A COMPARATIVE APPLICATION OF A PARTICLE TRACKING VELOCIMETRY AND LASER DOPPLER VELOCIMETRY FOR PARTICLE-WALL COLLISION MEASUREMENTS

Heshmat Massah
Chemical Engineering Department
Carnegie Mellon University
Pittsburgh, PA 15129

Mehrdad Shahnam
Gilbert Commonwealth
Library, PA 15236

Franklin Shaffer
Pittsburgh Energy Technology Center
US Department of Energy,
Pittsburgh, PA 15236

Jennifer Sinclair
Chemical Engineering Department
Carnegie Mellon University
Pittsburgh, PA 15129

ABSTRACT

The properties of particle-wall collisions measured using a particle tracking velocimetry (PTV) system and a laser Doppler velocimeter (LDV) are compared. The measured parameters are rebound angles and velocities and approach angles and velocities. From these measured parameters, normal coefficients of restitution (e), the ratio of the tangential approach to tangential rebound velocities (β) and the ratio of rebound to approach angle (φ_r/φ_a) are derived. In this study, 191 μm spherical glass particles were collided with a smooth glass plate with a narrow range of approach angle around a mean value of 50° (with respect to the glass plate) and with a narrow range of approach velocity around a mean value of about 18 m/s. Despite differences in the way φ_r/φ_a, e, and β are calculated for LDV and PTV, both PTV and LDV measurements led to almost identical results. The experimental uncertainty in velocity for both techniques was less than three percent.

NOMENCLATURE

V	Velocity vector (m/s)
u	Axial component of velocity (m/s)
v	normal component of velocity (m/s)
β	The ratio of the tangential approach to the tangential rebound velocities
e	Normal coefficient of restitution
φ_i	Approach angle (degree)
φ_r	Rebound angle (degree)

INTRODUCTION

Particle-wall collisions are encountered in many industrial systems such as particle deposition in combustion systems, erosion of turbine blades in jet engines by airborne particulate, fluidization for chemical processing, and the pneumatic transport of particles from one location to another.

To predict the behavior of particulate flow systems using either Lagrangian or Eulerian models, one needs to understand the physics of collisions between particles and the boundary walls and between particles themselves. Specifically, the changes in the tangential and the normal components of velocity upon collision are needed.

Tabakoff and Malak (1987) have used laser Doppler velocimetry (LDV) to measure the collisional properties of fly ash impacting different plates made of aluminum, titanium and stainless steel.

Massah et al. (1994,1995) used a PTV system developed by Shaffer et al. (1988) to track individual particles and to measure their velocities before and after collision with a wall. Sommerfeld (1993) used a similar PTV system to measure large quantities of particle-wall collisions to characterize diffuse scattering by a rough surface.

The purpose of this study is to compare LDV and PTV measurements of glass spheres colliding with a glass plate. The parameters measured include time-averaged approach angle and velocity and time-averaged rebound angle and velocity. Of particular interest are the restitution coefficients calculated from these measured parameters.

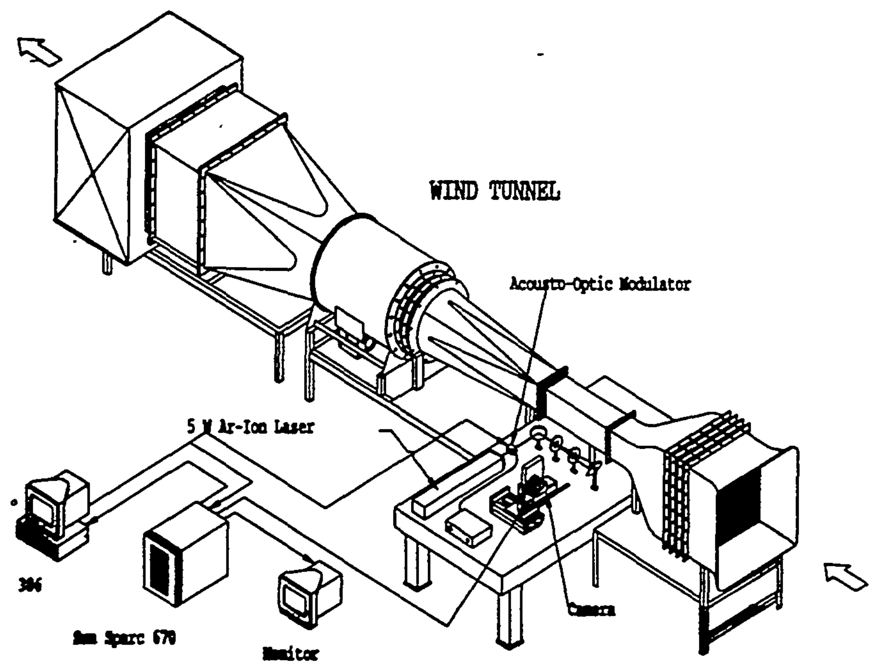


FIGURE 1. SCHEMATICS OF EXPERIMENTAL SETUP

The glass particles were sieved to a size range of 175-208 μm and the glass plate is a piece of smooth glass sheet, 3 mm thick. Only spherical particles with a sphericity of 95% or higher were used. The particles are injected at a mean angle of 50° with respect to the glass plate and a mean velocity of 18 m/s. The range of approach angle and approach velocity was kept narrow with a standard deviation of 4° and 3 m/s, respectively.

EXPERIMENTAL SETUP

The experimental system originally designed by Shaffer *et al.* (1989) was used in this study. It is located in the Flow Analysis Facility of the Department of Energy's Pittsburgh Energy Technology Center. Figure 1 shows the configuration of the experimental equipment (the feeding system is not shown). In the test section of the wind tunnel, glass particles are brought into collision at the center of a smooth glass plate under accurately controlled conditions. The particles are driven by pneumatic transport through a 4 mm tube. The exit of the injection tube is placed about 2 cm above the glass plate and is tilted downward to an angle of about 50° with respect to the glass plate. Particles are fed into the pneumatic transport line at a steady rate. The effect of drag on measured properties was minimized by using a wind tunnel sweep velocity of 4 m/s.

The glass particles have a material density of 2.47 g/cm^3 and a diameter distribution of 175 to 208 μm with a mean of 191 μm. The glass particles are nearly perfect spheres; aspherical particles are removed using a proprietary technique under development at PETC.

The dimensions of the glass plate were 27 cm x 27 cm with a thickness of 3 mm. Support posts were placed at the corners of the plate. The size of the plate and the distance of the support posts from the collision point were sufficient to ensure that the collisions are independent of the finite plate dimensions. This was verified based on the criteria given by Sondergaard et al. (1990).

A. PTV MEASUREMENTS

The beam from an acousto-optically modulated, 7W argon laser is transmitted through a series of cylindrical lenses forming a thin (1 mm) sheet of pulsed laser light. The sheet was directed parallel to the flow upward through and normal to the glass plate. The laser sheet was pulsed at a rate of 25 KHz, with pulse duration of 5 μs.

As particles pass through the light sheet, they scatter light into a high-resolution (1024 x 1024 pixel) video camera positioned with its line-of-view normal to the laser sheet. This produces a multiple-exposure picture showing a series of images of a particle along its trajectory. By measuring the distance between images and knowing the time between laser pulses, a velocity vector was derived. To minimize the uncertainty associated with the distance, the distance was measured between the first image and the fifth image closest to the wall. The field-of-view size was 34.69 x 26.92 mm.

The PTV pictures are digitized at 30 pictures/second with 8-bit (255 levels) gray-scale resolution into a SUN 670 computer with an ANDROX parallel image processor. Only a 3.42 mm region of the PTV picture near the wall is stored permanently. Particle images are detectable within one particle image diameter of the plate surface.

Lighting conditions were set so that the raw digital pictures have a uniform background gray-level. This was accomplished by increasing the camera black-level above the background level. With a uniform background, the image compression efficiency is more than 95%; this is necessary to economically store thousands of images.

Software has been developed at PETC to automatically analyze multiple-exposure pictures of particle trajectories (Ramer and Shaffer, 1990, and Singh et al , 1993). The first step in the image analysis is recognition of particle images and calculation of image centroids. The next step is to recognize groups of centroids as belonging to an approach or rebound trajectory. This is achieved using an iterative Kalman filtering algorithm with a likelihood function based on apriori knowledge of the number of particle images along a trajectory. Next, the approach and rebound trajectories are extrapolated to their intersection points with the glass plate. If the intersection points of a pair of approach and rebound trajectories with the plate are close, within an adjustable tolerance, they are assumed to be from the same particle. For this work the tolerance was set at two particle image diameters. This tight tolerance restricts the data to particles with instantaneous contacts with the plate; particles that slide or roll upon contact are automatically excluded. The last step in the analysis process involves calculation of angles, velocities and restitution coefficients. The angles and velocities were calculated using the first and fifth image closest to the wall of a trajectory. This falls within a 1.5 mm region next to the wall. The entire image acquisition, analysis and storage process takes about one second per picture. This enables rapid analysis of the thousands of trajectories required for statistical convergence.

B. LDV MEASUREMENTS

A two-component, fiber-optic LDV was used to measure the approach and rebound velocity components of the glass particles colliding with the glass plate. The LDV system consists of a Spectra-Physics argon laser (5W), a TSI Colorburst model 9201 coupled to a two-component, fiber-optic transmitting/receiving probe and a DANTEC 58N10 PDA signal processor. The LDV probe was placed where the camera is shown in Figure 1. The rest of the experimental setup remained as shown in Figure 1. Data acquisition was controlled via a 80486-DX2 computer. Table 1 lists the LDV characteristics.

To place the LDV measuring volume very close to the glass plate, the LDV probe was rotated 45° about its line-of-view and tilted downward about 3° so that two of the four beams were almost parallel to the glass plate. Figure 2a shows a schematic drawing of the fringes in the measurement volume created by the blue and green beams. Figures 2b and 2c show the fringes created by the blue and green beams alone. They are perpendicular to each other and at a 45^{o} angle to the plate. In Figure 2, U1 and U2 are components of the velocity measured by the blue and the green beams, respectively. The normal component (v) and the tangential component (u) of the velocity in the "plate" coordinate system were calculated from equations (1) and (2).

$$v = -U1 \times \cos(45^{o}) + U2 \times \sin(45^{o}) \quad (1)$$
$$u = U1 \times \sin(45^{o}) + U2 \times \cos(45^{o}) \quad (2)$$

TABLE 1. LDV PARAMETERS

Color	Green	Blue
Wavelength (µm)	514.5	488
Front lens focal length (mm)	350	350
Fringe spacing (µm)	3.611	3.425
Measuring volume diameter (µm)	163	160
Measuring volume length (mm)	2.28	2.24
Number of stationary fringes	45	47

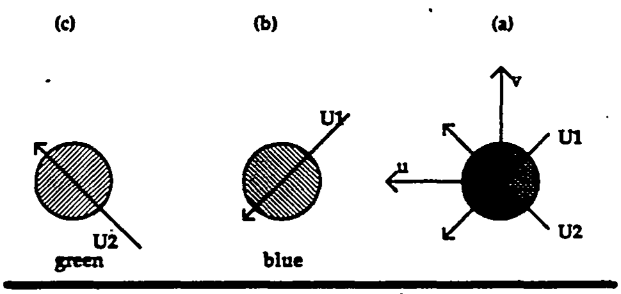


FIGURE 2. DIRECTION OF FRINGES IN THE LDV MEASUREMENT VOLUME

Care was taken to ensure that LDV measurements covered the same volume over which PTV measurements were made. The LDV measurement volume was placed about 2 mm above the plate at a location where PTV measurements were done. PTV results are based on images within 2.5 mm above the plate and along a 5 mm length of the plate. Therefore, LDV measurements were taken at five points, 1 mm apart, over the same 5 mm length, as shown in Figure 3. Three thousand samples were taken at each point with LDV. The data from all five points was then combined.

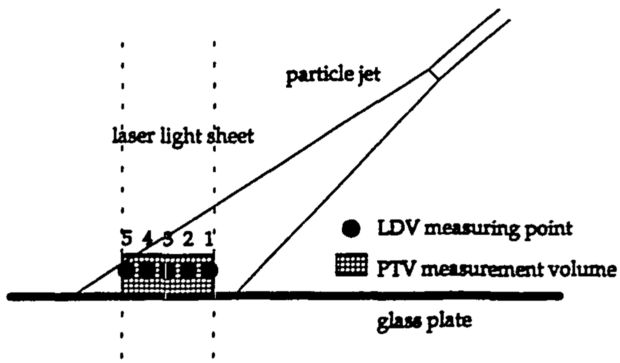


FIGURE 3. MEASUREMENT VOLUMES OF PTV AND LDV

Figure 4 shows two typical paths that particles take. Some particles (particle 1) collide with the plate and cross the measurement volume on their rebound path. The vertical component of velocity of these particles has a positive sign. Such data were taken as rebound data (i.e., rebound tangential and normal velocities and angle). Other particles (particle 2) cross the measurement volume on their approach path and then collide with the plate. The vertical component of velocity of these particles has a negative sign. These data were taken as approach data (i.e., approach tangential and normal velocities and angles). The measurements at the middle 3 points (points 2,3 and 4) shown in Figure 3, resulted in almost equal number of approach and rebound data. Point 1 contained mostly approach data and point 5 contained mostly rebound information.

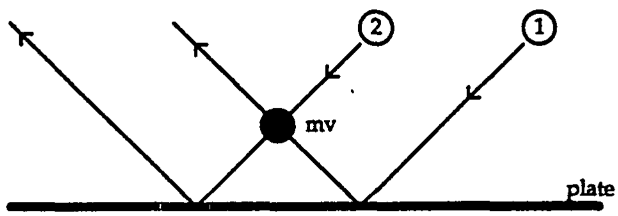


FIGURE 4. TYPICAL PATHS OF PARTICLES IN THE LDV MEASUREMENTS

DISCUSSIONS AND RESULTS

The experimental uncertainty in PTV measurements arises from two factors: 1) uncertainty in measuring the distance between the centroids of images and, 2) uncertainty in the timing of laser pulses. The digital pulse-generator used in this experiment has nanosecond resolution making the timing uncertainty negligible. The uncertainty in measuring the distance is limited by the pixel resolution of the imaging system and the resolution of the scale used to calibrate the imaging system. For the experimental conditions of this study, the average uncertainty in measuring the mean tangential component of velocity is 0.30 m/s and that for the mean normal velocity is 0.23 m/s.

The uncertainty in LDV measurements is mostly due to limitations in the resolution of the frequency bandwidth of the signal processor. The uncertainty in measuring both the mean tangential component of velocity and the mean normal component of velocity is 0.155 m/s.

TABLE 2. PTV AND LDV MEASUREMENTS IN THE PARTICLE JET

	PTV	LDV
V m/s	18.97 ± 0.37	18.84 ± 0.16
u m/s	11.18 ± 0.30	11.36 ± 0.16
v m/s	15.27 ± 0.23	14.98 ± 0.16
φ degrees	53.90 ± 1.97	53.20 ± 1.20

To verify the performance of both LDV and PTV, measurements were done with the plate removed. The rest of the experimental conditions were as described earlier. Table 2 shows that the values measured for the jet were the same within experimental uncertainty. The histograms of velocity and angle are shown in Figures 5 & 6.

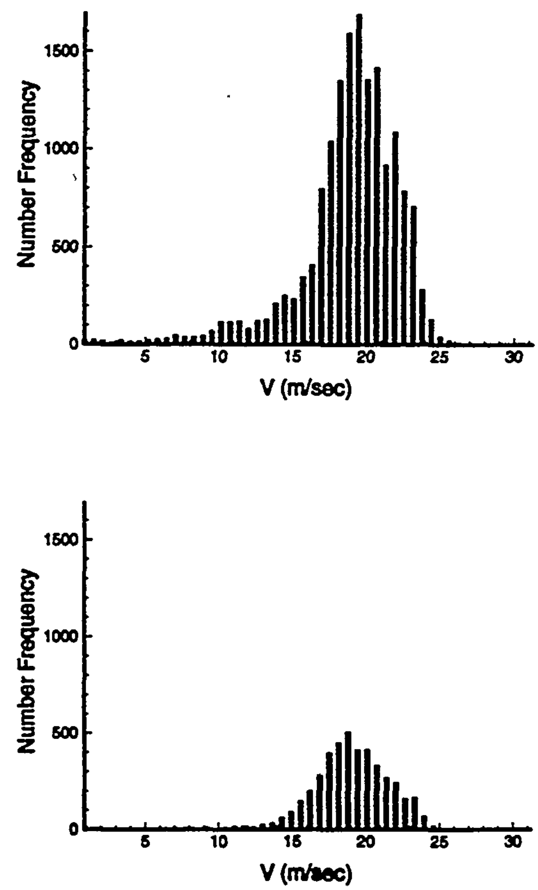
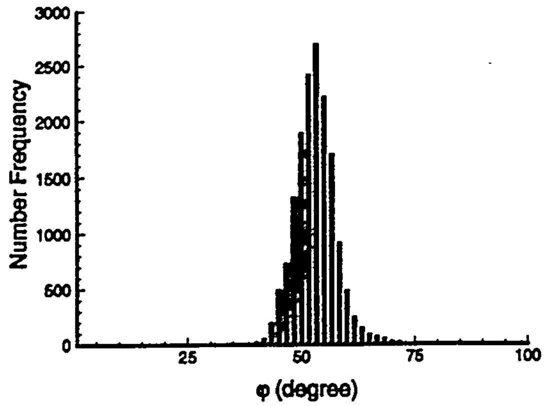


FIGURE 5. HISTOGRAMS OF VELOCITIES MEASURED FOR JET BY LDV (TOP) AND PTV (BOTTOM)



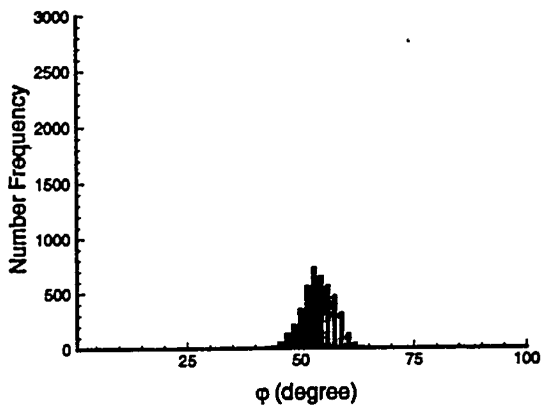


FIGURE 6. HISTOGRAMS OF ANGLES OF TRAJECTORIES MEASURED FOR JET BY LDV (TOP) AND BY PTV (BOTTOM)

Particle wall collision properties are often expressed in terms of e, β and the ratio of rebound to approach angle (φ_r/φ_a). Table 3 shows that these nondimensional parameters obtained by PTV and LDV are in good agreement.

TABLE 3. COLLISION PARAMETERS MEASURED BY PTV AND LDV

	PTV	LDV
φ_r/φ_a	1.11 ± 0.08	1.12 ± 0.03
e	0.95 ± 0.03	0.95 ± 0.02
β	0.75 ± 0.05	0.76 ± 0.02

The number of data taken with LDV is about 15000 while the number of data taken by PTV is about 1500. A statistical analysis of the data showed that 1000 data were sufficient for convergence of both mean and standard deviation values.

The normal restitution coefficient and tangential velocity ratio are given by:

$$e = \frac{v_r}{v_a} \qquad \text{normal coefficient of restitution}$$

$$\beta = \frac{u_r}{u_a} \qquad \text{tangential velocity ratio.}$$

Therefore the normal restitution coefficient and the tangential velocity ratio of a sample with N collisions is

$$\bar{e} = \sum_{m=1}^{N} e_m = \sum_{m=1}^{N} \left[\frac{v_r}{v_a}\right]_m \qquad (1)$$

$$\bar{\beta} = \sum_{m=1}^{N} \beta_m = \sum_{m=1}^{N} \left[\frac{u_r}{u_a}\right]_m \qquad (2).$$

However, due to inability of LDV to follow the same particle before and after a collision, the values of e and β are calculated using the mean rebound and approach particle velocities as:

$$\bar{e} = \frac{\bar{v}_r}{\bar{v}_a} = \frac{\sum_{m=1}^{N} [v_r]_m}{\sum_{m=1}^{N} [v_a]_m} \qquad (3)$$

$$\bar{\beta} = \frac{\bar{u}_r}{\bar{u}_a} = \frac{\sum_{m=1}^{N} [u_r]_m}{\sum_{m=1}^{N} [u_a]_m} \qquad (4)$$

Even though equations (1) and (2) are different than equations (3) and (4), the results of LDV and PTV measurements are in good agreement. This indicates that LDV and PTV provide the same results for collisions where the variations in approach and rebound velocities and angles are small. Work is underway to extend the present study to diffuse particle collisions and to investigate the possible effect of approach angle and velocity on the collisional parameters.

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