ABSTRACT
The response of glass beads was examined in a fully developed turbulent channel flow of air with Reynolds number \( \text{Re}_h = 4500 \) where \( h \) is the channel half width. Five sets of monodisperse particles were tested with integral Stokes numbers in the range 0.2-10 at the channel centerplane. Particle-to-air mass loadings were of order 10%. Laser sheets were aligned in streamwise-spanwise flow planes, and seeded, particle-laden flow was imaged with a dual-frame camera. A separation algorithm was used to obtain simultaneous gas and particle velocity measurements of homogeneous flow planes over a range of wall-normal distances. Profiles of single-point velocity statistics including mean and rms slip velocity, particle drift velocity, and gas-particle correlation were computed. In addition, two-point gas-particle and particle-particle velocity correlations were obtained. Near the wall, the gas-gas correlations yielded long, narrow patterns related to near-wall low-speed streaks. At the centerplane, the correlations were broader in the spanwise direction. Gas-particle and particle-particle correlations resembled the gas correlations in shape and size, but the values were smaller. The gas-particle covariance tended toward zero for \( St = 10 \). Particle-particle correlations were still significant for \( St = 4 \).

INTRODUCTION
Industrial and environmental applications often involve turbulent flows of gas laden with solid particles or droplets. Direct numerical simulations (DNS) of these practical flows are prohibitively expensive due to the wide range of time and length scales in turbulent gas flow and the complicated interaction mechanism between turbulence and particles. Prediction and understanding of such flows become especially challenging when particles are large enough to cross gas streamlines yet small enough to interact with the eddying motion of the gas. To predict such flows on a computer, simplified yet accurate two-phase turbulence models are needed (see e.g. Elghobashi and Abou-Arab\(^1\), Simonin\(^2\)). These models, in turn, require experimental data for testing and closure. One goal of the current study is to provide such data in the form of single- and two-point gas and particle velocity correlations. Another goal is to understand the effect of particle inertia on the particle-turbulence interaction mechanism. For ease of comparison with numerical simulation and models, the present work focuses on a fully developed, turbulent channel flow of air at low Reynolds number and low mass load of particles (10%).

Previous experimental (e.g. Kulick et al.\(^3\)) and DNS (e.g. McLaughlin\(^4\), Rouson et al.\(^5\)) studies of particle-laden turbulent channel flows in a similar regime included single-point velocity statistics and some preferential concentration measurements. Recently, several groups (e.g. Caraman et al.\(^6\), Kiger and Pan\(^7\)) have measured particle velocities \( v_i \) and the related ‘unperturbed’ gas velocities \( \tilde{u}_i \) in turbulent flows. Such measurements allow particle velocity response to be quantified in terms of local slip velocity \( (\tilde{u}_i - v_i) \), drift velocity \( \langle \tilde{u}_i, \rangle_p \), and gas-particle velocity correlation \( \langle \tilde{u}_i v_j \rangle_p \), where angle brackets denote ensemble averaging and primes denote deviations from the local mean velocity. Here, the drift velocity is defined as the difference between the average ‘unperturbed’ gas velocity at particle locations and the average gas velocity. Typically, particles with smaller inertia respond more quickly to changes in gas velocity, resulting in smaller slip velocities and larger gas-particle velocity correlations.

In the present work, we use a PIV-based method to determine the quantities mentioned above as well as two-point gas-particle \( \langle \tilde{u}_i (0,0) v_j (x_1,x_2) \rangle_p \) and particle-particle \( \langle v_i (0,0) v_j (x_1,x_2) \rangle_p \) velocity correlations. These results can be used for testing PDF-type models and also for understanding the non-local nature of particle response to eddies. Two-point gas-particle velocity correlations over short distances were measured previously in a phase-discriminating LDV study by Härdrich and Erdmann\(^8\). Preliminary results based on the present work can be found in Longmire and Khalitov\(^9\).

EXPERIMENTAL METHOD
The channel flow facility is shown in Figure 1. Humidified air mixed with particles enters the top portion of the flow conditioning section and passes through a series of
grids and honeycombs to achieve uniformity in both phases. A small amount of fog is added to the flow at the entrance to the development section. Fog particles (glycerin droplets 1-3 µm diameter) provide a means for measuring gas velocity.

Sets of sized solid glass spheres with five mean diameters were examined in separate experiments. Table 1 shows the five mean number diameters, particle Stokes numbers based on Kolmogorov $St_K$ and integral $St_h$ time scales, and particle Reynolds numbers $Re_p$ based on the sum of squares of the mean and rms slip velocity. The mass loading ratio was 10% for all cases except for the 20-µm particles where the mass loading ratio was 0.7%.

Tests show that, after passing through the development section and entering the test section, the flow was fully developed in both phases with a gas centerline turbulence level of 4%. Over 60% of the channel span, the mean flow was two-dimensional to within 1% of the channel centerline mean which was $U_0=10$ m/s. The channel half-width was $h=7.5$ mm, the channel Reynolds number based on this width and the centerline velocity was $Re_c=4500$, and the friction Reynolds number was $Re_f=240$. Ultimately, the flow exited to a recycle bin where the particles were collected for future use.

In the test section, simultaneous gas and particle planar velocity fields were measured with two-phase PIV (see Khalitov and Longmire\textsuperscript{10}). The camera field of view was 10x10 mm. Velocities of individual particles were computed by tracking, and gas velocities were computed by cross-correlation on rectangular grids with interrogation spot dimension of 0.62 mm and 50% overlap, resulting in grid spacing of 0.31 mm. For these parameters, the gas valid data yield was above 98% for all cases presented. The measurements were performed in $(x_1,x_2)$ planes at eight wall normal locations $x_2$. The wall distance was varied by traversing and realigning the channel.

The velocity data was processed with custom statistical software, which computed 'unperturbed' gas velocities $\bar{u}$, by interpolating from the four nearest grid points to the particle locations. Then, various single-point statistics were computed.

To compute two-point correlations, the program applied a direct cross-correlation algorithm. The particle velocity fields were projected onto rectangular grids. In these grids, each ‘vector’ represented average particle velocity and the number of particles within the cell. For gas-particle correlations, the grid spacing was kept the same as in the gas fields, whereas for particle-particle correlation it was doubled to obtain higher quality plots. At these parameters, more than one particle can fall into a cell, and therefore any subgrid particle-particle interaction was ignored. However, previous tests on finer grids containing no more than one particle per cell did not indicate any particle-particle correlation patterns.

For single-point statistics, the dataset size varied from 1400 to 9800 vector fields, thus resulting in 5000 to 10000 statistically independent samples for each data point. Measurements next to the wall required larger number of fields. For two-point correlations, up to 16800 vector fields were used to obtain smooth plots. An exception was made for 20-µm particles, where the dataset sizes were smaller: for both single- and two-point correlations, the number of vector fields was from 700 to 2100. Also, the 20-µm particle concentration was lower, thus resulting in lower quality correlation plots.

<table>
<thead>
<tr>
<th>$y^*$</th>
<th>$d_p, \mu m$</th>
<th>$St_K$</th>
<th>$St_h$</th>
<th>$Re_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>20</td>
<td>14.1</td>
<td>0.56</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>31.6</td>
<td>1.26</td>
<td>3.56</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>126.5</td>
<td>5.03</td>
<td>7.28</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>351.4</td>
<td>13.97</td>
<td>13.45</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>899.5</td>
<td>35.77</td>
<td>20.80</td>
</tr>
<tr>
<td>240</td>
<td>20</td>
<td>2.1</td>
<td>0.18</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>4.7</td>
<td>0.35</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>18.8</td>
<td>1.37</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>52.2</td>
<td>3.94</td>
<td>5.99</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>133.6</td>
<td>10.24</td>
<td>16.12</td>
</tr>
</tbody>
</table>

Table 1. Particle properties
SINGLE-POINT RESULTS

Profiles based on single-point gas and particle velocity statistics are presented in Figure 2. The gas mean velocity profiles (solid lines in Fig. 2a) agree to within uncertainty (<0.5%) at the centerline, but show a spread of up to 2.3% at other positions. This result suggests that particles may slightly alter the mean gas profile, most likely due to the additional momentum flux in the particle phase. No systematic effect of particle size on the gas mean velocity profile could be observed, however. Particle size did not seem to have any

Fig 2. Single-point statistics
significant effect on the gas rms velocity profiles (lines with no markers in Fig. 2b). In this plot, only the unladen profiles are shown because rms values for all particle sizes agreed with this case to within the 3% uncertainty. Thus we can conclude that gas turbulence was not affected by particles at the mass loading used. This result is consistent with Kulick et al. In Kulick’s experiments (Re,=13800), however, particles always moved faster than gas at the channel centerplane. In the present work, where larger particles move slower than the gas at the centerplane, the channel is narrower (Re,=4500), and we suspect that a greater percentage of particles lose momentum when colliding with channel walls.

In the particle phase, both mean $V_i$ and rms $v_i'$ streamwise velocity profiles become steeper with decreasing particle size until 30 µm at which point the particle profiles are steeper than the corresponding gas profiles (see Fig 2a,b). The profiles for the 20 µm particles then decrease in slope to values close to those observed in the gas profiles. The spanwise component of the particle rms velocity $v_i'狞 is always smaller than the streamwise component and, in general, decreases with increasing particle size (Fig. 2b). The spanwise rms component of slip velocity (Fig 2e), on the contrary, increases with particle size, due to increasing inertia. The streamwise component of rms slip velocity reveals some trends similar to those observed for $v_i'$. Near the wall, the rms slip velocity increases as particle size decreases until $d_p = 30$ µm. The profile slope is strongest for 30 µm particles, and the slip velocity for 20 µm particles is smaller at all positions measured.

Particle size affects the slopes of both mean slip and drift velocity profiles (Fig 2d,f). Since drift velocities are small compared with slip velocities, Fig. 2d effectively shows that with increasing particle size, particle velocity profiles become flatter, as observed previously in Fig. 2a.

Although the drift velocities in Fig. 2f are small, the profiles reveal some consistent trends. The plot indicates that, close to the wall, smaller particles ($S_n < 2$) tend to be located in low-speed regions, whereas the larger particles are located preferentially in high-speed regions. The latter effect is very weak, however.

Gas-particle correlations (Fig 2c) increase consistently as the particle size decreases. The correlations increase with wall normal distance for the two smallest particle sizes, but are fairly flat for larger particles. Typically, the streamwise correlation is larger than the spanwise correlation, a trend found also by Rouson et al. The largest particles examined (160 µm) have correlations near zero at the centerline. Near the wall, however, these particles indicate a significant correlation in the streamwise direction.

TWO-POINT CORRELATIONS

Figures 3 through 6 show two-point correlation contour plots. Each figure is organized so that near-wall data ($y^+ = 16$) is on the left, and centerplane data ($y^+ = 240$) is on the right. The top row always represents gas-gas correlation, and in the other rows, particle size increases from top to bottom. Two-point correlations were not computed for 160 µm particles, due to an insufficient number of particles. To clarify some of the values and trends in the correlations, Figures 7 through 9 show line plots extracted from the contour plots.

The gas correlations (Figs 3a,f, 4a,f, and 5a,f) indicate the presence of low speed streaks surrounded by higher speed streaks close to the wall and inclined vortex tubes at the centerplane, as discussed previously in Anderson et al. and Longmire and Khalitov. Note that in all cases shown, both gas-particle and particle-particle correlations resemble the gas-gas correlations in contour shape. All correlations become narrow and more elongated close to the wall, due to the long, narrow streaks observed there. Towards the centerplane, the spanwise dimension of these structures (quantified as the integral length scale $L_y$) grows from 0.2h to 0.5h. The particles are therefore partially correlated with gas velocities over length scales corresponding to the typical large eddy size. With increasing particle size, however, the correlations decrease steadily in amplitude.

The streamwise-streamwise (‘11’) gas-particle velocity correlation $\langle u''_1(0,0)v'_1(x_1,x_3)\rangle_p$ is elongated in the flow direction more than any other correlation in any direction (Fig. 3). Figure 3 shows that the ‘11’ correlations have asymmetries in the streamwise direction. Based on data from smaller particles only, Longmire and Khalitov assumed that the asymmetry was caused by particle residence in low-speed streaks. The newer data including larger particles suggests a different explanation. The peak position is typically shifted opposite to the mean slip velocity direction both near the wall and at the centerplane (see also Figure 7a,b). Therefore, large particles near the wall (which move faster than the local flow) are correlated more strongly with the fluid slightly upstream, and large particles near the centerline (which move slower than the local flow) are correlated more strongly with fluid elements slightly downstream, for example.

Since the mean slip velocity is directed along the flow and the rms slip velocity has larger values in the flow direction, Figure 3 tells us that all particles are more likely to respond over the length (streamwise dimension) of the structures. The length changes very little with the wall-normal distance and scales with the channel half-width $h$ over the range of wall distances shown. Therefore, $h$ was used for estimates of both dissipation $\left<(u')^2/h\right>$ and integral fluid time scale $(h/u')$ to obtain the Stokes numbers in Table 1.

In the spanwise direction, all of the ‘11’ correlations (see also Fig. 8a,b) contain negative lobes close to the wall. In the gas flow, these lobes occur because low-speed streaks are surrounded by high-speed regions. Particles respond to both high- and low-speed streaky structures faster than they move spanwise because the particle spanwise rms velocity is much smaller than the streamwise component (see Fig 2b). This near-wall anisotropy of the particle response helps explain the negative lobes observed for all particle sizes. At the centerplane, where the flow becomes more isotropic, negative
lobes become weak (20 µm particles) to insignificant (Figs. 3f-j and 8b).

The spanwise-spanwise ('33') gas-particle correlation contours $\langle \tilde{u}_3(0,0)v_3(x_1,x_3) \rangle_p$ shown in Fig. 4 are nearly circular at the centerplane and stretched in the flow direction close to the wall. These correlations also lack symmetry in the...
flow direction, but the peak location seems to be shifted mostly downstream of the origin. This displacement is about the same for 20-, 30- and 60 µm particles whose slip velocities at the centerplane are small. For 100 µm particles, the peak is shifted upstream because of the large positive slip velocity. Close to the wall, the asymmetry is much weaker, except for 60 µm and 100 µm particles, where it is enhanced by the large negative slip velocity. These results are displayed more clearly in Fig. 9a,b.

The values of the two-point gas-particle ‘11’ and ‘33’ correlations at the origin (see Figures 7-9) correspond well with the single-point correlation values plotted in Figure 2c.

Due to asymmetry in the streamwise direction, though, we note that these are not necessarily the maximum possible correlation values.

The streamwise-spanwise (‘13’) correlations (Figure 5) are also asymmetric in the streamwise direction. Near the wall, individual fields contain low-speed regions (most probably corresponding to upwash of low-momentum fluid by hairpin structures) that are stronger and more localized than the high-speed regions. This observation suggests that, most of the time, $u_1' < 0$ in the contributing products in Figure 5. Then, the strong downstream patterns in Figure 5a can be

---

**Figure 5.** Streamwise-spanwise gas-particle two-point correlation $<u_1'(0,0)v_3'(x_1,x_3)>_p$

**Figure 6.** Streamwise-streamwise particle-particle two-point correlation $<v_1'(0,0)v_1'(x_1,x_3)>_p$
interpreted as inward spanwise motion of the gas beneath the hairpin legs located downstream. At the centerplane, the correlation peaks have shifted upstream of zero. Possibly, fluid immediately upstream of the angled vortex tubes is correlated more strongly than the fluid downstream. Additional measurements show that these upstream peaks first emerge at $y^* = 30$ and become dominant at $y^* = 100$. Further
analysis is needed to determine conclusively the reasons for the asymmetries observed. As in the previous figures, the gas-particle correlations in Figure 5 have similar shapes but smaller values compared with the gas-only correlations. Particles respond to the local vortices to some degree, and smaller particles respond better. In gas-particle ‘13’ correlations, the peaks move away from the origin as the particle size increases. This result suggests possibly that larger particles respond to rotating motion over longer distances.

The values of the particle-particle velocity correlations (see Figure 6) are smaller than those observed for gas-particle correlations (see Figure 3), and, as expected, the values decrease as particle size increases. Based on the argument given above concerning particle-eddy interactions, it makes sense that neighboring particles are positively correlated. Note that even the 100 µm particles ($St_h = 3.9$) yield small positive correlation values near the wall suggesting that we have not reached the upper limit on $St_h$ for significant interparticle correlation. Figures 7c, 8c, and 9c provide a more detailed comparison among particle-particle correlations for various particle sizes.

Finally, correlations between vorticity $\omega_2$ and spanwise

Figure 9. Spanwise-spanwise ‘33’ gas-particle (a,b) and particle-particle (c) two-point correlations in flow direction

Figure 10. Vorticity correlation with spanwise velocity in flow direction
velocity were computed. Close to the wall (Figure 10a), the vorticity-gas correlation has one positive and one negative peak, whereas each vorticity-particle correlation has only a negative peak (downstream of the vorticity location). Additional examination of near-wall contour plots and vector fields (not shown) reveals that particles of all sizes are being swept into low-speed streaks. However, only particles with $S_t < 2$ tend to remain there, according to the present drift velocity measurements. Similar results were obtained by Li, Mosyak and Hetsroni\(^1\) in a horizontal water channel. At the centerplane (Figure 10b), particle response upstream and downstream of a vortex is more symmetric.

CONCLUSIONS

Detailed single- and two-point velocity statistics were obtained for particles and gas in a fully-developed channel flow. In this section, integral Stokes numbers based on centerplane values are used to summarize some of the key results. In the flow studied, larger particles ($S_t > 1.4$) lagged the gas at the centerplane and moved faster than the gas near the wall. Particle drift velocities were significant near the wall for $S_t < 0.35$ suggesting that smaller particles tended to reside in low speed streaks. Drift velocities near the centerplane were very small for all particles tested.

Two-point gas correlations documented the size and shape of dominant structures at different wall-normal positions. Two-point gas-particle correlations revealed that particle and gas velocities were correlated for all cases examined ($S_t < 4$) and that particle-particle correlations were positive for $S_t < 4$. Measurements of gas-particle covariance for $St = 10$ were near zero except for the streamwise component near the wall. In general, both gas-particle and particle-particle correlations resembled the gas correlations in shape and size, but the values were smaller. All correlation values decreased as particle diameter (or Stokes number) increased.

We hope that the data resulting from this study can be used to test the performance of numerical models and simulations on dilute particle-laden flows. The joint gas-particle statistics demonstrate the Stokes number ranges and spatial ranges over which particles are correlated with turbulent structures. In addition, the particle-particle statistics show ranges over which the motion of neighboring particles is correlated. The nonzero correlations documented by this study are important, in particular, for models of interparticle collision frequency.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the National Science Foundation (CTS-9457014) and the University of Minnesota Graduate School, which provided a Doctoral Dissertation Fellowship.

REFERENCES


9 Longmire, E.K., and Khalitov, D. “Particle and fluid velocity correlations in a turbulent channel flow,” *10th Workshop on Two-Phase Flow Predictions, Merseburg, Germany*, 2002

