EFFECT OF INTER-PARTICLE SPACING ON TURBULENCE MODULATION BY LAGRANGIAN PIV

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ABSTRACT

Turbulence modulation by particles in a fully-developed channel flow was investigated by Lagrangian measurement technique. Digital particle image velocimetry and a high-speed CCD camera mounted on a shuttle moving with particle mean streamwise velocity were used to simultaneously detect particle and fluid information amongst particles. Turbulence augmentation by particles greater than the Kolmogorov micro scale was induced by the region of the high-strain rate and high vorticity on both sides of particles. The Rapid Distortion Theory first applied to dispersed two-phase turbulent flows indicated that the directional non-isotropic structure was observed with an increase in particle volumetric fraction. The enstrophy amongst particles increased due to enstrophy production with a decrease in inter-particle spacing.

INTRODUCTION

One of the most important aspects of dispersed two-phase flows is the interactions of solid particles or liquid droplets with turbulent flow fields. In fact the performance of many engineering devices as well as natural processes encompass dispersed two-phase flows. An increased understanding of the fundamental phenomena that drive the complex interactions between the particle cloud and turbulent carrier flow is needed to ultimately improve the design of engineering devices in which these flows occur. The available experimental data show that the addition of small particles suppresses turbulent kinetic energy, while large particles increase turbulence (Tsuji and Morikawa 1982, Tsuji *et al.* 1984, Fleckhause *et al.* 1987, Rogers and Eaton 1991, Kulick *et al.* 1994). While the works using direct numerical simulation by Squires and Eaton (1990), and Elghobashi and Truesdell (1993) have advanced our understanding, the effect of particles on turbulence modulation is not fully resolved up to this day.

To date the "macro"-analyses present the following consensus interpretation. Gore and Crowe (1989*a*, 1989*b*) compiled data, foremost expressing the ratio of particle diameter to a characteristic length scale of the turbulence as a key parameter. They suggested that the critical value of the ratio separating regions of attenuation and augmentation was on the order of 0.1. Eaton (1994) reviewed past experiments and simulations in turbulence modification of simple flows and showed significant turbulence attenuation for mass loading ratios greater than 0.1. Sato and Hishida (1996) introduced the multiple-time-scale concept to more accurately model the energy transport due to particles from the production range to the transfer range. An outcome of these works revealed that the particle size and loading have a significant influence on turbulence modification.

The objective of this study is to investigate the turbulence distortion process in the presence of particles in a turbulent channel flow via Lagrangian measurement. A non-uniform distortion of turbulence amongst particles was first detected by a digital particle image velocimetry (Sakakibara *et al.* 1993) using a high-speed CCD camera mounted on a shuttle moving with particle streamwise mean velocity. The present study focuses on the "directional" flow structure in terms of the "inter-particle spacing" (Crowe and Gillandt 1998, Crowe 1998).

EXPERIMENTAL SETUP

Experimental Facility

The present experiments were performed in a two-dimensional, vertical channel with downflow of water, identical to that of Sato *et al.* (1997). The channel was vertically oriented so that the gravitational force on the particles was aligned with the direction of flow. The particle feeder was mounted above the entrance of the channel. The particle loading uniformity was ensured by vibrating the particle feeder with a DC-motor. Boundary-layer trips were affixed to both walls at the entrance of a 1.0 m long, 30×250 mm test section. The flow exited the test section into a drain tank, where the particles were collected for reuse. Measurements confirmed that the flow was fully-developed at the test section's centerline. All the experiments were run at a centerline mean velocity of 155 mm/s, corresponding to a Reynolds number of 5,740 based on channel width. The temperature of water was kept constant by using a heater to avoid varying fluid properties. The Kolmogorov micro length scale, η, at the channel centerline was 252 μm which was

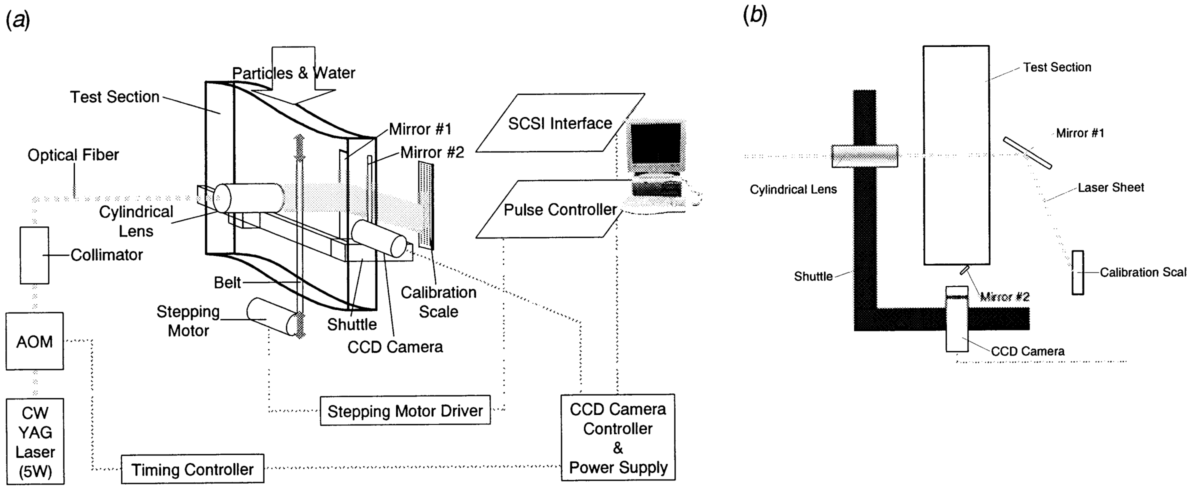

Figure 1. Schematic of experimental apparatus. (*a*) Schematic of digital particle image velocimetry and vertical water channel; (*b*) Top view of experimental facility.

Table 1. Particle properties

Properties	glass	glass
number mean diameter d_p [μm]	189.5	396.4
stan. dev. of diameter σ_p [μm]	18.0	32.3
density ρ_p [kg/m^3]	2,590	2,590
terminal velocity V_t [mm/s]	43.1	102
particle time constant τ_p [ms]	4.40	10.4
particle Reynolds number Re_p	10.1	50.0
particle mass loading ratio ϕ_{mass}	4.10×10^{-4}	3.32×10^{-4} 8.63×10^{-4}
particle volumetric fraction ϕ_{vol}	1.77×10^{-4}	1.80×10^{-4} 3.32×10^{-4}

calculated by direct measurements of dissipation rate of turbulent kinetic energy.

Two classes of particles were used in the present set of experiments and their characteristics are compiled in table 1. The particle size was chosen with the following strategy: (i) smaller than the energy-containing scales of the flow and (ii) comparable to or slightly greater than the Kolmogorov micro scale of turbulence. The particle size distributions were determined by using successively smaller sieves, while the particle sphericity was checked using a microscope.

Experimental Techniques

Lagrangian statistics of both phases were obtained using a digital particle image velocimetry (DPIV) developed by Sakakibara *et al.* (1993), Hishida *et al.* (1996) and Sato *et al.* (1997). Shown in figure 1 is a schematic illustration of the digital particle image velocimetry. Velocities were calculated by a cross-correlation technique between two images. Polyethylene particles of 5 μm (density of 960 kg/m^3) were added as a tracer to the liquid phase. The thickness of the YAG-laser light sheet was 3.0 mm in the test section.

A high speed CCD camera (KODAK Motion Corder Analyzer SR-500) and a cylindrical lens were mounted on a moving shuttle in order to establish the Lagrangian measurement technique. The present measurement system simultaneously detected particles and fluid information. The shuttle moved from top to bottom, parallel to the water channel with mean streamwise velocity of the particles focused upon. A stepping motor was used to control the shuttle's velocity and it is necessary to calibrate influence of vibration of shuttle on its velocity. A special calibration scale in which solid marks were randomly distributed as if particle concentration were detected,

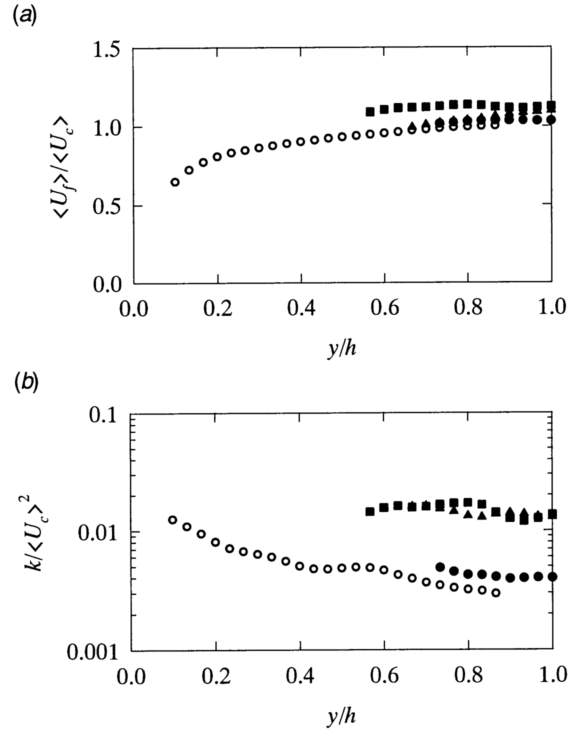

Figure 2. Profiles of (*a*) mean streamwise velocity of water; (*b*) turbulent kinetic energy of water in the presence of glass particles. ○, ϕ_{vol} = 0.0; ●, glass 189 μm at ϕ_{vol} = 1.77×10^{-4}; ▲, glass 396 μm at ϕ_{vol} = 1.80×10^{-4}; ■, glass 396 μm at ϕ_{vol} = 3.32×10^{-4}.

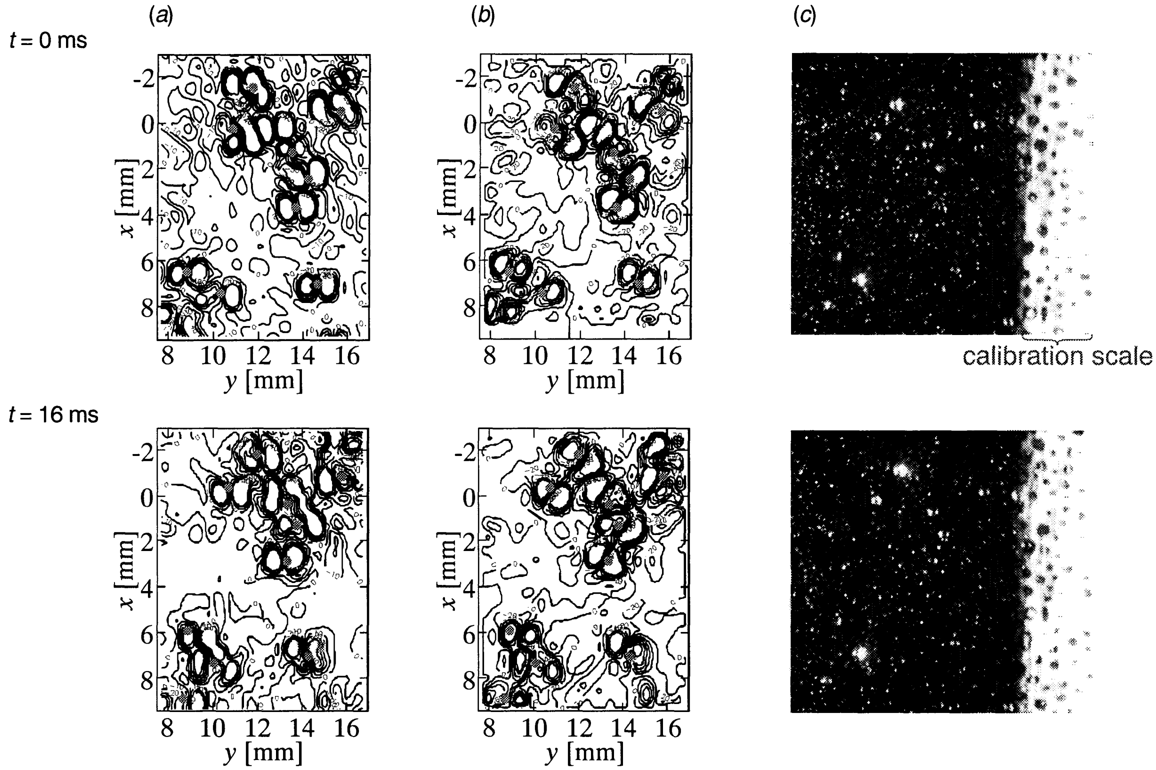

Figure 3. Time development of instantaneous maps of (*a*) the rate of strain, s^L_{12}; (*b*) vorticity, ω^L_{12}; (*c*) images of flow field in the presence of 396 μm glass particles at volumetric fraction of 3.32×10^{-4}. Range of s^L_{12} is [-40, -30, -20, -10, 0, 10, 20, 30, 40] and ω^L_{12} is [-80, -60, -40, -20, 0, 20, 40, 60, 80]. Both coordinates were fixed in the Lagrangian reference frame. This means that a Cartesian (Eulerain) coordinate system with the origin at boundary-layer trips was not used in figures 3, 4, and 5.

as shown in figure 1 and figure 3(*c*), was added to the present system (Sato *et al.* 1997). The CCD camera captured the images of flow field in the test section and the calibration scale by using mirror 2, illuminated by a laser sheet via mirror 1. Figure 3(*c*) displays a representative time series of the instantaneous flow field and the calibration scale captured by the CCD camera. By using the DPIV system combined with the moving shuttle it is possible to calibrate the shuttle's vibration per unit image. The measurement uncertainty in these experiments due to the velocity calibration was 2.0% for instantaneous velocity measurements. The particles and surrounding fluid were measured by the high-speed CCD camera in a matter of few seconds. Subsequently velocities in time series were calculated within an interval of 1/62.5 s (= 16 ms).

RESULTS AND DISCUSSION

Properties of the Eulerian Field

Figure 2 shows profiles of the mean streamwise velocity and turbulent kinetic energy of water in the presence of glass particles. The coordinates of the figure have nondimensionalized values based on the centerline mean velocity in single phase, $\langle U_c \rangle$, of 155 mm/s and a channel width, h, of 30 mm. It is observed that the particle-laden mean fluid velocity was accelerated by only 396 μm glass particles at high particle volumetric fraction and all the particles augmented the turbulent kinetic energy. The degree of turbulence augmentation in the core region increases with increasing particle volumetric fraction. In the present paper the distortion process by particles at the channel centerline is reported.

Ongoing research investigations conducted by the authors using the laser technique indicate that particles which are comparable to or slightly greater than the Kolmogorov length scale of the flow with a large particle time constant augment the turbulence energy, while particles smaller than the micro scale attenuate the turbulence (compiled in Hishida and Sato 1999). Sato and Hishida (1996), and Hishida and Sato (1999) then concluded that the effect of particles on turbulence structure is dependent upon the scale of turbulent flow, thus depending on this scale, one can propose a criterion whereby there is separating turbulence attenuation or augmentation in the presence of particles. Their analyses were performed from a "macroscopic" point of view; therefore a "microscopically" viewed investigation of the existing data has proven to be somewhat controversial.

Crowe and Gillandt (1998), and Crowe (1998) recently proposed an inclusion of "inter-particle spacing" into the model of the dissipation rate. The discussions in the following subsections have been inspired by the idea of "inter-particle spacing" and emphasize the turbulence distortion in the presence of particles from a "microscopic" point of view.

Distortion of Turbulence Continuously amongst Particles

The results presented in this and the following sections use physical quantities in the Lagrangian reference frame. The

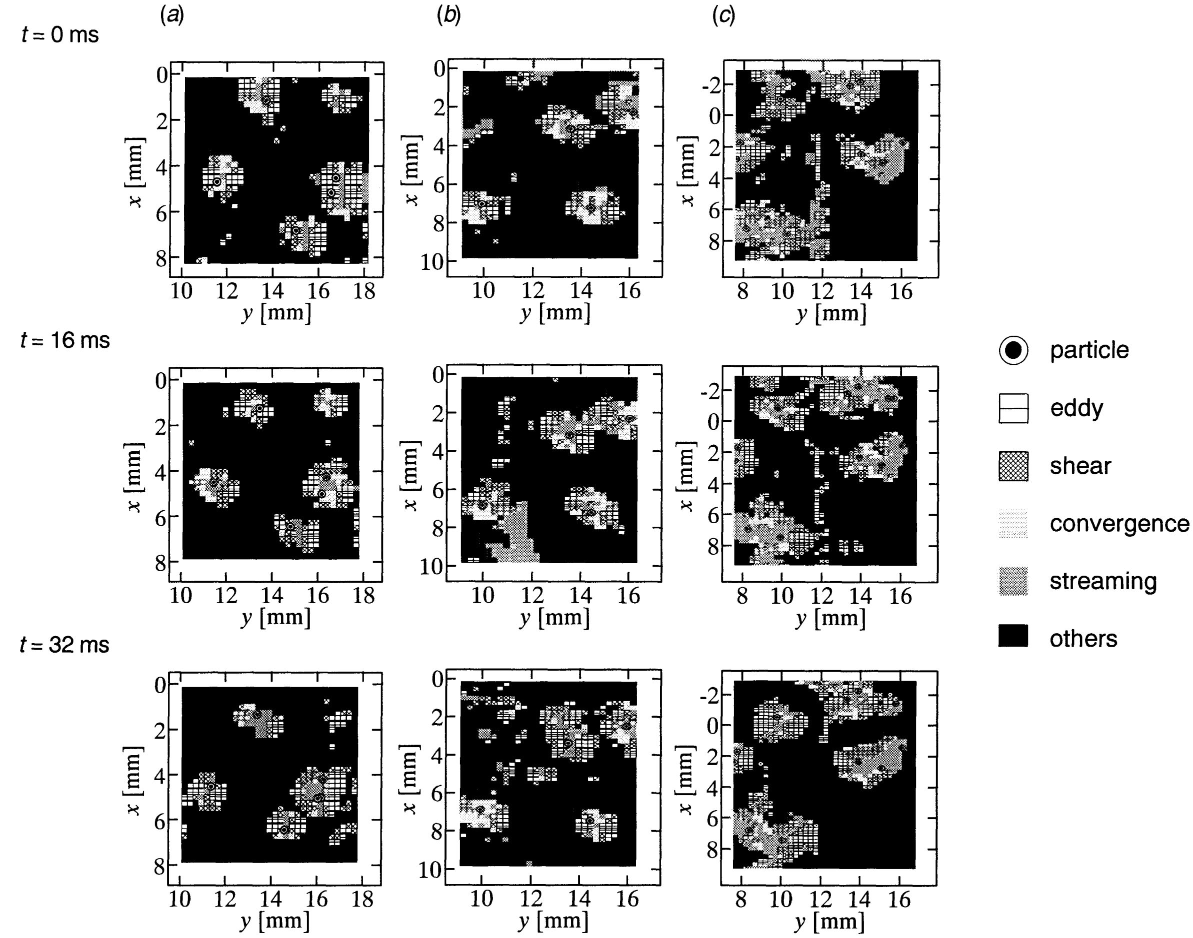

Figure 4. Time development of non-isotropic flow structure in the presence of particles based on the RDT by Kevhahan (1993). (*a*) Glass 189 μm at $\phi_{vol} = 1.77\times10^{-4}$; (*b*) Glass 396 μm at $\phi_{vol} = 1.80\times10^{-4}$; (*c*) Glass 396 μm at $\phi_{vol} = 3.32\times10^{-4}$.

present study adopts the fluctuating fluid velocity expressed as u^L_{f}. The rate of strain is defined as,

$$s^L_{ij} = \frac{1}{2}\left(\frac{\partial u^L_{f_i}}{\partial x^L_j} + \frac{\partial u^L_{f_j}}{\partial x^L_i}\right), \qquad (1)$$

and the vorticity, ω^L_{ij}, is calculated by the circulation around each grid point, which was found to vary within 3% of the following definition:

$$\omega^L_{ij} = \frac{1}{2}\left(\frac{\partial u^L_{f_i}}{\partial x^L_j} - \frac{\partial u^L_{f_j}}{\partial x^L_i}\right). \qquad (2)$$

Figure 3 illustrates the time development of instantaneous maps of the rate of strain, s^L_{12}, vorticiy, ω^L_{12}, and images of the flow field in the presence of 396 μm glass particles at a volumetric fraction of 3.32×10^{-4}. It is observed that decreasing values of distance between particles, i.e., inter-particle spacing, have a significant effect on the rate of strain and the vorticity. This effect becomes more apparent as particle volumetric fraction increases. The inter-particle spacing, l_p, on the upper side of each figure has values of $l_p/\eta \approx 10$ and $l_p/l_e \approx 0.6$, where l_e is the energy-containing eddy scale. This means that there exist a few particles (a calculated value using experimental data shows 1.7) inside the energy-containing eddy as the turbulence was augmented by particles greater than the Kolmogorov micro scale. In contrast when particles attenuate turbulence, the number of particles of the order of 10^3 can be found inside the energy-containing eddy using direct numerical simulation (Sato *et al.* 1998, unpublished).

We can see that in the regions of high-strain rate contain large vorticity on both sides of the particle. We subsequently think it is plausible, from a "microscopic" point of view, that "directional" interaction between flow and a particle consequently induced distortion of turbulence by particles. We believe this to be a physically plausible argument not yet presented based on existing data sets.

Directional Non-Isotropic Flow Structure Based on the Rapid Distortion Theory

Sato and Hishida (1996) first pointed out energy transfer from large to small scale by particles, subsequently reflected in a multiple-time-scale model. That is to say, the large-scale structures determine the distortion experienced by small-scales and by the particles. In this subsection the extent of this distortion is investigated using Rapid Distortion Theory (RDT). The flow is divided into different structural types using an algorithm developed by Kevlahan (1993), based on values of velocity and the parameter Σ^L defined as,

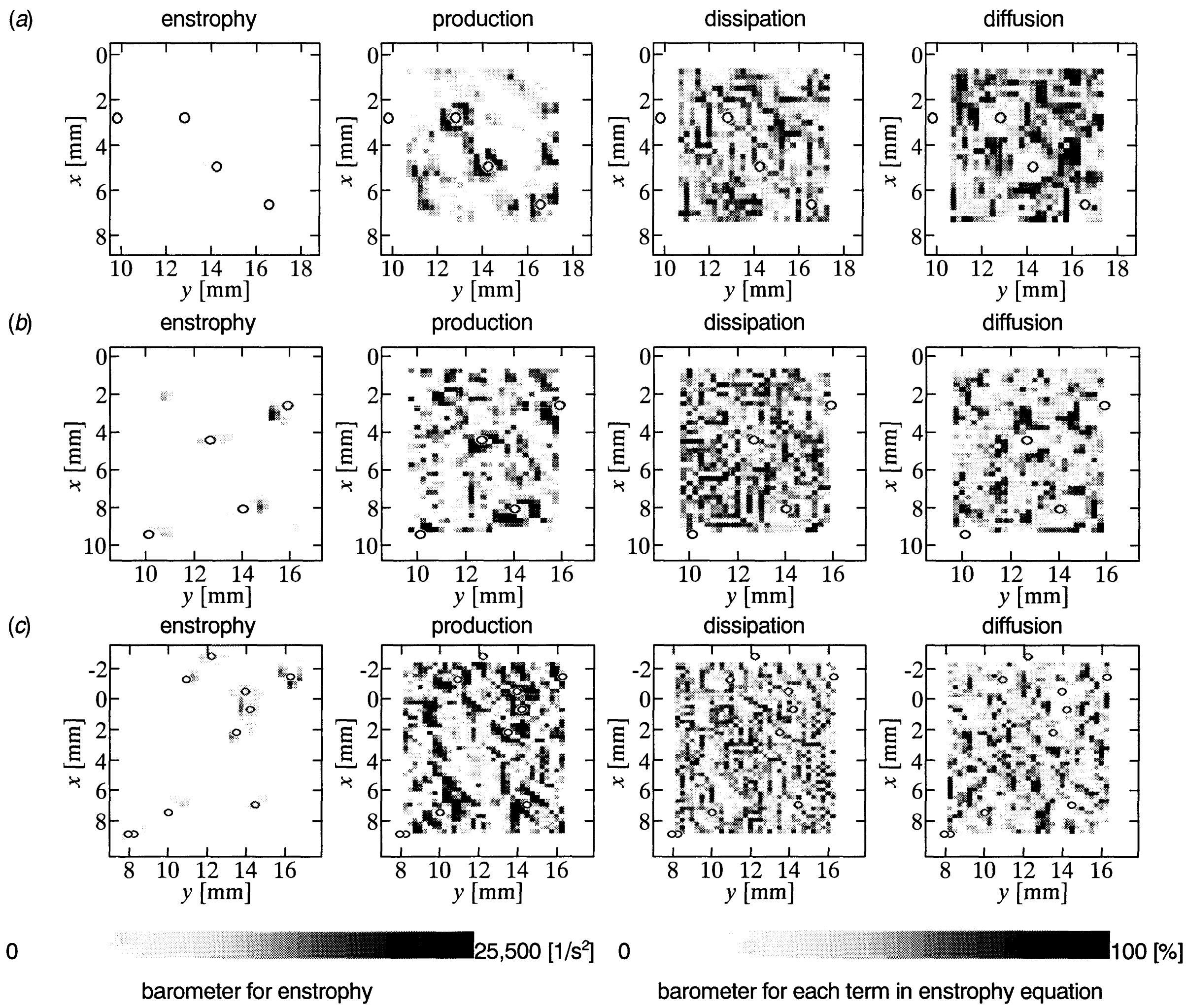

Figure 5. Bit map images of the enstrophy and each term in the enstrophy evolution equation; production, dissipation and diffusion terms, in the presence of (*a*) glass 189 μm at $\phi_{vol} = 1.77\times10^{-4}$; (*b*) glass 396 μm at $\phi_{vol} = 1.80\times10^{-4}$; (*c*) glass 396 μm at $\phi_{vol} = 3.32\times10^{-4}$. The enstrophy distribution has dimensional values in 1/s^2. The distribution maps of each term have values of the ratio to the total in the right-hand-side of enstrophy evolution equation.

$$\Sigma^L = \left(s_{ij}^{L^2} - \omega_{ij}^{L^2}\right)\Big/\left(s_{ij}^{L^2} + \omega_{ij}^{L^2}\right), \tag{3}$$

where s^L_{ij} is the rate of strain tensor, and ω^L_{ij} is the vorticity tensor in the Lagrangian reference frame. The four basic structural types are:

(1) eddy: $\Sigma^L < -1/3$.
Kevlahan (1993) used values of pressure, p, to distinguish between eddy ($p < 0$) and donor eddies ($p > 0$). However, in the present study it is impossible to measure fluctuating pressure using DPIV. Therefore these two regions have been combined into one region. By using a threshold value of 1/3 we naturally focus on the flow structure in the region of the energy-containing eddy.

(2) shear: $-1/3 \le \Sigma^L \le 1/3$.

(3) convergence: $\Sigma^L > 1/3$.

(4) streaming:

$$\left|u_{f_i}^L\right| > \sqrt{\left\langle u_{f_i}^{L^2}\right\rangle}, \left|\omega_{ij}^L\right| < \frac{1}{2}\sqrt{\left\langle\left|\omega_{ij}^L\right|^2\right\rangle}, \left|s_{ij}^L\right| < \frac{1}{2}\sqrt{\left\langle\left|s_{ij}^L\right|^2\right\rangle}.$$

Figure 4 shows the time development of instantaneous flow structure amongst particles based on the RDT. With wide inter-particle spacing, as supported by figure 4(*a*) for 189 μm particles at $\phi_{vol} = 1.80\times10^{-4}$, the eddy region is noticeable especially along both sides of several particles. Then complexity of the flow structure evidently increases in (*b*), as particle size increases to 396 μm and then additionally as volumetric fraction increases, yielding narrow inter-particle spacing. One can see that a non-isotropic flow structure appears amongst particles in figure 4(*c*). It can be concluded that particles greater than the Kolmogorov length scale significantly distort the flow around particles, yielding a narrow inter-particle spacing and "directional," non-isotropic and complex interaction of the flow structures.

Small-Scale Structure of Turbulence Modulation

Since non-uniform distortion of turbulence is characterized by vortex structure, further insight into the small-scale structure of dispersed two-phase turbulent flow may be provided by the enstrophy, ω_i^{L2}, amongst particles. In order to examine the small-scale structure, the enstrophy evolution equation is defined as,

$$\frac{D}{Dt}\left(\frac{1}{2}\omega_i^{L^2}\right) = \omega_i^L \omega_j^L s_{ij}^L + \nu \frac{\partial^2}{\partial x_j^{L^2}}\left(\frac{1}{2}\omega_i^{L^2}\right) - \nu\left(\frac{\partial \omega_i^L}{\partial x_j^L}\right)^2 - \text{(extra term due to particles)}, \quad (4)$$

where the terms on the right-hand side of equation (4) are the enstrophy production, which is due to vortex stretching, enstrophy diffusion, enstrophy dissipation and lastly an additional term due to particles.

Figure 5 depicts bit map images of the enstrophy and the ratio of each term to the total of the right-hand-side of equation (4), in the presence of particles. Except for the fourth term the ratio to the total was calculated using an absolute value of each term. The intensity scale of each quantity is given at the bottom of the figure in gray-scale. The enstrophy is largest in figure 5(*c*); that is, for 396 μm particles at $\phi_{vol} = 3.32\times10^{-4}$, inter-particle spacing is substantiated by enstrophy production. For $\phi_{vol} = 1.80\times10^{-4}$, the region of large enstrophy is located at the sides of the particles, as shown in figure 5(*b*). A concentration of enstrophy appears in the region where the inter-particle spacing is narrower. Figure 5(*c*) indicates that the enstrophy production significantly contributes to total enstrophy in comparison to figure 5(*a*).

We can thus conclude that the dominant factor responsible for the small-scale structure of turbulence modulation is the inter-particle spacing which has been neglected in the modeling of dispersed two-phase flows. The present "microscopic" approach indicates that the inter-particle spacing and the "directional" interaction must be considered in the process of turbulence distortion by particles. It thus appears that turbulence models derived from a large-scale structure of turbulence approach does not accurately simulate turbulence modulation in the presence of particles. We thus propose an approach taking into consideration of the relationship between the inter-particle spacing and the scale of turbulence (Sato and Hishida 1996), as well as the "directional" non-isotropic flow structure.

CONCLUSIONS

A Lagrangian measurement technique has been used to investigate the distortion of turbulence in the presence of particles. The present study focused on the small-scale structure of turbulence modulation in terms of the inter-particle spacing. Two classes of particles at particle volumetric fraction up to $\phi_{vol} = 3.32\times10^{-4}$ were employed to provide charcteristic values of length ratio and distance between particles, i.e., inter-particle spacing.

Turbulence augmentation by particles was induced by detected regions of high-strain rate and the high vorticity along side of particle. An application of the Rapid Distortion Theory to dispersed two-phase turbulent flows indicated a "directional" interaction between the flow field and particles as the particle volumetric fraction increased.

Further insight into the small-scale structure of turbulence modulation by particles was obtained by examining the enstrophy distribution. With a decrease in inter-particle spacing the enstrophy amongst particles increased, mainly due to enstrophy production. We thus propose an approach that considers the effect of the inter-particle spacing and the "directional" nature of non-isotropic flow structure, in terms of turbulence modeling for dispersed two-phase flows.

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