TURBULENCE MODIFICATION BY SOLID PARTICLES IN UPWARD GRID TURBULENCE OF WATER

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ABSTRACT

Turbulence modification by solid particles in grid turbulence of water is examined experimentally. Glass particles, 2450kg/m^3 in density, are suspended in an upward turbulent flow behind a grid with M=12mm. Two particle diameters, d_p=1.00mm and 1.25mm, are examined. The flow velocity is adjusted so that the particles stay quasi-stationary in the test section by the force balance between gravity and drag exerting on the particles. The resultant Reynolds numbers based on M and d_p are respectively 1660 and 140 for d_p=1.00mm and 2000 and 210 for d_p=1.25mm. Kolmogorov length scales in single-phase flows are 0.43mm (Re_M=1740) and 0.40mm (Re_M=2000). PIV measurements of turbulence are carried out by using fluorescent tracer particles 26μm in diameter to avoid the effect of strong light scattering by the glass particles. It is found that the turbulence in the streamwise direction increases remarkably and selectively with C, the volumetric concentration of glass particles, in the range of C<0.50%. This increase is associated with the occurrence of columnar particle accumulation (CPA) into a region elongated in the streamwise direction. CPA alters significantly the longitudinal two-point velocity correlation, $R_{uu}(\Delta x)$, and vorticity correlation, $R_{\omega_z\omega_z}(\Delta x)$, while it affects little the transverse two-point velocity correlation, $R_{vv}(\Delta x)$, where Δx is the streamwise separation between the two points.

INTRODUCTION

Turbulence modification by particle suspension is an important research subject of dispersed two-phase flows as this phenomenon is observed in a wide variety of flows both in industry and nature such as atmospheric flows containing droplets and dusts, river and sewage flows carrying sands and solids, duct and pipe flows conveying particular matters, and spray and injection of droplets and particles. Of these flows, particle suspension in isotropic turbulence is the most fundamental one, which permits computational approach as well as experimental approach. The present study deals with turbulence modification by solid particles in grid-generated turbulence in an upward water flow.

Modification of grid-generated turbulence by solid particles was studied experimentally by Schreck and Kleis (1993). Their LDV measurements were done in a vertically downward channel flow of water suspended with plastic particles or glass particles. They reported larger decay rates of turbulence intensity for a range of concentration of suspended particles (C=0-1.5%). Their finding is explained by the increase in energy dissipation rate by the suspension of solid particles. It should, however, be noticed that turbulence characteristics of vertically downward flows suspended with heavier-than-water particles are complicated by the large-scale particle accumulation structures created by the particle motions themselves (cf. Hishida et al. 1996). In other words, the potential energy released by the settling particles are converted to the kinetic energy of the primary flow, the energy which must be dissipated by the increase in dissipation rate due to the particle-fluid interaction. To minimize this complexity, the present study is conducted with heavier-than-water particles of quasi-stationary suspension in a vertically upward water flow.

Wang and Maxey (1993) performed a direct numerical simulation (DNS) of particle behaviors in isotropic turbulence and found that the heavy particles tend to accumulate in elongated sheets of the peripheries of local vortical structures, resulting in a significant increase in the average settling velocity. More recently, Kajishima and Takiguchi (2002) conducted a DNS of dispersed two-phase flow in suspension of solid particles. Their Reynolds numbers based on the slip velocity, Re_p, are 50, 100, 200 and 400. They found the generation of particle clustering in their simulated flow fields and concluded it is due to the wake behind each particle. These phenomena revealed by DNS can be examined in the present flow configuration,

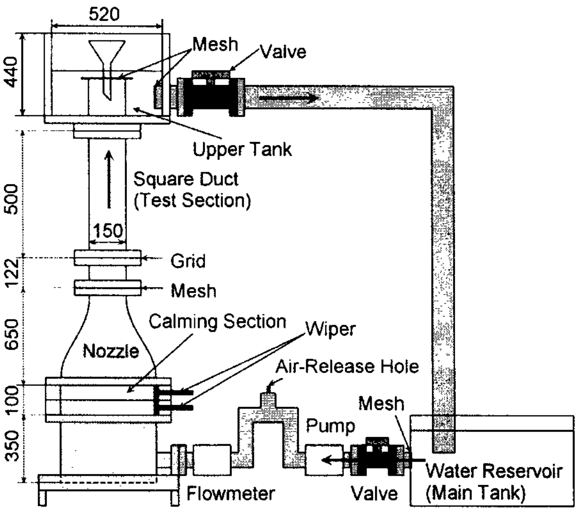


Fig. 1 Upward grid-turbulence water channel facility.

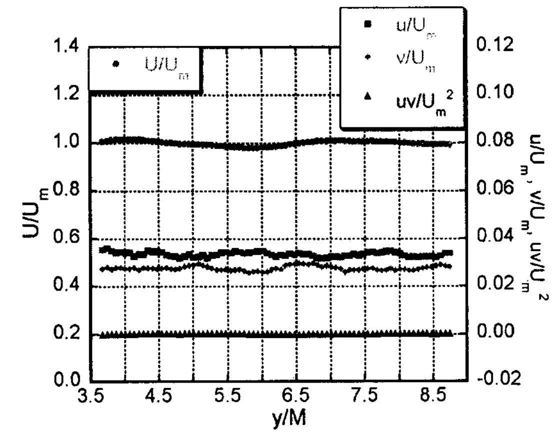


Fig. 3 Spanwise uniformity of the mean velocity and the Reynolds stresses measured at $x/M = 21.1$.

where the particle behaviors are observed in detail during their quasi-stationary suspension in a vertically upward water flow.

METHOD

All experiments are conducted in a grid-turbulence water channel facility (Fig. 1). The flow direction is vertically upward. The test section has a 150×150mm^2 cross-section and is located downstream of a 1:10 contraction nozzle. The maximum flow speed at the test section is about 300mm/s. The grid is formed by circular rods, each 2.0mm in diameter. Its mesh spacing is M=12mm. The distance between the test section and the grid is 190-240mm (x/M=17-21). The particles suspended in the water are glass particles, 1.00mm and 1.25mm in diameter and both 2450kg/m^3 in density. The flow velocity is adjusted carefully to achieve neutral suspension of particles, in which the particles stay quasi-stationary in the test section by the force balance between gravity and drag exerting on the particles. The particles are introduced from the upper outlet of the test section. To prevent the particles from flowing out of the test section, fine-mesh screens are installed at the exit of the channel as well as under the grid as shown in the figure. A small opening is, however, made in the center of the upper mesh so that the particles can gradually flow out of the test section. This results in a slow decrease in the number of particles remaining in the test section, thus permitting the change of volumetric concentration of particles, C, slowly and continuously in a single run of experiment. Typically, 30 minutes elapse until C becomes nearly zero. A laboratory-developed image-processing technique based on particle counting is used to quantify C in real time.

Turbulence is measured with a conventional particle image velocimetry (PIV) system (Fig. 2). A sheet of laser light, 0.7mm in thickness, cuts the test section. The flow is seeded either with nylon particles 28-32μm in diameter for single-phase flow measurement or with fluorescent particles 26μm in diameter for two-phase flow measurement. The fluorescent particles are used in conjunction with a red-pass optical filter. It is placed in front of the camera lens in order to accept only fluorescence whose wave length is 612nm, in contrast to 538nm of the laser light. Without the filter, the particles images acquired would be degraded significantly by the flare due to strong laser scattering by the glass particles in the test section. A 12-bit CCD camera having 1280×1024 cells is used for image acquisition. Due to its slow framing speed, image acquisition is limited to 2fps.

A conventional cross-correlation technique is used for particle image analysis. The correlation-window size is 32x32 pixels, corresponding to 1.6×1.6mm^2 in the flow domain. More than 3000 pairs of particle

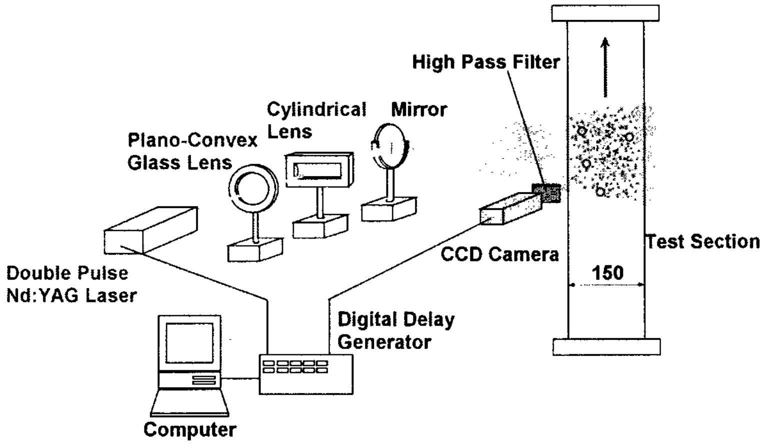


Fig. 2 Configuration of PIV system.

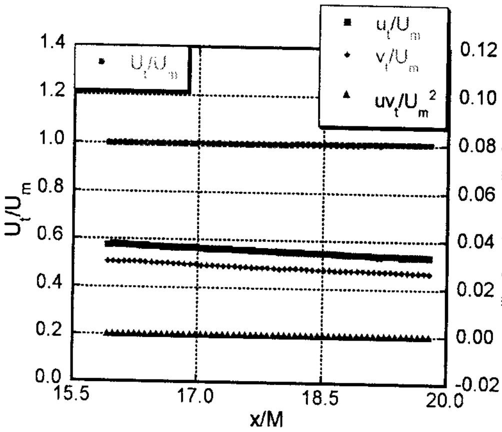


Fig. 4 Streamwise variations of the mean velocity and the Reynolds stresses.

images are acquired in each run of single-phase flow measurement. Figure 3 shows spanwise (or transverse) uniformity of the mean velocity and the Reynolds stresses, all non-dimensionalized by the bulk mean velocity, U_m, which is 210mm/s, giving Re_M=2000. The streamwise turbulence intensity is about $0.033U_m$ and slightly higher than the spanwise component which is $0.028U_m$. The Reynolds shear stress is zero in the entire region shown here. The streamwise variations of turbulence quantities are shown in Fig. 4, where span-averaging is also taken along with ensemble averaging. Both turbulence intensities decrease linearly in the downstream direction. Their decrease is expressed by the following linear relations:

$$U_m^2/u_t^2 = 36.7(x/M + 1.0), \quad (1a)$$
$$U_m^2/v_t^2 = 73.8(x/M - 4.6). \quad (1b)$$

These relations compare reasonably well with those reported by Schreck & Kleis (1993), who measured the turbulence intensities in the range of x/M=15-33.

Dissipation rate of turbulent kinetic energy, ε, is evaluated from the decay of the turbulent kinetic energy, k, as follows:

$$\varepsilon = -U_m\, dk/dx. \quad (2)$$

Basic flow conditions, including Kolmogorov length scale $\eta = (\nu^3/\varepsilon)^{1/4}$ based on ε evaluated at x/M=18 from Eq. (2), are summarized in Table 1. Note that the values of ε

Table 1 Basic flow conditions

	d_p=1.00mm	d_p=1.25mm
U_m [mm/s]	177.4 (164.6)	198.5 (199.0)
ν [mm^2/s]	1.223 (1.193)	1.239 (1.193)
Re_M	1740 (1660)	2000 (2000)
Re_p	(138)	(208)
η [mm]	0.43	0.40

The parenthesized values are those for two-phase flows at C=0%

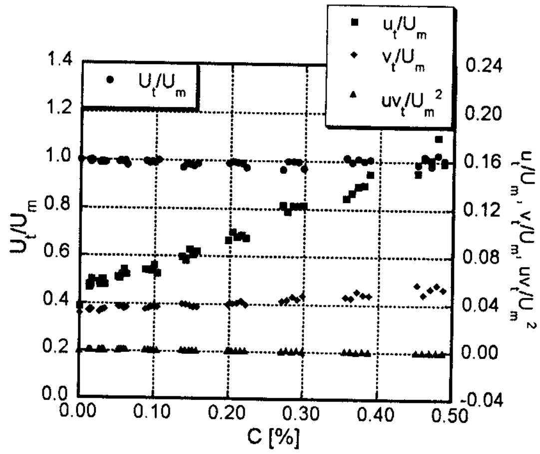


Fig. 5 Turbulence modification by 1.00 mm particles plotted as function of volumetric concentration.

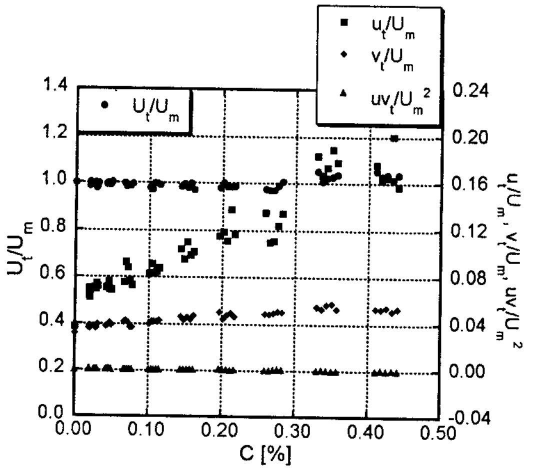
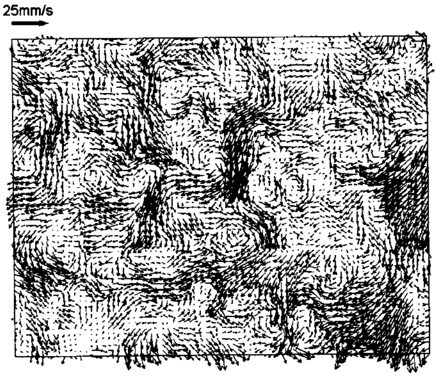


Fig. 6 Turbulence modification by 1.25 mm particles plotted as function of volumetric concentration.

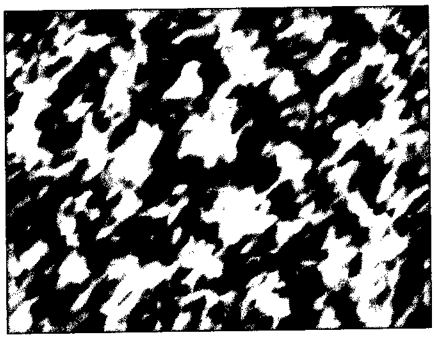
evaluated by $\varepsilon = \nu\langle\omega_i\omega_i\rangle$, the relation valid in isotropic turbulence, are very close to those evaluated from Eq. (2). This indicates good spatial resolution of the present PIV measurement.

RESULTS AND DISCUSSION

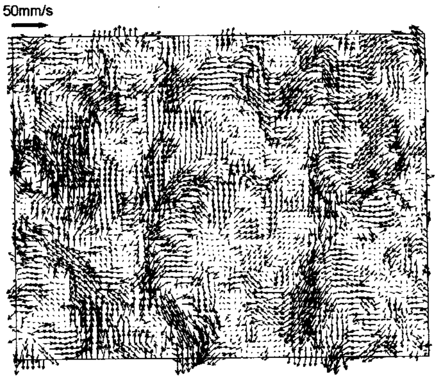
Figures 5 and 6 show the turbulence modification by glass particles plotted as function of volumetric concentration of particles, C. As mentioned above, each of these results was taken in a single run of experiment starting with the highest value of C followed by the gradual decrease of C. The mean velocity and the Reynolds shear stress are invariant with C. The streamwise turbulence intensities increase remarkably with C for both d_p=1.00mm and 1.25mm. It increases from 0.06 at C=0.02% to 0.16 at C=0.50% for d_p=1.00mm while it increases from 0.07 at C=0.02% to 0.20 at C=0.45% for d_p=1.25mm. In contrast, the spanwise component increases only slightly with C. Shreck and Kleis (1993) measured the decay of turbulence



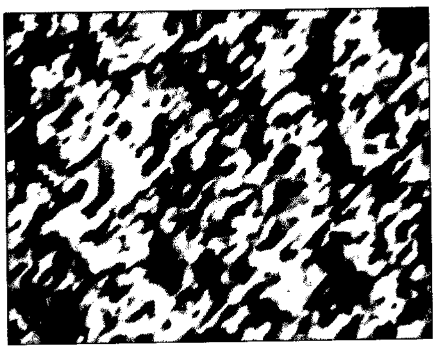
(a) turbulence field at C=0%



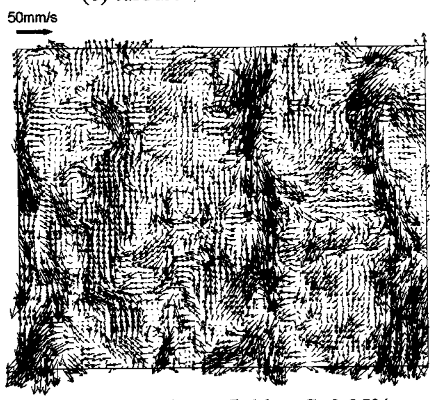
(b) vorticity field at C=0%



(c) turbulence field at C=0.02%

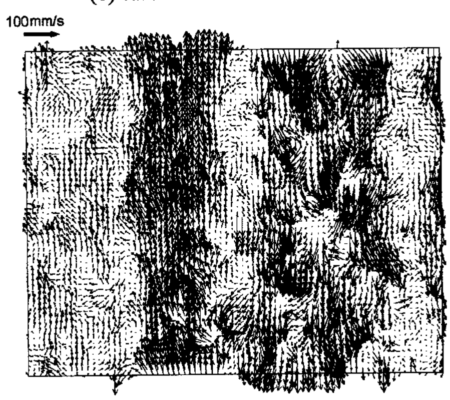


(d) vorticity field at C=0.02%



(e) turbulence field at C=0.05%

(f) vorticity field at C=0.05%



(g) turbulence field at C=0.375%

(h) vorticity field at C=0.375%

Fig. 7 Instantaneous turbulence (left) and vorticity (right) fields at C=0%, C=0.02%, C=0.05% and 0.357%. The diameter of particles is 1.25mm. The size of the area shown is 64×51.2mm^2. The flow direction is from bottom to top. The bulk mean velocity is subtracted from velocity vector fields.

in a two-phase water flow in suspension of glass particle 0.6-0.7mm in diameter. The measured decay at C=1% was shown to be correlated by

$$U_m^2/q^2 = 68.9(x/M - 7.8), \tag{3}$$

where $q^2=(u^2+2v^2)/3$. This should be compared with the decay of single-phase flow given by,

$$U_m^2/q^2 = 52.8(x/M - 6.7). \tag{4}$$

These results give nearly the same turbulence intensities in the single-phase and two-phase flows (i.e., $q=0.038U_m$ vs. $0.034U_m$ at x/M=20). It is obvious that the present result is in contrast with their result in that the turbulence intensities in the present two-phase flow are significantly larger (nearly three times larger) than that in the single-phase flow even at C=0.50%.

Instantaneous turbulence and vorticity fields at C=0%, 0.02%, 0.05% and 0.375% are shown in Fig. 7. The diameter of particles is 1.25mm. The size of the area shown here is 64×51.2mm^2. At C=0% (single-phase flow), many circular vortical structures are seen both in the velocity field and in the vorticity field. The integral length scale evaluated from the longitudinal two-point correlation coefficient (CC) is 6.5mm, in reasonable agreement with sizes of vortical structures seen in these figures. The presence of such circular vortical structures becomes less in number at C=0.02%, and the vorticity field starts to exhibit a kind of streamwise coherency. Such coherency is clearly observable in turbulence fields at C=0.05% and 0.375%, exhibiting the presence of elongating regions with large velocity fluctuations in the streamwise component. The vorticity fields display a pair of negative and positive regions at locations corresponding to the regions with high turbulence. These results indicate that the selective increase of streamwise turbulence intensities as shown in Figs. 5 and 6 is due to the occurrence of the elongated regions of high turbulence of streamwise velocity component.

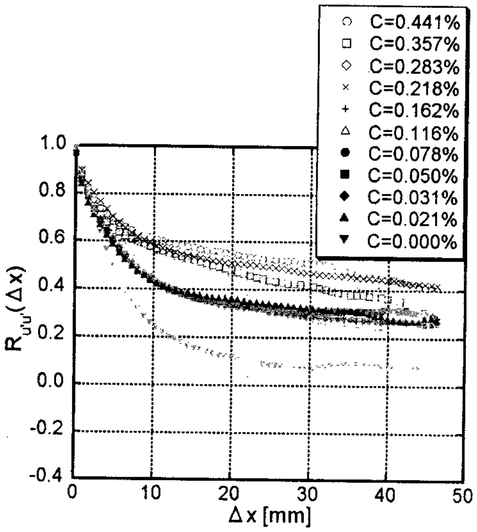
Not shown here, separate flow visualization for the behavior of glass particles in the present two-phase flow facility has revealed the occurrence of columnar particle accumulation (CPA, hereafter) into a region elongated in the streamwise direction. This structure is believed to be corresponding to the particle clustering observed by Kajishima & Takiguchi (2002) in their DNS of a two-phase flow in suspension of solid particles. They reported that the particle clustering becomes obvious for Re_p>300.

Figure 8 shows two-point CC of velocity fluctuations and vorticity fluctuations defined as follows:

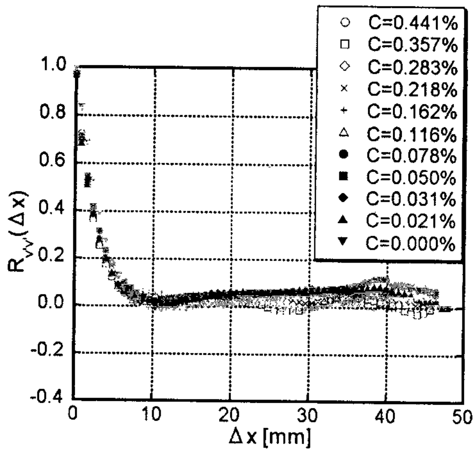
$$R_{u'u'}(\Delta x) = \frac{\langle u'(x)u'(x+\Delta x)\rangle_t}{u(x)u(x+\Delta x)} \tag{5}$$

$$R_{v'v'}(\Delta x) = \frac{\langle v'(x)v'(x+\Delta x)\rangle_t}{v(x)v(x+\Delta x)} \tag{6}$$

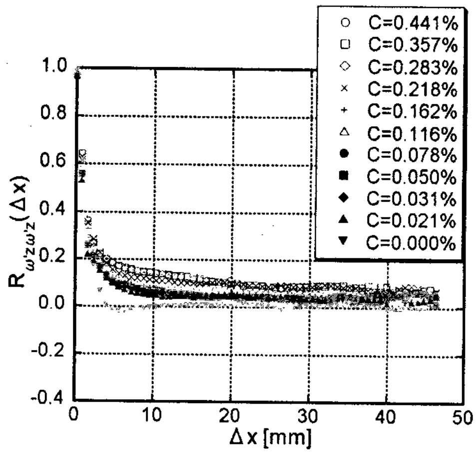
$$R_{\omega_z'\omega_z'}(\Delta x) = \frac{\langle \omega_z'(x)\omega_z'(x+\Delta x)\rangle_t}{\omega_z(x)\omega_z(x+\Delta x)} \tag{7}$$



(a) Longitudinal two-point correlation coefficient.



(b) Transverse two-point correlation coefficient



(c) Correlation coefficient of vorticity fluctuation

Fig. 8 Two-point correlation coefficients for various volume ratios. The diameter of particles is 1.25mm.

where $R_{u'u'}(\Delta x)$ and $R_{v'v'}(\Delta x)$ are the longitudinal and transverse CCs of velocity fluctuations, respectively. The longitudinal CCs for a wide range of C shown in Fig. 8(a) indicate that the values become appreciably higher than that of single-phase flow even at the lowest C shown here (C=0.021%). This is consistent with the turbulence modification, though slightly, seen in Figs. 7(c) and 7(d). As expected, the most remarkable increase of longitudinal CC occurs at the highest C. On the other hand, the transverse CCs shown in Fig. 8(b) exhibit little modification by the suspension of glass particles. Their curves of two-phase flows (C=0.021-0.441%) are more or less the same as that of the single-phase flow. The two-point CCs of vorticity fluctuation, $\omega'_z = \partial v'/\partial x - \partial u'/\partial y$, exhibit an appreciable increase with C as shown in Fig. 8(c). This is consistent with the appearance of elongated vorticity regions recognized in Fig. 7(h).

CONCLUSIONS

Turbulence modification by solid particles in grid turbulence of water is examined experimentally. Glass particles, 2450kg/m^3 in density, are suspended in an upward turbulent flow behind a grid with M=12mm. Two particle diameters, d_p=1.00mm and 1.25mm, are examined. The flow velocity is adjusted so that the particles stay quasi-stationary in the test section by the force balance between gravity and drag exerting on the particles. The resultant Reynolds numbers based on M and d_p are respectively 1660 and 140 for d_p=1.00mm and 2000 and 210 for d_p=1.25mm. Kolmogorov length scales in single-phase flows are 0.43mm (Re_M=1740) and 0.40mm (Re_M=2000). PIV measurements of turbulence are carried out by using fluorescent tracer particles 26μm in diameter to avoid the effect of strong light scattering by the glass particles. It is found that the turbulence in the streamwise direction increases remarkably and selectively with C, the volumetric concentration of glass particles, in the range of C<0.50%. This increase is associated with the occurrence of columnar particle accumulation (CPA) into a region elongating in the streamwise direction. It is revealed that CPA alters significantly the longitudinal two-point velocity correlation, $R_{uu}(\Delta x)$, and vorticity correlation, $R_{\omega_z\omega_z}(\Delta x)$, while it affects little the transverse two-point velocity correlation, $R_{vv}(\Delta x)$.

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NOMENCLATURE

C	:	volume concentration of particles
d_p	:	particle diameter
k	:	turbulent kinetic energy
M	:	mesh spacing
q	:	turbulence level=$(u^2+v^2+w^2)/3$
R_{ij}	:	correlation between i and j
Re_M	:	mesh Reynolds number $= U_m M/\nu$
Re_p	:	particle Reynolds number based on slip velocity
U	:	streamwise mean velocity
U_m	:	bulk mean velocity
u, v	:	streamwise and spanwise turbulence intensities
x, y, z	:	streamwise, spanwise and depth directions
$\Delta x, \Delta y$	:	separations in x- and y-directions
ε	:	dissipation rate of turbulent kinetic energy
η	:	Kolmogorov length scale
ν	:	kinematic viscosity
ω	:	vorticity fluctuation
$\langle\ \rangle$	:	ensemble averaging
$(\ )'$	:	fluctuating components
$(\ )_t$	:	span-averaged quantities

REFERENCES

Hishida, K., Hanzawa, A., Sakakibara, J., Sato, Y. & Maeda, M., 1996, Turbulence structure of liquid-solid two-phase channel flow (1st report, measurement of two-phase flow by DPIV), (in Japanese), *Transaction of Japan Society of Mechanical Engineers*, Series B, Vol. 62, No. 593, pp. 18-25.

Kajishima, T. & Takiguchi, S., 2002, Interaction between particle culsters and particle-induced turbulence, Int. J. Heat and Fluid Flow, Vol. 23, pp. 639-646.

Schreck, S. & Kleis, S. J., 1993, Modification of grid-generated turbulence by solid particles, *Journal of Fluid Mechanics*, Vol. 249, pp. 665-688.

Wang, L.-P. & Maxey, M. R., 1993, Settling velocity and concentration distribution of heavy particles in homogeneous isotropic turbulence, *Journal of Fluid Mechanics*, Vol. 256, pp. 27-68.