed that the mean velocity, even though being a non-stationary variable, changes more slowly (is of lower frequency) than the random component of particle velocity, and therefore is fixed over a small period of time [22,15,5]. Hence, within a small volume, we can have a multitude of particles whose average velocity is the Eulerian particle velocity for that volume. It should be noted that the Eulerian particle velocity is common for all particles in that volume/region, while each particle has an additional random component of velocity.

There are several approaches to calculating an Eulerian mean particle velocity for a time series. The mean velocity can be calculated by taking an overall average over the entire time series of data ([8,16], etc.) or it can be calculated for each camera frame [23]. The average velocity for a single camera frame, or the frame averaged velocity (\( \bar{v}_F \)), is calculated by averaging all particle velocities within a camera frame (\( N_p \)),

\[ \bar{v}_F = \frac{\sum_{i=1}^{N_p} v_i}{N_p} \]

Our high speed PIV data shows that there are two drawbacks to this technique that can lead to erroneous values of both the mean and random components of velocity. This will be demonstrated in detail later in this paper. The first is that particle concentration is at times low enough, e.g., only one or two particles in a camera frame, that there are not enough velocity measurements in a single frame to yield the correct mean velocity for each camera frame. The second drawback is that size of the field of view is determined by considerations such as particle size and flow velocity. Hence the number of detected particles in a frame, and in turn the calculated parameters such as mean velocity, granular temperature, etc., can vary with particle sizes and flow speeds, making it inaccurate for comparing kinematic properties of different kinds of particles. One way to address the low particle concentration, when the time resolved data is available, would be to apply a low pass filter to the calculated frame averaged velocity. When we used this approach, the frequency spectrum of the frame averaged velocity (not shown in this paper) had multiple harmonic peaks due to the finite value of the low pass filter. Further, applying a fixed size low pass filter produces a different converged mean for higher concentration regions than in lower concentration regions due to the presence of more particles. The current method does not produce artificial frequencies and is not biased by concentration.

In order to overcome these drawbacks, we propose a modified decomposition method for calculating mean and random components of particle velocity that uses a local averaging window around each camera frame. The method consists of the following steps:

1. For a given camera frame, which we call the base frame, the number of velocity vectors (\( N_p \)) in a frame (\( k \)) is calculated.
2. If the number of velocity vectors in the base frame is less than the minimum number of velocity vectors required (\( N_{\text{min}} \) to be defined below) to yield an accurate mean velocity, a local averaging window is created that spans an equal number of frames before and after the base frame.
3. The span of the local averaging window (\( 2N_j + 1 \)), where \( N_j \) is the number of frames in the local averaging window, is increased about the base frame until the total number of...
velocity vectors \((N_f)\) in the extended local averaging window is large enough to yield an accurate mean velocity for the base frame. In other words, the number of velocity vectors in the local averaging window is equal to or greater than \(N_m\):

\[
N_f = \frac{k_f N_f}{k_f - N_f} N_p \geq N_m
\]  
(1)

(4) The local mean particle velocity, \(\bar{v}_{LM}\), is calculated by averaging the velocity of all the particles present in the extended local averaging window,

\[
\bar{v}_{LM} = \frac{1}{N_f} \sum_{k = k_f - N_f}^{k_f} \bar{v}_i N_p
\]  
(2)

Subsequently, this local mean velocity can be subtracted from each individual particle velocity in the base frame to obtain the random component of the individual particle velocity for the base frame, \(v_{RI}\).

\[
v_{RI} = v_i - \bar{v}_{LM}
\]  
(3)

Before proceeding to explain how the specific value of \(N_m\) is calculated, we would like to elaborate the reason for choosing a single value for \(N_m\) rather than calculating a specific value of \(N_m\) for each frame using individual frame based criteria. The primary reason for using the extended local averaging window, rather than single frame averaging, is the lack of sufficient particles in the low concentration region to provide us a local mean velocity. Hence, as we expand the extended window around the base frame, we can look at the convergence of local mean velocity, i.e., \(dv_{LM}/dN_m\) reaches zero, to obtain the optimum size. However, the problem is that the local mean velocity is a user-defined quantity rather than a property of the flow. High speed images clearly show discontinuities in concentration and local mean velocity for individual frames, i.e., one section of the frame has particles moving at a different speed and having a different concentration when compared to another. This behavior exists even when the size of the field of view is of the order of the particle size. Hence calculating a specific value of \(N_m\) for every frame might introduce complications due to these discontinuities.

However, we find that the variation of the local mean velocity and other statistics with varying \(N_m\) becomes very small after \(N_m\) exceeds certain low values (which we call the under-sampled range, discussed in the next section). The local mean velocities vary by 0.2–3% for all our data, even when the size of the extended local averaging increases by 50% once we avoid this under-sampled range. Hence whether we choose the single \(N_m\) value or pick a frame based \(N_m\) the effect on calculated parameters is negligible. This reflects the high accuracy of the measured data, which has a multitude of tracked particles in most frames.

4. Selection of minimum number of velocity vectors

The next step is to establish a method of determining a specific value of \(N_m\) required in the local averaging window to yield an accurate value of the local mean velocity. The method should be easy to implement and suitable for a wide range of flow conditions (i.e., particle types, velocities, concentrations, etc.). We have examined the sensitivity of \(N_m\) to calculated flow parameters such as overall mean of local mean velocity and the RMS of the local mean velocity. However, we found that dependence of \(N_m\) on these quantities is small and hence we cannot use these bulk averaged quantities to determine the optimum value of \(N_m\). To determine a specific value of \(N_m\), a parameter is needed that is sensitive to the window size used to calculate the local mean velocity. The following steps explain the calculation of such a parameter.

1. First we assume a fixed value of \(N_m\) and calculate \(\bar{v}_{LM}\) using Eqs. (1) and (2).
2. We then subtract the local mean velocity for the extended window from each individual particle velocity in the base frame and then calculate the mean square value of the subtracted portion.
3. Then the geometric average of the horizontal and vertical components of this temporary mean square velocity is calculated. This is done so that the calculated parameter has a structure close to the kinetic energy.
4. This process is repeated for all frames in the time series \((N_m)\), and an overall average is calculated. We call this parameter the “mean square of the high frequency component of the particle velocity” or \(<v^2_k>\).

\[
<v^2_k> = 0.5 N_m \sum_{i=1}^{N_m} \left( \left( \frac{1}{N_p} \sum_{i=1}^{N_p} (v_i - \bar{v}_{LM})^2 \right)_{Hor} + \left( \frac{1}{N_p} \sum_{i=1}^{N_p} (v_i - \bar{v}_{LM})^2 \right)_{Ver} \right)
\]  
(4)

5. This process is repeated for a range of \(N_m\) (0–300), leading to the generation of Figs. 2 and 3 showing the variation of \(<v^2_k>\) with \(N_m\).

The results are shown for both dense up-flow regime (PSRI riser) and core annulus regime (NETL riser), for both the central and the wall locations in Figs. 2 and 3. When \(N_m\) is increased, thereby increasing the size of the local averaging window, \(<v^2_k>\) increases first at a steep slope, due to the reduction of under-sampling caused by very few particles in the extended window. We call this region the “under-sampled range.” Then the slope decreases after \(N_m\) exceeds a sufficiently large value, preventing the under-sampling problem. In this “non-stationary range” the increase in \(<v^2_k>\) is due to the changing local mean velocity due to non-stationary flow. The slope of \(<v^2_k>\) vs \(N_m\) is higher in the under-sampled range than in the unsteady range because changes in \(\bar{v}_{LM}\) occur much slower over the time frame of the local averaging window. Since the under-sampled and non-stationary range occur in different ranges of \(N_m\), we can properly choose a specific value of \(N_m\) that is large enough so that it has adequate sampling of particle velocities and small enough so that it is unaffected by the slow variation of the local mean velocity.

For the purpose of detecting a specific value of \(N_m\) in a quantitative manner, in order to eliminate the need for a subjective choice, we use a first order polynomial to provide a good fit for the non-stationary range data. The intersection of this linear fit with \(N_m = 0\) can be
considered to represent the flow field without the random component of velocity. Hence, we suggest using the specific value of $N_m$ such that the calculated value of $\langle v^2 \rangle$ matches the intercept. This technique is illustrated in Fig. 3. The specific value of $N_m$ could be obtained by several other techniques, e.g., where the linear fit deviates from the curve, but we found that the values obtained in this manner are close and do not affect the results. Fig. 4 shows that this decomposition method appears to accurately separate/decompose the low frequency mean from the random component.

5. Comparison with prior techniques

To show the value of this new decomposition method, we compare the results it produces with the results produced by previous methods. Previous methods decompose the particle velocity by subtracting the individual particle velocity from

(i) the overall or ensemble mean particle velocity (referred to as the Total Average Method)
(ii) the frame averaged velocity (referred to as the Frame Average Method) and
(iii) the local mean velocity (referred to as the Local Averaging Window Method) following Eq. (3).

Calculation of an important modeling parameter called granular temperature provides a relevant way to compare the methods. In the calculation of granular temperature for a riser flow field, the contribution of the component of particle velocity that is normal to the field-of-view of the camera is assumed to be equal to the horizontal component of particle velocity. At the riser wall the out-of-plane component goes to zero. Details of these assumptions and subsequent calculations to obtain the granular temperature are well known [23].

Figs. 5a, b and 6a, b show the comparison of the calculated values of the granular temperature by these three different decomposition methods as a function of relative particle concentration. The relative particle concentration is calculated by normalizing the total number of detected particles in each frame by the maximum number of particles in a frame in the entire time series. Further, the relative particle concentration is averaged over neighboring frames to remove high frequency fluctuations caused by limited particles in a frame. We present these results in terms of relative particle concentration instead of absolute particle concentration because calculation of absolute particle concentration requires an estimate of the depth-of-field. The nature of the results using relative particle concentration is the same as if absolute particle concentration or void fraction were used.

The values of granular temperature show that using the Total Average Method leads to large over predictions of granular temperature. This is especially true near the wall where the Total Average Method predicts a large value of granular temperature for the region where the particles are known to be at relatively low granular temperatures. Hence, subtracting a local mean can prevent the non-stationary mean component of particle velocity from being introduced into the calculation of granular temperature. If we compare the current method with the Frame Average Method, we see that the magnitude of granular temperature is enhanced for the Local Averaging Window method for low relative particle concentrations in all cases. This is because with the Frame Average Method portions of the random velocity component are treated as local mean velocity, particularly in the low concentration regime, due to the small number of particles. Finally, we can see that for high concentration regions the two techniques converge, indicating that they are compatible with each other.

One of the advantages of the Local Averaging Window method over the Frame Average Method, assuming there should be at least four particles in a frame for frame averaged velocity to be calculated [23], is that it enables us to obtain time series of data. For example, in Fig. 7 we can clearly see that for the central region of the NETL...
riser data, at low flux conditions, the Frame Average Method loses most of the time series information of the average velocity due to the sporadic distribution (Fig. 7c), while the Local Averaging Window method produces almost continuous local mean velocity data (Fig. 7d). This enables us to calculate temporal statistics like autocorrelation and Fourier Transforms which will be analyzed in future works.

The comparison of methods can be enhanced by reducing the field-of-view size so that more periods of low particle concentration occur. Table 3 shows that the Local Averaging Window method is also more robust when the size of the field-of-view is reduced. Granular temperature was recalculated using a fraction of the field-of-view. When the size of the field of view is reduced by 50–67%, the granular temperature calculated by the Frame Average Method decreases by 12–20%, whereas the current method sees a change of 1–2%. The 1–2% change is within measurement uncertainty.

6. Conclusion

A high speed PIV system has been utilized to visualize and measure particle flow fields in two different CFB risers (12 in. NETL riser and an 8 in. PSRI riser). Using a custom borescope designed for high speed PIV in high concentration particle flows, measurements have been made at all radial locations in the interior of the riser. Measurements were made with two different types of particles of size 80 and 800 μm under industrially relevant flow conditions. The NETL high speed PIV system achieves sustained sample rates in the range of 0.1 to 1 million samples per second, orders of magnitude higher than previous measurements. With such high sample rates, the full range of temporal scales of particle flow fields can be resolved for flow fields up to 100 m/s.

A Local Averaging Window method to decompose the individual particle velocity into a mean and random component has been introduced. The new decomposition method takes advantage of the high data rate achieved by high speed PIV. It is shown that the new decomposition method provides accurate measurement of granular temperature while previous decomposition methods can lead to errors in parameters like granular temperature. It has been shown that the new decomposition method is insensitive to reductions in the field-of-view size, while previous methods produce larger errors as the field-of-view size decreases.

To the best of our knowledge, this paper presents the first accurate measurements of granular temperature in a large scale CFB riser because previous measurement techniques did not have sample rates high enough to detect the full range of frequency components of the velocity time series.

Acknowledgment

We thank the management of NETL for providing direction in this research and for providing the necessary resources, including one of the best high speed cameras available. In particular we would like to thank Bill Rogers and Chris Guenther. We also thank the PSRI team in Chicago for providing unique experimental facilities for studying particle flow fields, and for their unprecedented expertise in this field. Finally, we would like to thank Tim Palucka, National Interest Security Company, for pointing out the grammatical inaccuracies in the earlier versions of our paper.

**References**


**Table 3**

Mean granular temperature (GT) calculated for various field of view for Condition 3 at the center of the PSRI riser using Local Averaging Window method and that of Tartan and Gidaspow [23].

<table>
<thead>
<tr>
<th>Field of view</th>
<th>GT With Local Averaging Window method</th>
<th>GT With Frame Average Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>No subdivision</td>
<td>17.25</td>
<td>15.17</td>
</tr>
<tr>
<td>2 regions</td>
<td>16.93</td>
<td>13.33</td>
</tr>
<tr>
<td>3 regions</td>
<td>17.06</td>
<td>12.24</td>
</tr>
</tbody>
</table>

**Fig. 7.** a–d: Plots comparing the frame averaged velocity calculated using (a) Local Averaging Window method and (b) Frame Average Method for \( U_g = 7.58 \text{ m/s} \) and \( M_r = 96 \text{ kg/m}^2\text{s} \) at the center of the NETL riser. Corresponding zoomed in portions are seen in figures (c) and (d).