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PARTICLE MOTION AND TURBULENCE IN DENSE TWO-PHASE FLOWS

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Abstract—Measurements of particle mean and r.m.s. velocity were obtained by laser–Doppler anemometry in a descending solid–liquid turbulent flow in a vertical pipe with volumetric concentrations of suspended spherical particles of 270 μm mean diameter in the range 0.1–14%. Similar measurements were obtained in the flow downstream of an axisymmetric baffle of 50% area blockage placed in the pipe with volumetric concentrations of 310 μm particles up to 8% and of 665 μm particles up to 2%. In order to enable measurements in high particle concentrations without blockage of the laser beams the refractive index of the particles was matched to that of the carrier fluid.

The results show that the particle mean velocity profiles become more uniform and the particle r.m.s. velocity decreases with increasing concentration in both flow cases. The particle mean velocity in the pipe flow also decreases with concentration and the relative velocity, the difference between the particle velocity and the fluid velocity in single-phase flow, decreases with increasing Reynolds number. The length of the recirculation region downstream of the baffle was shorter than in single-phase flow by 11 and 24% for particle concentrations of 4 and 8%, respectively. The particle mean velocities were hardly affected by size for concentrations up to 2%, but the r.m.s. velocities were lower with the larger particles.

1. INTRODUCTION

The flow of suspensions of particles can be influenced by drag, turbulence, the Magnus effect, the particle free-fall velocity, the virtual mass effect, particle–particle interaction, particle inertia and the crossing-trajectories effect. Previous investigations have been concerned with the determination of one or more of these effects on mostly gas–solid two-phase flows. A large number of related investigations have been reported in the literature and only a representative sample is considered below. The complexity of the two-phase flow processes limits the ability to calculate these flows accurately while, in experiments, the presence of the dispersed phase results in damage or contamination of measurement probes used or, with optical methods, in blockage of the beams at concentrations above ~0.5% by vol.

Measurements of solid suspensions have been limited to concentrations below 1% (e.g. Lee & Durst 1982) and, in a few exceptions to around 5% (e.g. Zisselmar & Molerus 1978). Particle–particle interaction is expected to be negligible for spherical particles with volumetric concentrations below 0.3% (Lumley 1978). At low Reynolds numbers (laminar flow) the fluid and particle velocities are identical, even for large concentrations of solids, if the particles are neutrally buoyant (Cox & Mason 1971; Yianneskis & Whitelaw 1984). Wells & Stock (1983) investigated the effects of crossing trajectories and of particle inertia on the dispersion of particles in turbulent flow; they found that for both 5 and 57 μm size particles inertia effects decreased the particle r.m.s. velocities and that crossing-trajectory effects can decrease the particle dispersion but were negligible when the particle free-fall velocity was smaller than the fluid r.m.s. velocity. Birchenough & Mason (1976), Lee & Durst (1982) and Tsuji *et al.* (1984) have measured turbulent gas–solid upflow in vertical pipes for volumetric concentrations up to 0.4% (mass loadings up to 4.0) with laser anemometry; Modarress *et al.* (1982) also used LDA to measure the downflow of a round particle-laden jet in a co-flowing stream.

In solid–liquid flows the maximum particle concentration through which beam penetration is possible in laser anemometry can be increased if the refractive indices of the particle material and of the carrier fluid are closely matched (e.g. Zisselmar & Molerus 1978; Yianneskis and Whitelaw 1984). In the present investigation, refractive-index matching of suspended acrylic particles and the carrier fluid enabled the measurement of particle velocities in volumetric concentrations up to 14%.

The suspended particles were denser than the fluid and, in order to have a symmetric influence due to gravity and to eliminate particle settling effects, descending flows were arranged in a vertical pipe. Fully-developed pipe flow and the flow around an axisymmetric baffle were examined: particle inertia effects were expected to be important in the latter due to the velocity gradients in the recirculation region behind the baffle. Particle concentrations in the range 0.1–14% and two particle sizes were examined. The flow configuration and experimental techniques are described in the following section. The results are presented and discussed in section 3, and a summary of the main findings is given in section 4.

2. FLOW CONFIGURATIONS AND EXPERIMENTAL TECHNIQUES

The flow configuration consisted of a vertical pipe of 25.4 mm dia (D), connected to a constant heat tank upstream and a second tank downstream of the pipe. The tanks were constructed so that their cross-sections contracted smoothly from the maximum area to the flow exit, and were aligned vertically with the pipe and pump, so as to prevent settling of the particles in low-velocity regions. For the same reason, the lengths of horizontal pipe sections were minimized. A 100 mm long part of the pipe, located 45 dia downstream of the inlet, was made of transparent acrylic plastic to allow optical access. This part was machined from a square cross-sectioned block of acrylic so that the outside surfaces were flat and refraction effects minimized. The refractive index of the transparent test section material was identical to that of the fluid so that the only refraction correction was that due to the flat air/plastic interface. As a result of the inlet conditions the flow at the acrylic test section was fully developed. A sharp-edged disc of 18 mm dia, area blockage of 50%, was located centrally in the pipe for the baffled flow experiments.

Water was used in some experiments, but the majority were made with a mixture of oil of turpentine and 31.8% by vol tetraline which had a refractive index identical to that of the acrylic (Diakon) particles (1.489) at a temperature of 25.15°C. The density and kinematic viscosity of the mixture were 894 kg m^{-3} and 1.631 cSt respectively, and the density of the particles was 1180 kg m^{-3}. The size range of the particles used in the unbaffled pipe flow was 100–500 μm, with a mean diameter (d_p) of 270 μm. In the baffled flow, particle size ranges of 240–400 and 600–730 μm were used with mean diameters of 310 and 665 μm, respectively. The characteristic time-response parameter for the particles is $t = d_p^2\, \rho_p/18\, \mu$, which is about 4 ms for the 270 and 310 μm particles and 20 ms for the 665 μm dia particles. The temperature of the mixture was controlled to within 0.02°C throughout the experiments. All the experiments were carried out with the same constant head condition. The bulk flow velocity can be affected when the particles are inserted in the flow, as the apparent density and viscosity of the suspension may vary from that in the single-phase case, but the results are representative of the situations encountered in practice when the loading of the flow is varied. The flow bulk velocities (V_b) and Reynolds numbers ($\mathrm{Re} = \rho V_b D/\mu$) for the single-phase unbaffled pipe flow were 2.33 m s^{-1} and 59,200 for the water flow and 2.45 m s^{-1} and 39,650 for the mixture flow. The baffled flow experiments were made with only the mixture fluid and the corresponding values were $V_b = 1.89$ m s^{-1} and Re = 29,500.

The refractive-index matching technique employed has been described in detail by Nouri *et al.* (1986). The principle is that equal refractive indices of the continuous and the discontinuous phases render the particles transparent so that only the micro-size contaminants following the fluid motion scatter sufficient light to allow the measurement of the velocity of the fluid phase by a laser–Doppler anemometer. Zisselmar & Molerus (1978) used this approach to measure fluid velocities in the presence of concentrations of glass particles. In order to measure the particle velocities, a small number of non-matched particles can subsequently be added to the flow, and the solid-phase signals measured by amplitude discrimination as the signal intensity is strongly related to particle size, while the flow remains sufficiently transparent for the laser beams to penetrate. However, there are no spherical particles currently available without inclusions (air bubbles, voids etc.) and these inclusions, around 0.2–0.5 of the particle diameter, produce Doppler signals of amplitudes greater than those obtained with the micron-size seeding particles and provide particle velocity information. The degree of transparency that can be achieved is therefore restricted by the presence of the inclusions so that only particle velocities can be measured, using amplitude discrimination to detect

Table 1. Optical characteristics of the laser anemometer

Half-angle of beam intersection in air (deg)	8.85
Frequency-to-velocity transfer constant (m s^{-1} MHz^{-1})	2.04
Intersection volume diameter at $1/e^2$ intensity (μm)	50
Intersection volume length at $1/e^2$ intensity (mm)	0.43
Number of fringes in intersection volume without shifting	25
Fringe separation (line-pair spacing) (μm)	2.04

the high-amplitude signals produced by the inclusions, in volumetric concentrations more than one order of magnitude higher than would be possible without matching.

The laser–Doppler anemometer was operated with forward-scatter light and made use of a 5 mW He–Ne laser, a rotating diffraction grating and a frequency counter. Measurements of the mean and r.m.s. streamwise velocity components of single-phase flow in each configuration were made first, and then the photomultiplier voltage was reduced and an adjustable aperture placed in front of the photomultiplier was partially closed so that no signals corresponding to the fluid could be detected. The particles were inserted and the particle mean and r.m.s. velocity components measured. The principal characteristics of the optical system are given in Table 1. The measurements errors are of the order of 1%, rising to 2–3% in regions of steep gradient. A check on the accuracy of the results was obtained by the integration of the single-phase mean velocity profiles which indicated conservation of mass to within 1%.

3. RESULTS AND DISCUSSION

3.1. Pipe flow

The particle mean velocities measured in the water pipe flow with volumetric concentrations (C_v = volume of solids/volume of fluid) up to 0.75% are shown in figure 1, together with the single-phase velocities. The particle velocities are consistently larger than the single-phase fluid velocities ($\bar{U}_{f,1}$), but there is no discernible trend or variation of $\bar{U}_p$ with concentration. It is useful to consider a relatively velocity, $\bar{U}_s = \bar{U}_p - \bar{U}_{f,1}$; but the interpretation of the $\bar{U}_s$ results must be made with care as the fluid velocities in the two-phase situation, $\bar{U}_{f,2}$, may be different from $\bar{U}_{f,1}$, i.e. the fluid velocity may vary in the presence of the particles. The magnitude of $\bar{U}_s$ is on average 65 mm s^{-1}, i.e. around 0.025 V_b.

The mean velocity results obtained with the turpentine/tetraline mixture and suspensions of particles with C_v = 2–14%, i.e. with up to a 20-fold increase in the concentration of the solids, are shown in figures 2(a, b). There are differences of up to 3% in the water and mixture single-phase profiles which are due partly to the change in Reynolds number and partly due to experimental scatter. The particle velocity profile shape changes with particle concentration. At the lowest

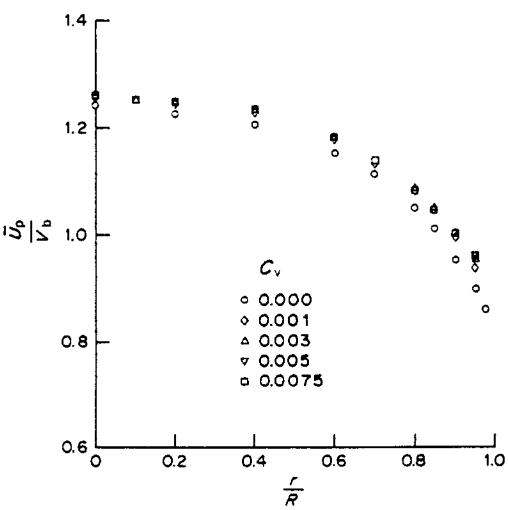
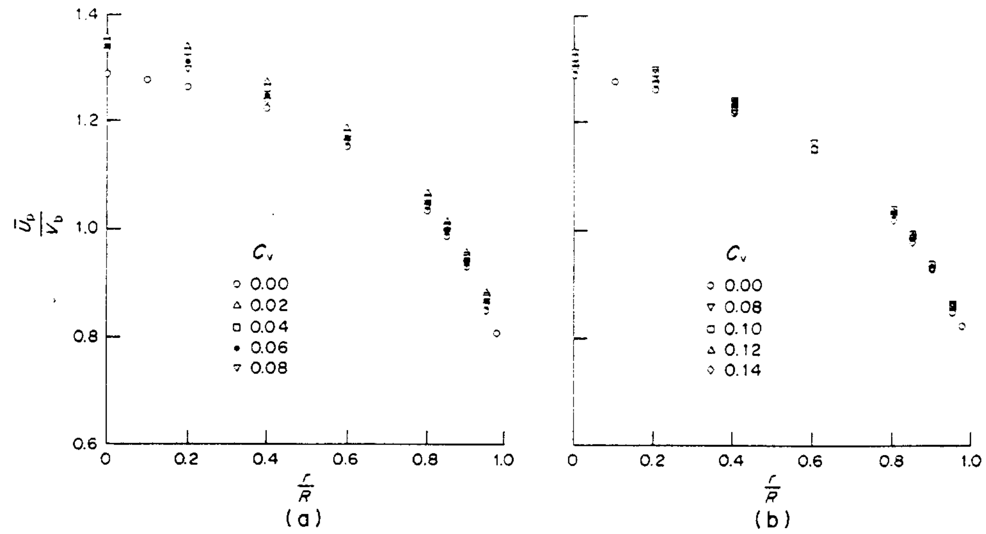


Figure 1. Water flow in the pipe: single-phase and particle axial mean velocities.



Figures 2(a, b). Turpentine/tetraline mixture flow in the pipe: single-phase and particle axial mean velocities.

concentration of particles the $\bar{U}_p$ profile has a pronounced peak on the axis in comparison to the single-phase velocities. The particle velocity profiles become flatter and more similar in shape to that of single-phase flow as the concentration is increased. The flattening of the profile with increased concentration is in agreement with all previous investigations cited. The peak in the particle velocity profile (in comparison to the single-phase result) has been attributed to the radial migration of particles towards the tube wall for spheres more dense than the fluid in a downflow, while in an upflow of denser spheres the profile becomes blunter (Cox & Mason 1971); as a result the effective viscosity of the suspension in the present flow is greater near the wall [Maude (1960), for example, has suggested that $\mu = \mu_0/(1–2.5C_v)$ for laminar flow and $5\% < C_v < 28\%$, i.e. μ increases with C_v] and the near-axis velocities are larger. Shih & Lumley (1986) reached a similar conclusion for particles located far from the centre of a two-phase mixing layer: the local density was lower than that near the mixing layer and particles were travelling faster than average. Here $\bar{U}_s$ varies from 165 mm s^{-1} near the axis to 70 mm s^{-1} near the wall for the 2% solids suspension; the relative velocities decrease as C_v increases and the corresponding values for 8% are 102 and 35 mm s^{-1} respectively, and for 12%, 46 and 7 mm s^{-1}.

The terminal velocity of the particles due to drag and gravity forces, U_T, was calculated for the flow of a single particle in an infinite amount of mixture fluid from

$$U_T = \{[4\, d_p\, (\rho_p - \rho)g]/(3\rho C_D)\}^{0.5}$$

to be 10 mm/s. The measured relative velocities are considerably larger, partly because of the non-uniform velocity and concentration gradients present in the flow which imply that particle–particle and wall interaction effects are important. In addition, as the difference between the particle and the fluid density is small, the terminal velocity estimate from the above relationship is also small and laminar (Stokes) flow around the particle is implied and $C_D \simeq 10$; the assumption of laminar flow around the spherical particle in the above estimate is incorrect as the particle r.m.s. velocities are of the order of 200 mm s^{-1}, i.e. much higher than the calculated terminal velocity. Wells & Stock (1983) have shown that turbulence strongly influences the particle motion for $\tilde{\mu}_p$ greater than the terminal velocity. The corresponding terminal velocity estimate from the above relationship for turbulent flow around the particle (using a value of $C_D = 0.44$) is 50 mm s^{-1}, which is more appropriate, but the results show that the effect of the suspension is to reduce the drag on each particle even further. A similar conclusion may be reached from inspection of the results of Lee & Durst (1982) and Tsuji et al. (1984): the drag coefficient for a particle in suspension is almost always lower than that for a single particle in a laminar flow and, a a result, the terminal velocities are larger in a suspension (Lee 1985). By comparison with the results of other investigations, e.g. that of Tsuji *et al.* (1984), it can be expected that the $\bar{U}_p - \bar{U}_{f,2}$ velocities will be smaller than $\bar{U}_s$ and closer to the estimates of terminal velocity for turbulent flow.

The decrease in $\bar{U}_p$ with increasing C_v is in agreement with well-established empirical relationships that state that in general the $\bar{U}_p - \bar{U}_{f,2}$ velocity is proportional to $(1 - C_v)^{1.325}$ and with the results of Birchenough & Mason (1976) and Tsuji *et al.* (1984), which showed that the particle velocities decrease with increasing loading of solids. Tsuji *et al.* have stated that $\bar{U}_p$ increased with C_v, but their results show the opposite effect and their conclusion was based on velocity magnitudes which were not normalized by the same value. The value of $\bar{U}_s$ also decreases with C_v in the present results; Tsuji *et al.* found that $\bar{U}_p - \bar{U}_{f,2}$ decreased, whereas $\bar{U}_p - \bar{U}_{f,1}$ increased with mass loading in upflow—and Birchenough & Mason's findings are in agreement with the latter result. In conjunction with the present results, it can be concluded that in both upflow and downflow of particles denser than the fluid, an increase in concentration results in a decrease in particle velocities and therefore the $\bar{U}_s = \bar{U}_p - \bar{U}_{f,1}$ velocities will be larger or smaller respectively, as the gravity acts in opposite senses.

The differences in the $\bar{U}_s$ velocities measured in water and in the mixture are in agreement with the Reynolds number effect on the relative velocity shown by the results of Birchenough & Mason (1976); in that investigation the $\bar{U}_s$ velocities in upward flow increased by a factor of 1.7 as Re increased by a factor of 1.4, and similarly in the present results the average relative velocities (for $C_v = 0.75$ and 2%) decrease by a factor of 1.8 as Re increases by a factor of 1.5 from 39.650 in the mixture flow to 59,200 in the water flow. This result indicates that the importance of particle inertia increases with Reynolds number, and the particle lag is more significant. Thus in upflow the particles lag increasingly more behind the fluid and $\bar{U}_s$ increases as the Reynolds number increases, whereas in downflow the lead of the particles over the fluid becomes progressively smaller as the Reynolds number increases, i.e. $\bar{U}_s$ decreases.

The particle velocity at any point along the pipe radius remains nearly uniform with increasing concentration for the water flow, i.e. up to 0.75%, with the exception of the near-wall region at $r/R = 0.9$ and 0.95 where $\bar{U}_p$ increased. In the higher concentrations in the mixture flow, the particle velocity at a point decreased with increasing concentration, and the decrease near the axis was twice that in the near-wall region. This local variation in the magnitude of $\bar{U}_s$ is associated with particle migration and the local increase in the viscosity and density of the suspension, as mentioned earlier. These effects are not as significant in the lower concentrations and, as a result, the $\bar{U}_p$ profiles tend to be more uniform for $C_v = 0.1$–0.75%.

The single-phase and particle r.m.s. streamwise velocity components are shown in figure 3 for the water flow and in figures 4(a, b) for the mixture flow. Figure 3 shows that the fluctuating velocity of the particles is always smaller than that of the single phase, by around 5% on the axis and 13% near the wall. A similar trend is shown by the particle r.m.s. velocities measured in the mixture, with levels lower by about 10% near the axis and up to 0.4 of the radius, and around 7% close to the wall. The levels at 0.8 of the radius are similar to those of the single-phase flow. The $\tilde{u}_p$ levels decrease with increasing concentration so that, for example, at $r/R = 0.4$ the levels

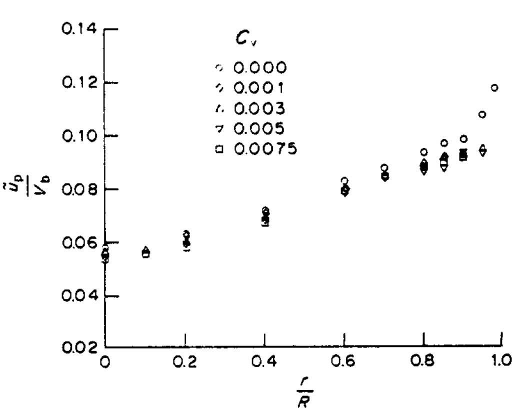
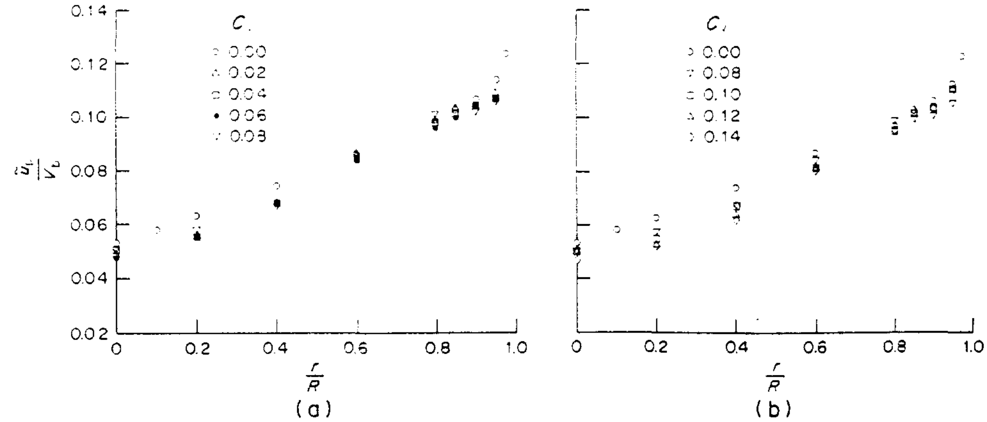


Figure 3. Water flow in the pipe: single-phase and particle axial turbulence levels.



Figures 4(a, b). Mixture flow in the pipe: single-phase and particle axial turbulence levels.

for $C_v = 6\%$ are 15% smaller than the single-phase value, whereas for 14% they are about 30% smaller.

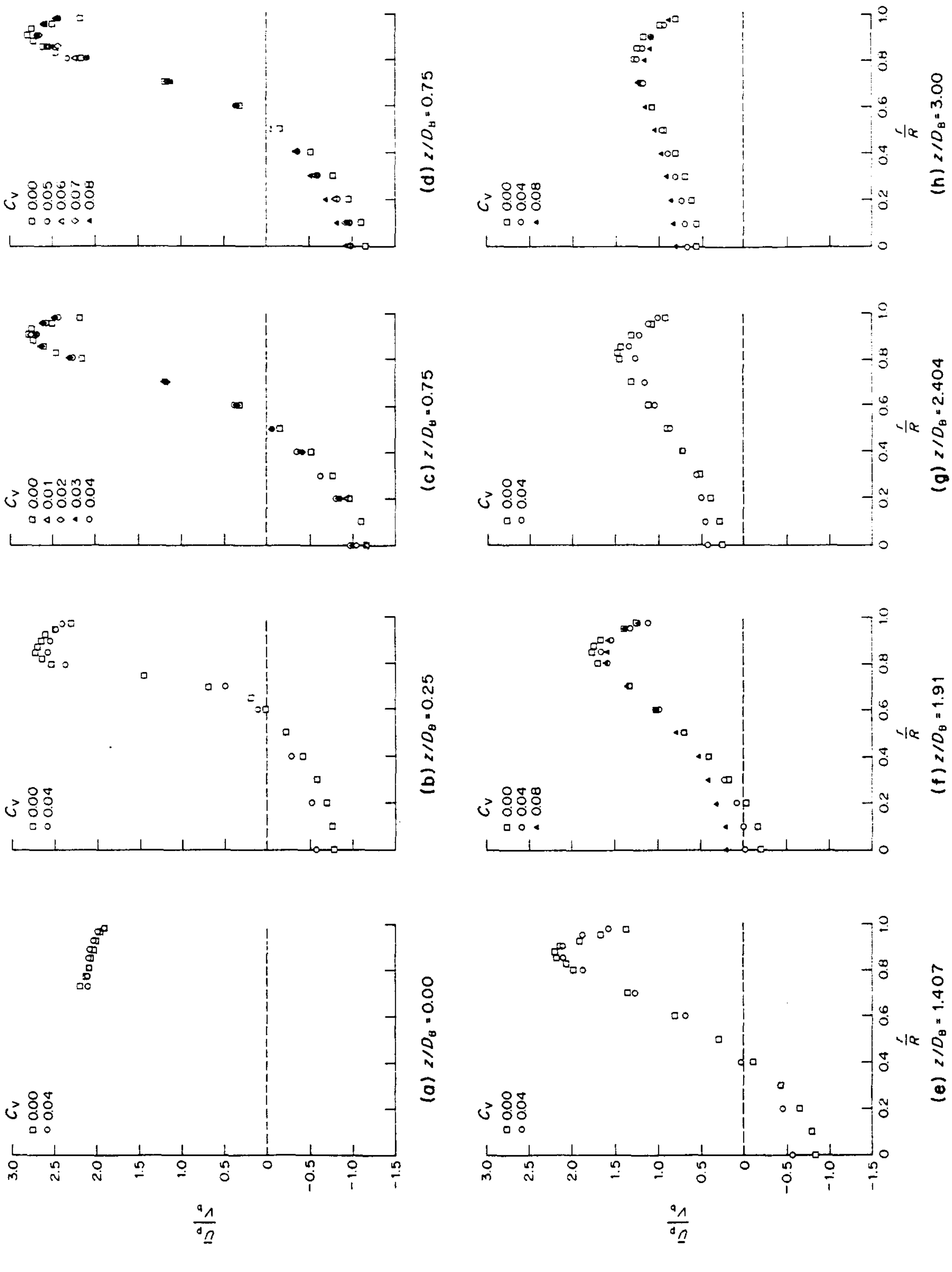
Tsuji *et al.* (1984) also found that, for the flow of 200 μm particles in air, $\tilde{u}_p$ levels are smaller than the single-phase levels and that they decrease with increasing concentration. Owen (1969) calculated that the fluid r.m.s. levels are decreased in comparison to the single-phase levels due to the presence of the particles by $[1 + (\rho_p/\rho_f)]^{-0.5}$, where ρ_p is the mass of the particles per unit volume and ρ_f is the fluid density. This result suggests that the $\tilde{u}_{f,2}$ r.m.s. levels for the present flow with $C_v = 10\%$ will be 6% smaller than the $\tilde{u}_{f,1}$ levels. By comparison the measured $\tilde{u}_p$ levels were 7% smaller than the single-phase levels. Tsuji *et al.* also found that $\tilde{u}_{f,2} \simeq 0.6\tilde{u}_{f,1}$ for 200 μm particles with $C_v \simeq 0.3\%$ and Zisselmar & Molerus (1978) reported that, for liquid–solid flow in an horizontal pipe, the fluid r.m.s. levels were reduced by 12–40% in the presence of concentrations of 57 μm particles of 1.7–5.6%, respectively. The result that the values of $\tilde{u}_p$ are larger in the presence of smaller particles [e.g. 57μm particles, Zisselmar & Molerus (1978)] than with larger ones [e.g. 200–300 μm particles Tsuji *et al.* (1984) and present results] is in agreement with the results presented in the following section for 310 and 665 μm particles. The reduction of $\tilde{u}_p$ in comparison to $\tilde{u}_{f,1}$ has been attributed to the particle inertia, which is characterized by the particle response time (Snyder & Lumley 1971). Boothroyd (1967) found that turbulence of the carrier phase is generated by the presence of the particles and suggested that the particles extract large-scale turbulence energy from the mean flow: in the present case the turbulence acquired by the solids is lower than the $\tilde{u}_{f,1}$ levels.

3.2. *Baffled flow*

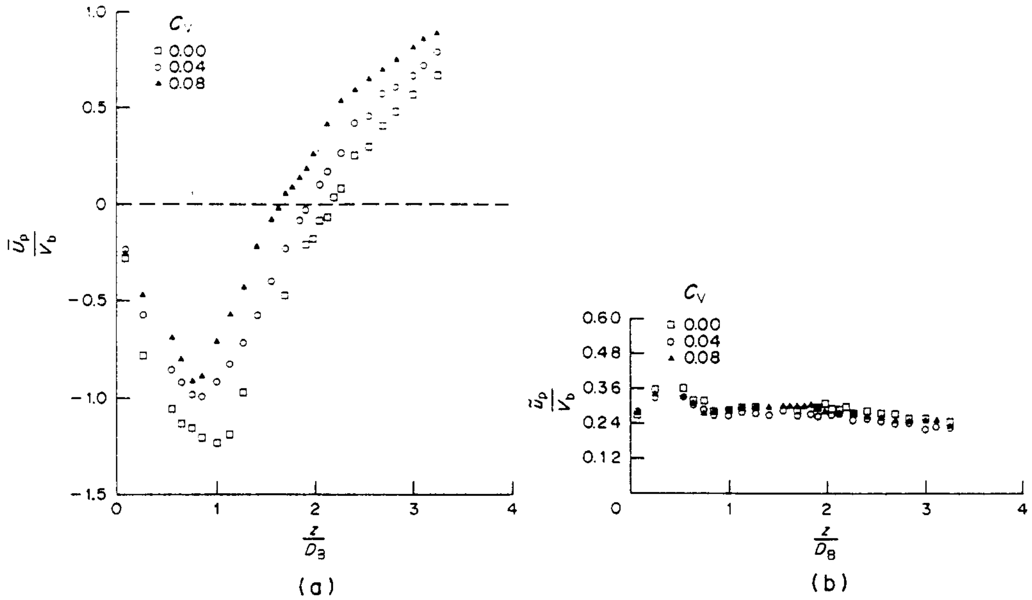
The mean streamwise velocities for suspensions of 310 μm mean diameter particles in the mixture flowing around the axisymmetric baffle are presented in figures 5(a–h). The axial distance is denoted as z, expressed in baffle diameters (D_B) from the baffle face, and results were obtained for values of C_v in the range 1–8%. A representative sample of results are shown, except at $z = 0.75D_B$ where all measured concentrations are presented.

The single-phase results show the presence of an annular jet near the walls, a recirculation zone behind the baffle which extends to the $z = 1.91D_B$ station, and the recovery region further downstream. The results are in excellent agreement with those obtained by Nouri *et al.* (1984) and Taylor & Whitelaw (1984) in horizontal flows past identical baffles. The probability density functions of the velocity measurements in the regions of steep gradients at the edges of the annular jet had strongly skewed distributions, which are typical of flow regions with strong gradients of turbulent intensity.

The particle velocity profile at the baffle tip [figure 5(a)] is flatter than the single-phase profile, and the same trend is evident in the profiles at all the subsequent axial stations [figures 5(b–h)]. The $\bar{U}_s$ velocities increase with concentration, and the particle velocities are smaller than the single-phase ones in the recirculation region and in the centre of the jet, while they tend to be larger in the near-wall region. The annular particle jet profiles are more uniform and the spread of the



Figures 5(a–h). Baffled flow: single-phase and particle axial mean velocities.



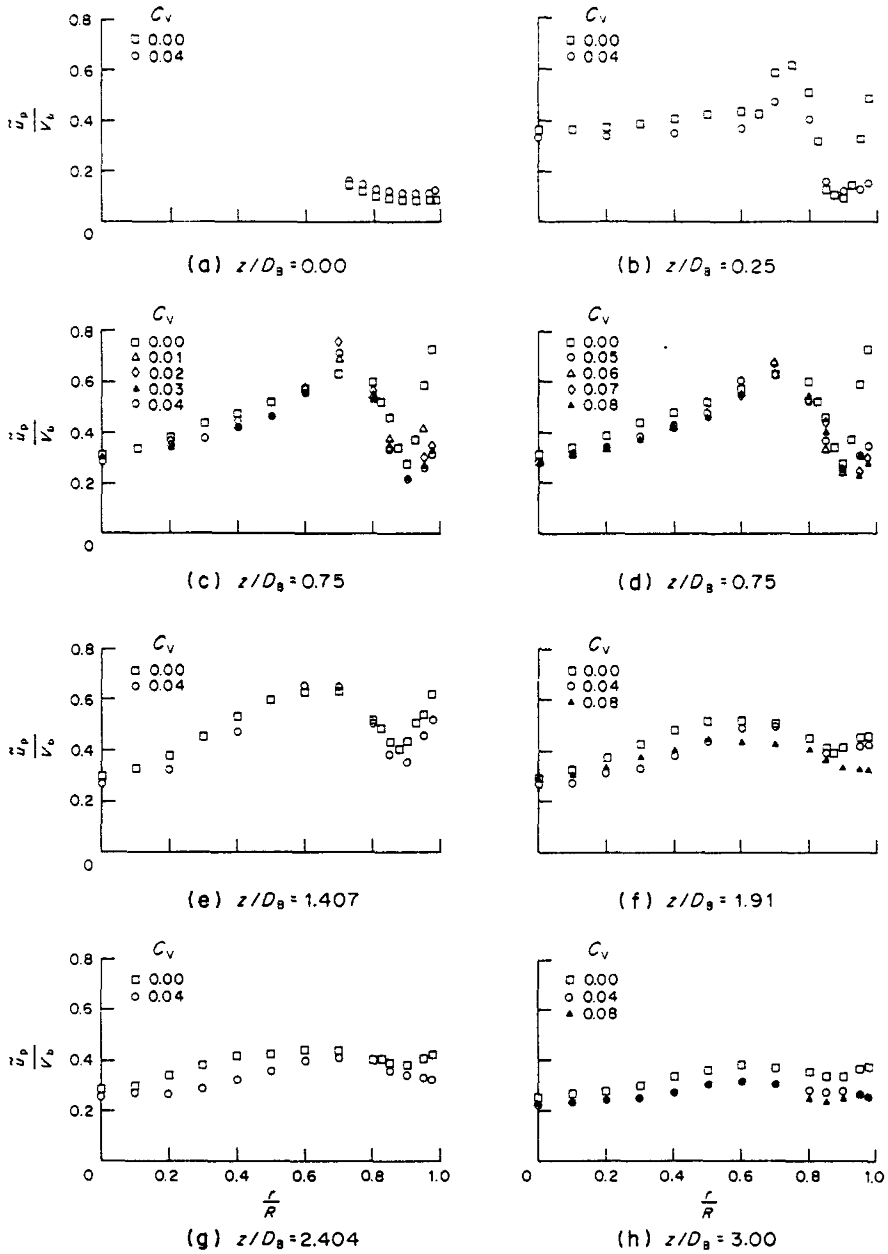
Figures 6(a, b). Centreline variation of axial mean (a) and r.m.s. (b) velocity components in baffled flow.

jet is smaller than in single-phase flow: this reduced spread of the jet is in agreement with the findings of Modarress *et al.* (1982) for a round two-phase flow jet discharging into a co-flowing stream. The probability density functions of the particle velocity measurements at the edges of the jet had velocity distributions with small skewness, in contrast to the single-phase flow. As the skewness appears in the mean square turbulent vorticity equation as a factor of the rate of production of vorticity, the present results suggest that the turbulent vorticity of the particles is destroyed by viscous effects more rapidly than in single-phase flow: this result is in agreement with the particle turbulence level results presented in this section, which are lower than the single-phase levels.

The differences in the $\bar{U}_p$ and $\bar{U}_{f,l}$ profiles become more pronounced as the particle concentration increases [figures 5(c, d)] with $\bar{U}_p > \bar{U}_{f,l}$ near the wall for all concentrations. The measured maximum of $\bar{U}_s$ for the 4% concentration was located near the axis and was 0.33, 0.47 and 0.19 m s^{-1} at $z = 0.75$, 1.407 and 3.0 D_B, respectively; while for $C_v = 8\%$ the relative velocities on the axis were 0.56, 0.75 and 0.47 m s^{-1} at $z = 0.75$, 1.91 and 3.0 D_B, respectively.

The variations of the single-phase and the particle velocities along the pipe centreline are shown in figure 6(a) with the change of sign of the particle velocities occurring nearer the baffle than for the single-phase flow, indicating that the particles leave the recirculation earlier. As there are strong accelerations and decelerations in the flow, especially in the recirculation region, particle inertia and virtual mass effects are more important than in the pipe flow and the results indicate that the particles follow the fluid motion less faithfully as concentration increases and the length of the recirculation region, in $\bar{U}_p$ terms, is shorter by 0.22 and 0.52 D_B (3.9 and 9.3 mm) for the 4 and 8% concentrations, respectively, than in single-phase flow where the recirculation length is 2.15 D_B or 38.6 mm. Consequently, the recovery of the flow downstream occurs earlier [figures 5(g, h)]. Hardalupas (1986) has found that few of the 40 μm glass particles in an annular gas–solid downflowing jet were entrained in the recirculation zone; in the present results the solid/fluid density ratio is much smaller and the particles enter the recirculation region but drop out due to gravity and inertia effects as they approach the low-velocity region near the stagnation point.

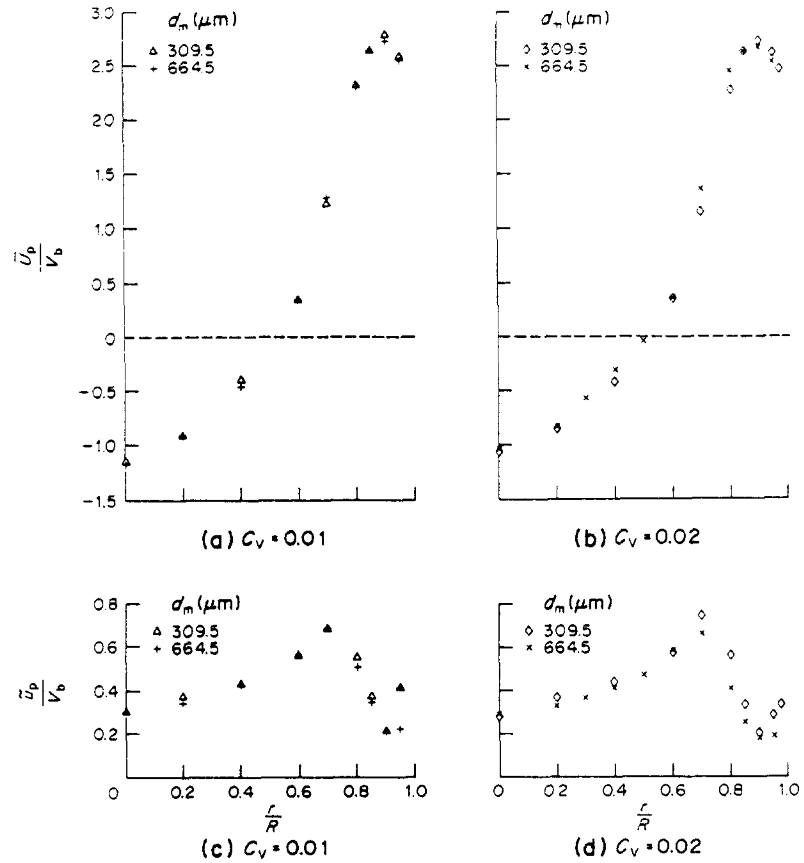
The particle r.m.s. velocities along the centreline [figure 6(b)] are slightly smaller than the fluctuating levels of the single-phase flow in most locations, with $\tilde{u}_p$ up to 15% lower than $\tilde{u}_{f,l}$ (at $z/D_B = 0.75$). The differences in the r.m.s. velocities are smaller than may have been expected, given the larger corresponding differences in the mean velocities [figure 6(a)]; however, as both $\partial\bar{u}_p/\partial z$ and $\partial\bar{u}_{f,l}/\partial z$ are small along the centreline, even relatively large changes in the local mean flow will not strongly affect the turbulence levels. The turbulence levels measured at the axial stations of figures 5(a–h) are shown in figures 7(a–h). For $C_v = 1\%$ [figure 7(c)] the $\tilde{u}_p$ levels are 5–10% lower



Figures 7(a–h). Baffled flow: single-phase and particle axial turbulence levels.

than the single-phase ones near the axis and 20–30% lower close to the wall. The particle r.m.s. levels are further suppressed for $C_v = 2\%$ and the corresponding values are 6–10 and 20–50% lower; for higher concentrations, 3–8%, the percentage reductions are around 10 and 30–65%, respectively. In the shear layer between the jet and the recirculation region, the particle r.m.s. levels are similar, to within 5–15%, to the $\tilde{u}_{f,1}$ levels. In the recovery region downstream the $\tilde{u}_p$ levels are on average 20% lower.

The influence of particle size on the mean and fluctuating particle velocities is shown in figures 8(a–d) by the results for $z = 0.75\ D_B$ with particles of 310 and 665 μm mean diameters. Measurements at concentrations of 1 and 2% are shown; no measurements were possible with higher concentrations of the large particles as they were damaged by the pump impeller. The differences in the mean velocities are small, with the velocities of the 665 μm particles a few percent smaller than those of the 310 μm particles, the differences are more pronounced at the higher concentration [figure 8(b)]. The results suggest that increased particle size does not affect the mean



Figures 8(a–d). Baffled flow: comparison of axial mean (a, b) and r.m.s. (c, d) particle velocities at $z/D_B = 0.75$ with 310 and 665 μm particles suspended in the flow.

flow as much as may be expected as the response time of the 665 μm particles is about four times larger than that of the 310 μm particles.

The r.m.s. levels of the 665 μm particles [figures 8(c, d)] are consistently smaller, by about 10% in the reverse flow region and by up to 30% close to the wall. Modarress *et al.* (1982) have also found that the suppression of turbulence in a round jet was greater with 200 μm than with 50 μm particles. Lee & Durst (1982) suggested that the fluid r.m.s. levels increase in gas–solid upward flow when large (800 μm) particles are suspended in the flow, whereas 400 μm or smaller particles dampen the turbulence levels. Tsuji *et al.* (1984) have confirmed the latter result and also showed that with intermediate particle size ranges (500 μm) turbulence is promoted at some locations, whereas in others it is suppressed. In comparison with the latter solid–gas findings, the present data show that in liquid–solid flow, where the particles follow the fluid motion more faithfully, a similar increase in particle size form 310 to 665 μm results in a reduction of the particle fluctuating velocities.

4. CONCLUDING REMARKS

1. Measurements of particle velocity have been obtained by LDA in a descending turbulent flow in a vertical pipe with volumetric concentrations of suspended particles up to 14%. Similar measurements were made in the flow downstream of an axisymmetric baffle placed in the pipe with particle concentrations up to 8%. In order to enable measurements in high particle concentrations without blockage of the laser beams the refractive index of the particles was matched to that of the carrier fluid.

2. The results in the pipe flow show that the mean particle velocity decreases and the profiles become more uniform as the particle concentration increases. The difference between the particle and the single-phase fluid velocities decreases with increasing Reynolds number.

3. The recirculation region of the flow of particles downstream of the baffle was shorter than in single-phase flow by 11 and 24% for particle concentrations of 4 and 8%, respectively.

4. The fluctuating velocities of the particles decrease with increasing concentration in both flow cases.

5. Measurements with 310 and 665 μm particles in the baffled flow with concentrations up to 2% showed that the particle mean velocities are hardly affected by particle size, whereas the fluctuating velocities were up to 30% lower with the larger particles.

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