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Effect of mixing gas–fine particle suspension flow with small amount of coarse ones in a horizontal pipe

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Abstract

A phase doppler anemometer (PDA) was used to measure axial components of mean and fluctuation velocities of air and particles in a pipe of 80 mm inside diameter. Glass beads having mean diameter of 55 and 468 μm, respectively, were used, the density being 2590 kg/m^3. The fine particles suppress the air flow turbulence while the coarse ones increase it. Mixing fine particles with coarse ones in 5–9% in mass increases the turbulence above that by coarse ones alone. The acceleration pressure drop due to the particles is increased as well above that by the fine particles alone, which is larger than that by the coarse ones alone. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Pipe flow; Multi-phase flow; Gas–solid flow; Mixed particles; PDA; Turbulence

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1. Introduction

It is important to examine the interaction between the gas flow turbulence and particles in the gas–solid two-phase flow to construct a turbulence model for the numerical simulation. There are already many references on this topic. The interaction is affected by factors like Reynolds number, relative velocity, mass flow rate ratio, physical and geometrical properties of particle and pipe, and so on. To examine the effect of particle size, Gore and Crowe (1989) introduce a ratio of particle diameter d to turbulence scale le, which can be evaluated by integral length scale of turbulence or size of energy containing eddy, and show that the turbulence is suppressed when d/le is below 0.1 and is enhanced above 0.1. Hetsroni (1989) explains by using the measurement according to Tsuji and Morikawa (1982a) that the turbulence is suppressed when $Rep \sim O\ (0.1)$

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and is enhanced when $Rep \sim$ O (1000) and that there is a mixed effect when $Rep \sim$ O (100), where *Rep* is the particle Reynolds number refers to the mean relative velocity between air and particle. In general, the fine particle suppresses the turbulence and the coarse one enhances it. Hussainov et al. (1999) investigated on turbulence modulation by using the grid-generated turbulence and show the generation of turbulence by the glass particles of 700 μm diameter with an increase of the particle mass loading. Yuan and Michaelides (1992) propose a simplified model for the total modification which is consisted of the reduction term and the production one of turbulence and show that this model predicts rather well the observed changes of turbulence intensity. Kenning and Crowe (1997) propose a simple physical model for turbulence generation and dissipation by the particles and suggest the importance of interparticle spacing in establishing a turbulence length scale in particle–gas suspensions. Yarin and Hetsroni (1994a,b,c) theoretically investigate on the turbulence intensity in dilute two-phase flow. They (Yarin and Hetsroni, 1994a,b) use the modified mixing-length theory to calculate the effect of the particle size distribution on the turbulence of the carrier fluid and to estimate the level of the temperature fluctuations in two-phase mono-disperse and poly-disperse mixtures. Furthermore, they (Yarin and Hetsroni, 1994c) combine the theory which takes into account two sources of turbulence and turbulent kinetic energy approach to evaluate the effect of particle size on the turbulence of the carrier fluid. Also they show that the various types of particle-laden flows are described by the proposed model and rather good agreement with the experimental data is observed. Crowe (2000) shows that the models for turbulence modulation based on treating the carrier-phase momentum equation as if it were a single-phase flow equation with properties defined at a point leads to an incorrect result for a simplified flow configuration and introduces a model based on the volume-averaged equations for kinetic energy of the carrier phase and confirms that the equation for turbulence modulation shows the same trends as the experimental results. Bolio et al. (1995) and Bolio and Sinclair (1995) propose an interaction model that considers the inter-particle collision of large particles in the dilute two-phase flow and show that the large particles augment the turbulence.

While most of studies except for the theoretical investigation by Yarin and Hetsroni (1994a,b,c) have been focusing on the mono-dispersed particles that consist of uniform size particles, the effect of the multi-dispersed particles that consist of different size particles has hardly investigated.

In this paper, we call as mono-dispersed particles a batch of particles that have a single peak in size distribution with a small standard deviation and characterize its size by the mean diameter. We experimentally study the effect of fine and coarse particles on the gas flow separately in this sense, and then examine the effect of mixing fine particles with small amount of coarse particles, which particles we call multi-dispersed particles for convenience' sake in the following.

2. Experimental apparatus and procedure

Fig. 1 shows a schematic diagram of the experimental apparatus. The particle conveying system is closed and circulatory to which we applied a positive pressure system. The test section consists of transparent acrylate tubes placed horizontally. The pipe inside diameter, *D*, is 80 mm. We used a phase doppler anemometer (PDA) system in the backward-scattered mode and measured the axial velocities of air and particles. The focal length is 160 mm, the intersection angle is 13.54° and a diameter of sphere that is equivalent to the measuring volume is about 190 μm, the length in

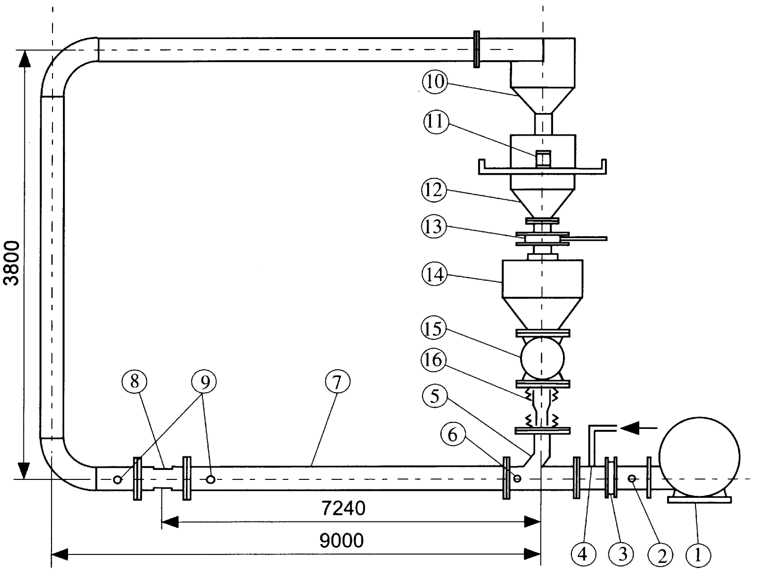

Fig. 1. Schematic diagram of experimental apparatus: (1) turbo blower; (2) thermometer; (3) quadrant flow nozzle; (4) tracer feeder; (5) particle feeder; (6) pressure sensor; (7) pipeline; (8) PDA measurement point; (9) differential pressure gauge; (10) cyclone separator; (11) loadcell; (12) particle tank; (13) valve; (14) electro magnetic feeder; (15) rotary feeder; (16) vibrating device.

traversing direction being 0.39 mm. Tracers for detecting the air flow velocity were ammonium chloride particles of mean diameter 4 μm and were seeded with the tracer feeder (4). The glass beads were separated from the air flow with the cyclone separator (10) and returned to the pipeline through the electro-magnetic feeder (14) and the rotary feeder (15). We also measured the mass flow rate of air and particles and the pressure distribution along the test section. For mono-dispersed particles we could measure both velocities of air and particles, but for the multi-dispersed particles the air velocity alone. The velocities of tracer particles and glass beads were discriminated by using the diameter information from PDA. The PDA probe was traversed to obtain the velocity profile in the vertical cross-section through the pipe axis at the position (8) about 7.2 m downstream from the feeder (4). Fig. 2 shows the size distribution of glass beads used in this experiment and Table 1 shows the properties of them. Both terminal settling velocities are 0.24 m/s for fine particle and 5.3 m/s for coarse one. According to the criterion by Gore and Crowe (1989), 55 μm particle will suppress the turbulence since d/le is smaller than 0.1 while 468 μm particle will augment the turbulence, provided that we put le as $0.05D$. We call the 55 and 468 μm particles the mono-dispersed particles when using separately without mixing. When mixing, we call them the multi-dispersed particles.

The measurement was carried out for three different mass flow rate ratios of particle to air, m, that is, $m = 0.05$, 0.1 and 0.2 and for three different pipe Reynolds numbers, $Re = UD/v$, that is, $Re = 42{,}200$ ($U = 8.1$ m/s), 84 900 ($U = 16.4$ m/s) and 158,000 ($U = 30.5$ m/s), where U represents the mean air velocity in the pipe cross-section and v the kinetic viscosity of air. The mixing ratio of fine particles to coarse ones in mass is 10:1 (coarse particles content 9.09%) and 20:1 (coarse particles content 4.76%).

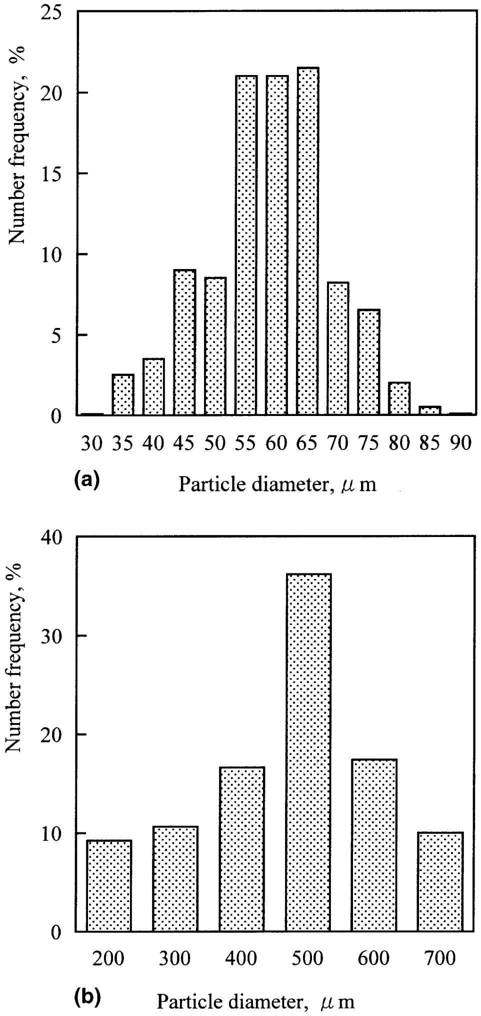

Fig. 2. Size distribution of test particles: (a) fine particles; (b) coarse particles.

The local mean velocity in the axial direction, $\bar{u}$, and the fluctuation velocity, $\sqrt{\overline{u'^2}}$, are calculated by

$$\bar{u} = \frac{1}{N} \sum_{i=1}^{N} u_i, \tag{1}$$

Table 1
Particle properties

Mean diameter (μm)	54.57	468.0
Standard deviation (μm)	6.11	54.75
Particle density (kg/m^3)	2590	2590
Refractive index (dimensionless)	1.51	1.51
d/le (dimensionless) (le = 0.05D)	0.0136	0.117

$$\sqrt{\overline{u'^2}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(u_i - \overline{u})^2}, \tag{2}$$

where u_i represents a sample velocity at the measuring point and N is the number of sample.

It is confirmed that the flow is fully developed because the profiles of static pressure along the pipe are linear in the measurement section and the mean velocity profiles of air alone obey the power law.

3. Results and discussion

3.1. Mono-dispersed particles

Fig. 3 shows the mean velocity of air and particles at $m = 0.1$ and that of air alone for $Re = 42{,}200$, 84,900 and 158,000, where y is the vertical distance from the pipe bottom. While, as to the air flow alone, we measured one side of the radius, we plotted the data on both radius

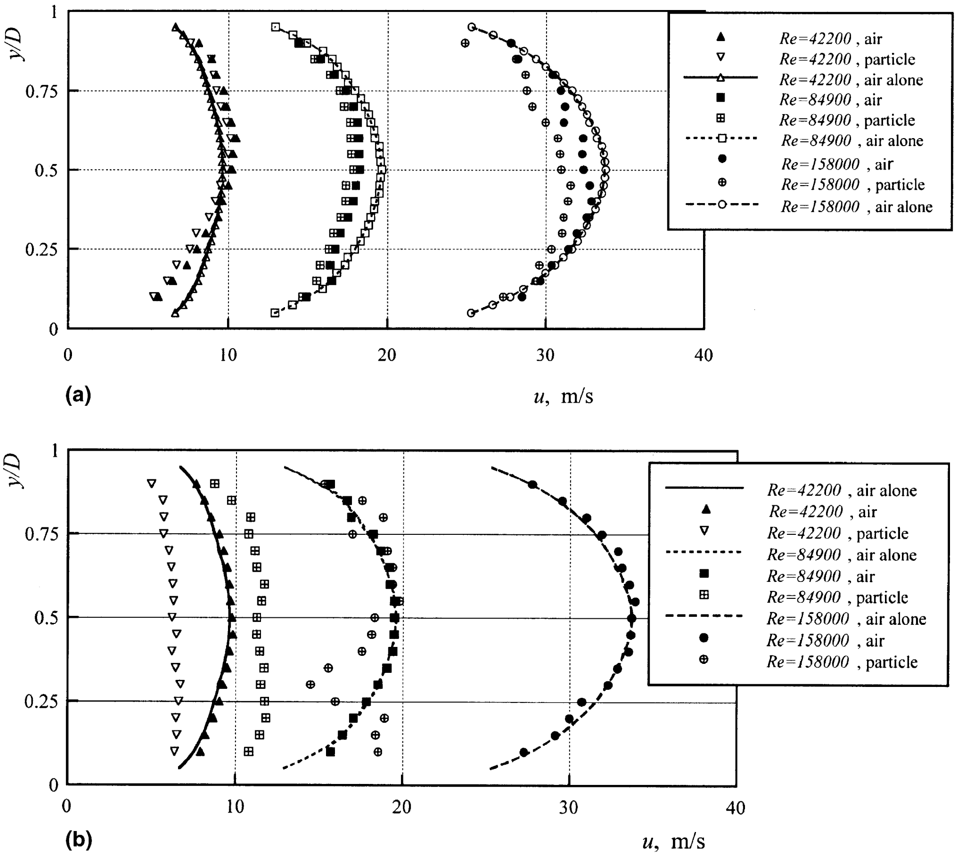

Fig. 3. Mean velocity profiles of air and particles ($m = 0.1$): (a) fine particles; (b) coarse particles.

assuming the axisymmetry. All profiles of air alone are fit by curves through the measuring points and are indicated by the curve except for Figs. 3(a) and 4(a). In the case of fine particle, the profile of air at $Re = 42{,}200$ is considerably asymmetric with respect to the pipe axis, the velocity in lower half being small. This is a typical profile observed in a degenerate homogeneous dispersed flow where most of the particles are transported near the pipe bottom. When increasing Re, that profile becomes symmetrical and the distortion from air alone is reduced. On the other hand, in the case of coarse particle, the profile of air is almost the same as that of air alone, the effect of particle on the mean air flow being small. While the velocity lag of fine particle to that of air is small, that of coarse particle is significant and the profile is almost flat.

As shown by the measurements by Tsuji and Morikawa (1982a) and Tsuji et al. (1982b), generally fine particles suppress the air flow turbulence and the coarse particles augment it. Fig. 4 shows the fluctuation velocity of air at $m = 0$ and 0.1 for $Re = 42{,}200$, 84,900 and 158,000. In the case of fine particle, $\sqrt{\overline{u'^2}}$ is decreased below that of air alone, except for the case of $Re = 42{,}200$, where the particles are exclusively transported near the pipe bottom. In the case of coarse particle, $\sqrt{\overline{u'^2}}$ is almost always increased and the increase is significant at $Re = 84{,}900$.

Fig. 5 shows the mean velocity of air and particles for $m = 0$, 0.05, 0.1 and 0.2 at $Re = 84{,}900$. The dotted line shows the velocity profile of air alone. The both profiles of air and particle become

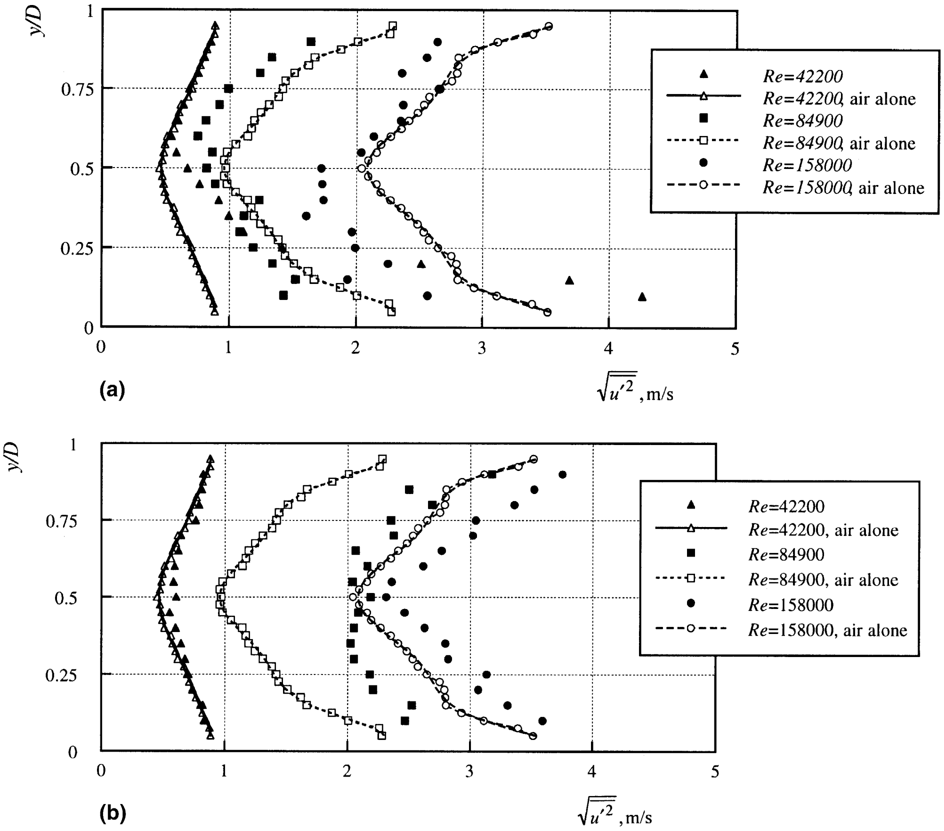

Fig. 4. Fluctuation velocity profiles of air ($m = 0.1$): (a) fine particles; (b) coarse particles.

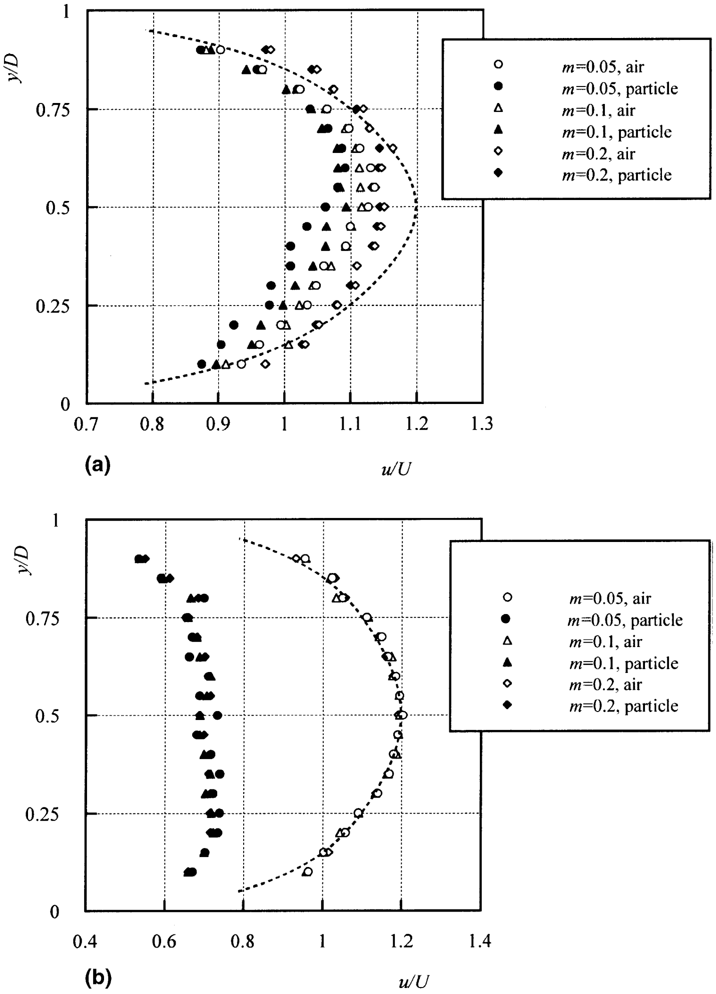

Fig. 5. Mean velocity profiles of air and particles ($Re = 84{,}900$): (a) fine particles; (b) coarse particles.

symmetrical with increasing m in the case of fine particles, while in the case of coarse ones the effect of m on the air velocity profiles is very small. In the case of coarse particles, for a given m, the particle number density is in inverse proportion roughly to the particle diameter to the 3rd power. Thus, for $m = 0.1$ the number of particles per 1 cm^3 is about 1 for the coarse particles and about 600 for the fine ones. This is because the effect of coarse particles on the mean air flow is small. Thus, for the present m and Re, the effect of particles on the mean air flow strongly appears in the case of fine particles.

Fig. 6 shows $\sqrt{\overline{u'^2}}$ for $m = 0$, 0.05, 0.1 and 0.2 at $Re = 84{,}900$. The dotted line shows the fluctuation velocity profile of air alone. It is found that the reduction of $\sqrt{\overline{u'^2}}$ is the most significant for $m = 0.1$ in the case of fine particles, which suggests that there is the most effective mass flow rate ratio for the suppression of air flow turbulence.

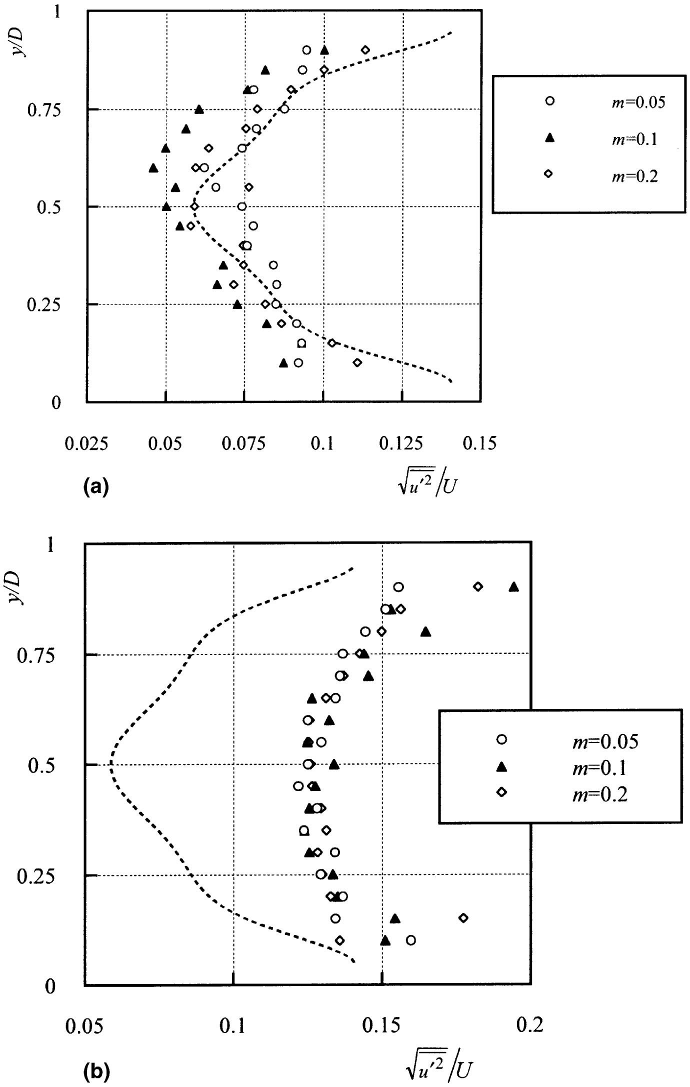

Fig. 6. Fluctuation velocity profiles of air for different mass flow rate ratios ($Re = 84{,}900$): (a) fine particles; (b) coarse particles.

In Fig. 7, we plotted the fluctuation velocity ratio $\sqrt{u'^2}/\sqrt{u_0'^2}$ against the particle Reynolds number Rep, where $\sqrt{u'^2}$ represents the fluctuation velocity of mono-dispersed particles flow, $\sqrt{u_0'^2}$ that of air flow alone and Rep is defined as $(\bar{u} - \bar{u}_p)d/\nu$, $\bar{u}$ and $\bar{u}_p$ being the local mean velocities of air and particle, respectively. It is found that the turbulence almost always increases for coarse particles and decreases for fine particles except for $Re = 42{,}200$, where the particle is not transported homogeneously dispersed across the pipe cross-section. Generally, the particles with low Rep suppress the turbulence and those with high Rep enhance that as concluded by Hetsroni (1989), but in order to predict the effect of particle on the turbulence, the particle flow pattern should be considered as well.

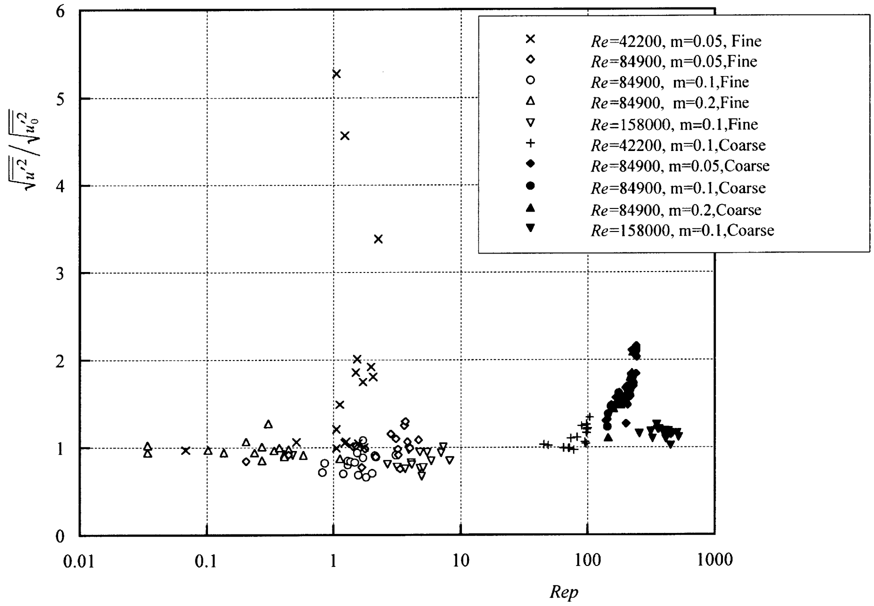

Fig. 7. Fluctuation velocity ratio and particle Reynolds number.

3.2. Multi-dispersed particles

We examined the effect of mixing fine particles with small amount of coarse particles for $m = 0.05$, 0.1 and 0.2 at $Re = 84{,}900$. Fig. 8 shows the effect on the mean air velocity profile. The dotted lines show those of air alone. When m is 0.05, the profile for multi-dispersed particles flow becomes almost the same as that of air alone for both mixing ratios. However, when m is increased, the effect of addition of coarse particles diminishes, that is, that profile becomes almost the same as that of fine particles alone and the profile in the central region becomes uniform. The distortion from that of air alone is significant for $m = 0.2$ and the mixing ratio 10:1, where the velocity in the central region is reduced below the case of fine particles alone.

Fig. 9 shows the effect on the fluctuation velocity profile. The dotted lines show those of air alone. It is found that the fluctuation velocity of fine particles is increased by adding the small amount of coarse particles and becomes almost the same order of magnitude as those of coarse particles alone even when the mass flow rate ratio is small as $m = 0.05$. Generally, $\sqrt{u'^2}$ is increased with increasing mass flow rate ratio above that for coarse particles alone. When $m = 0.2$, the increase is significant particularly in the lower half of the pipe cross-section. It is inferred that the velocity of fine particles is decreased by the collision with the coarse ones, and then most of fine particles are transported in the lower half of the pipe cross-section, which in turn enhances the turbulence. Furthermore, with increasing fraction of coarse particles, $\sqrt{u'^2}$ is also increased. We can conclude that by mixing fine particles with a small amount of coarse particles the turbulence is enhanced above that of coarse particles alone.

The particles in the theory by Yarin and Hetsroni (1994a) are in particle Reynolds number $Rep < 110$ and the effect of turbulent wakes can be neglected. However, as shown in Fig. 7, the

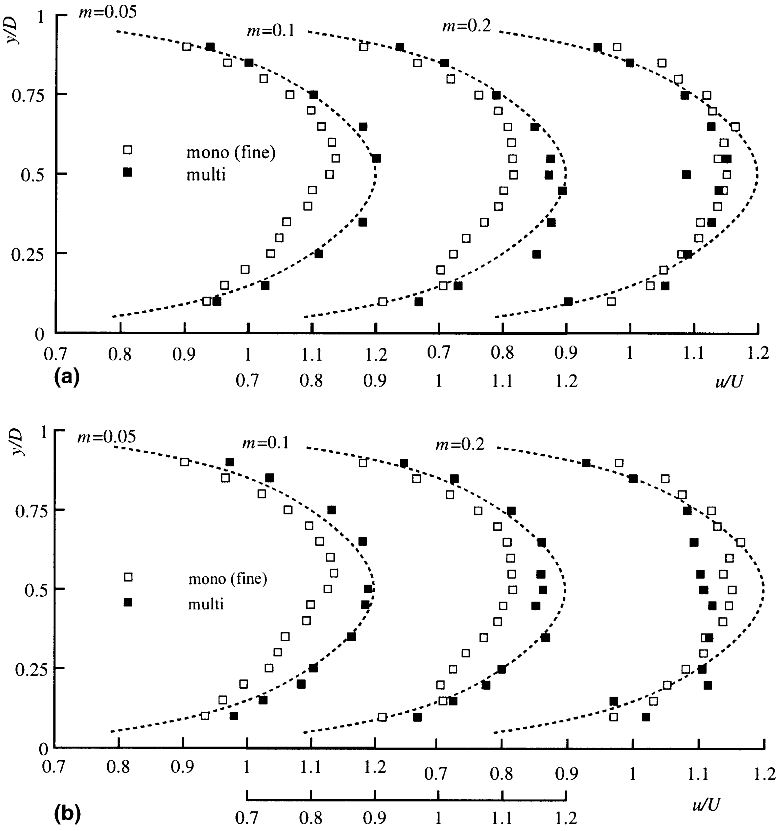

Fig. 8. Effect of mixing fine particles with coarse ones on mean air velocity profile ($Re = 84{,}900$): (a) 4.76% (20:1); (b) 9.09% (10:1).

coarse particles in this experiment are not in $Rep < 110$ except the case of flow near the pipe bottom and enhance the air flow turbulence, though the small particles in this experiment are in $Rep < 110$. While the conditions and assumptions are not always satisfied by our measurement, their following conclusions are qualitatively the same as our results; an increase in the content of coarse particles is accompanied by the turbulence intensity increase in the poly-disperse system and the turbulence intensity of the poly-disperse system is higher when the diameter of coarse particles in the poly-disperse system is larger than the diameter in the mono-disperse system in the case of equal total mass contents. While their model (Yarin and Hetsroni, 1994c) takes into account both the suppression of turbulence due to fine particles and its enhancement due to coarse ones, it is difficult to explain the result shown in Fig. 9 by their model.

3.3. Acceleration pressure drop

Fig. 10 shows the acceleration pressure drop due to the particles versus the mass flow rate ratio for the mono-dispersed and multi-dispersed particles at $Re = 84{,}900$. It is confirmed that the acceleration pressure drop due to the fine particles alone is larger than that due to the coarse ones

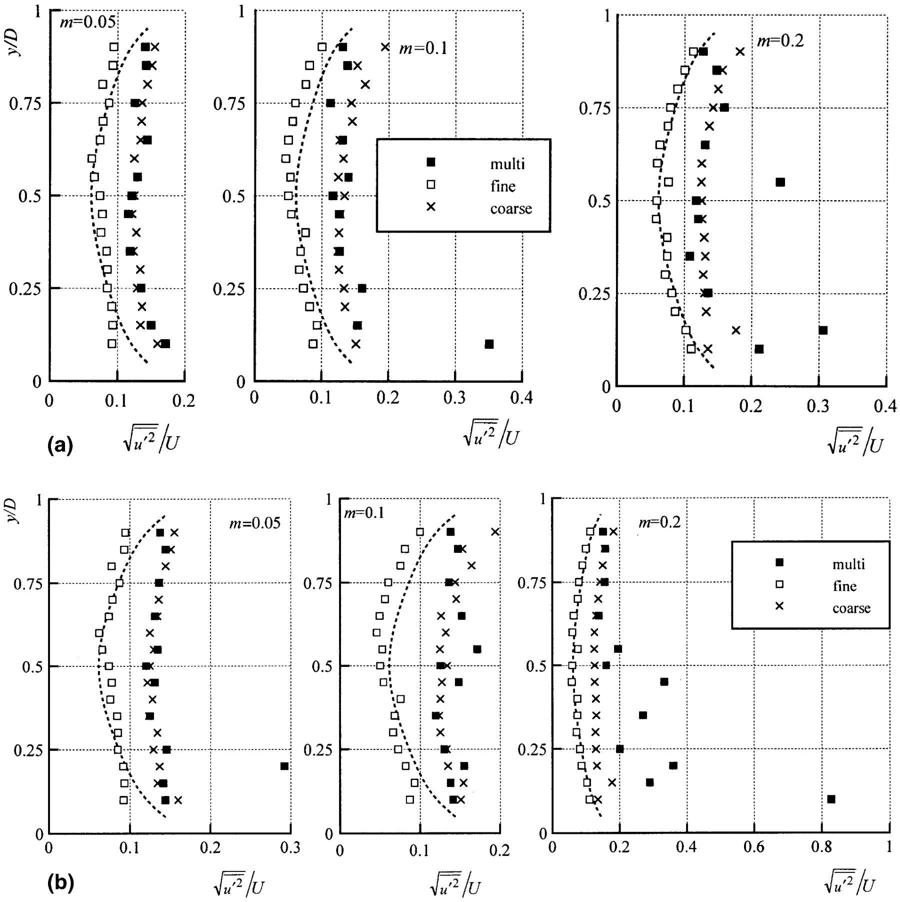

Fig. 9. Effect of mixing fine particles with coarse ones on fluctuation velocity of air ($Re = 84{,}900$): (a) 4.76% (20:1); (b) 9.09% (10:1).

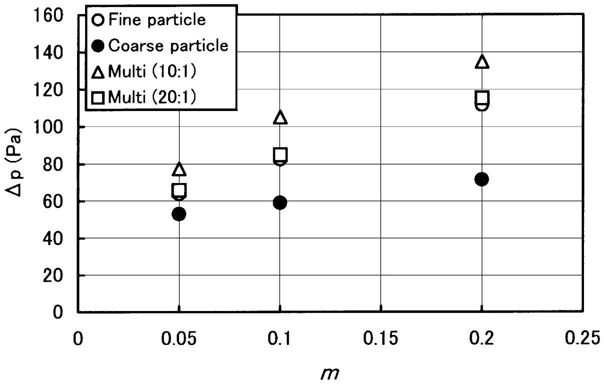

Fig. 10. Acceleration pressure drop due to particles versus mass flow rate ratio.

alone, as shown by Siegel (1970). Furthermore, it is found that the pressure drop of fine particles is increased by adding coarse particles and that the drop is increased with increasing fraction of coarse particles. The results for $m = 1$ at $Re = 42.200$ and 158,000 were also similar. However, as to additional pressure drop due to the particles in equilibrium region it was difficult to find the difference between the mono-dispersed and multi-dispersed particles.

4. Conclusions

The influence of dispersion of particle size on the air flow turbulence was experimentally examined by using a phase doppler anemometer (PDA) in a horizontal pneumatic pipeline. In this experiment, the fine particles suppress the gas flow turbulence and the coarse ones increase the turbulence. It was found that there is an effective mass flow rate ratio for the suppression of turbulence by fine particles and that by adding the coarse particles to fine particles in 5–10% in mass the turbulence is increased above that by the coarse particles alone. Furthermore, the acceleration pressure drop due to the particles is also increased by adding the coarse particles above the fine particles alone, which is larger than that due to the coarse particles alone.

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