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Particle–turbulence interactions in the turbulent boundary layer for cross flow over a tube

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Abstract

The turbulent fluid and particle interaction in the turbulent boundary layer for cross flow over a tube was studied experimentally. A phase Doppler anemometer (PDA) was used to measure the mean and fluctuation velocities of both phases. Two size ranges of particles (30–60 μm and 80–150 μm) at certain concentrations were used to investigate the effect of the particle size on the mean velocity profiles and turbulent intensity levels. The measurements clearly demonstrated that the larger particles damped the fluid turbulence. For the smaller particles, this damping effect was less noticeable. The measurement further showed a delay in the separation point for two-phase turbulent cross flow over a tube. © 1997 Elsevier Science S.A.

Keywords: Boundary layer; PDA measurement; Turbulent fluid and particle interaction; Two-phase turbulent cross flow over a tube

1. Introduction

Particle-laden turbulent cross flow over tubes occurs in many engineering situations, such as solid fuel combustion systems associated with fluidized bed reactors, shell and tube heat exchangers, aerosol sampling and air cleaning. It is also of theoretical interest because it involves the interaction between a turbulent fluid and particles in a boundary layer, which is not well understood at present.

To develop a basic understanding of the interaction of a gas–solid suspension with a boundary, earlier studies [1–3] treated the case of laminar boundary layer motion of a gas–solid suspension over a flat plate. It is suggested that, in near-wall turbulent particle-laden flow, the bursting phenomenon causes particle suspension in the flow [4,5]. Rashidi et al. [6] have studied particle–turbulence interaction in wall turbulent flows. They found that the larger polystyrene particles (1100 μm) caused an increase in the number of wall ejections, giving rise to an increase in the turbulent intensities and Reynolds stresses, whereas the smaller polystyrene particles (120 μm) acted in an opposite manner. The effect of small particles on fluid turbulence in a flat plate, turbulent boundary layer in air has been investigated by Rogers and Eaton [7]. Their measurements clearly demonstrated that the particles suppressed fluid turbulence, and they showed a strong correlation between the degree of turbulence suppression and the particle concentration in the log region of the boundary layer. In addition to turbulence effects, reductions in the boundary layer physical thickness were observed with higher velocity gradients at the wall by Lee and Durst [8] and Murray [9] for gas–particle suspension flows in pipes and across a staggered tube array respectively.

However, it should be pointed out that, until very recently, it was impossible to find in the literature a well-documented experimental study of turbulent fluid and particle interaction in a boundary layer for cross flow over a tube. Gas–particle turbulence interaction (small particles attenuate turbulence and large particles augment turbulence) has also been assessed on the basis of the ratio of the relative particle to eddy size by Gore and Crowe [10] and in terms of the particle Reynolds number by Hetsroni [11]. The crossover between attenuation and amplification was well correlated by both of these parameters, but the level of attenuation was widely scattered. Much of the scatter is due to poor control of the experimental conditions and to difficulties in measuring the gas phase velocity in the presence of a high concentration of particles. The turbulence intensity may be affected by the flow Reynolds number, the class of flow (e.g. homogeneous, wall-bounded or free shear flow), the particle diameter, the density ratio between the fluid and the particles and the mass loading ratio.

This paper reports the results from an experimental study aimed at assessing the turbulent fluid and particle interaction

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in the turbulent boundary layer for cross flow over a tube. Phase Doppler anemometer (PDA) measurements were conducted for varying particle sizes. The data resulting from this study can be used to enhance the understanding of two-phase turbulent cross flow over tubes, to evaluate the effect of the particles on the characteristics of the boundary layer and to provide a useful basis for validating proposed models for the two-phase turbulent boundary layer.

2. Experimental set-up

2.1. Test facility

In order to examine a particle-laden turbulent boundary layer for cross flow over a tube, a test facility was built. The test facility mainly comprised an exhaust blower, a cyclone and a tunnel that included a particle feeding section, a diffusion section and a test section. At the beginning of the tunnel was a contraction, which was used to reduce the entrance disturbance of the air flow. Air was drawn into the tunnel and was contaminated with flow tracer (titanium oxide powder). The flow was then passed through a 2 m long diffusion section. Particles were fed in at the beginning of the diffusion section, and a set of grids was mounted downstream from the particle feeder to enhance particle–fluid flow mixing. Before entering the test section, the particle-laden flow passed through a 3 : 1 contraction and a section of honeycomb which was mounted at the entrance of the test section. The use of the contraction and honeycomb additionally ensured a fairly uniform distribution of the particles in the cross-section at the entrance of the test section.

The test section was a rectangular duct (width, 14 cm; height, 20 cm; length, 100 cm), at the centre of which a glass cylinder with a diameter of 36 mm was horizontally fixed in the spanwise (z) direction. The boundary layer was developed when air and particles flowed over the cylinder. In order to allow optical access, all the test section walls were made from optical glass. These walls and the glass cylinder may be regarded as very smooth. Such a smooth surface facilitates the elimination of the influence of the wall roughness on the particle-laden boundary layer.

At the end of the tunnel, particles were separated from the air using a cyclone separator and the air was passed into an exhaust blower.

2.2. PDA system and signal processing

A three-component PDA system, schematically shown in Fig. 1, was used for the present study. A continuous power-adjustable argon ion laser with a maximum light power of 5 W was used as light source. The PDA transmitting optics were based on 60x fibre flow, in which a built-in Bragg cell was used for frequency shifting. With the configuration used here, the dimensions of the beam crossing ellipsoid were 0.04 mm × 0.04 mm × 0.5 mm for the blue beams, 0.04 mm × 0.04 mm × 0.9 mm for the green beams and 0.04 mm × 0.04 mm × 1.5 mm for the violet beams.

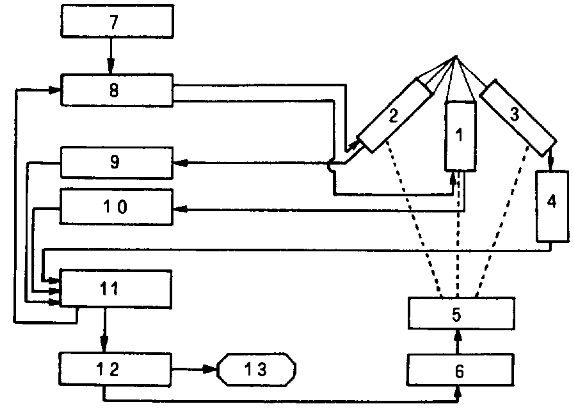

Fig. 1. Schematic diagram of PDA system: 1, one-dimensional transmitter; 2, two-dimensional transmitter; 3, receiver; 4, beam expander; 5, three-dimensional traverser; 6, traverser communicator; 7, laser (Ar^+ ion); 8, Bragg cell; 9, blue beam expander; 10, violet beam expander; 11, data processor; 12, PC; 13, data output.

Cross talk can occur in such a system when a large particle grazes the measuring volume producing a small signal amplitude. This effect is minimized by requiring a relatively large number of fringe crossings (number of fringes, 20) for a valid measurement. In adjusting the system, we relied on the fact that the mean velocity difference between the particles and gas in the stream is larger than the standard deviation of the velocity. Therefore cross talk was easily detected. The present experiments showed that the effect of cross talk was minimal for particle mass loadings up to 25%.

The receiving optics were based on a 57 × 10 PDA. The signal processing was based on a covariance processor (types 58n50 PDA enhanced signal processor) and a typical 486 personal computer. The sensitivity of the processor to signal noise was so low that high reliability and accuracy could be achieved even for low signal to noise ratio (SNR).

The computer was used to control the signal and receive the data for interpretation and post-processing. A special high speed direct access memory (DAM) method, allowing a transfer rate with a maximum limit of 170 000 bytes s^{-1}, was used for data transfer between the processor and the computer so that the system had the capability of handling data rates in excess of 10 000 particles s^{-1}, which is much higher than needed for the present measurements. The accuracy of this apparatus at system level was 4% for size measurement and 1% for velocity measurement.

3. Experimental results

In this study, we aimed to access the interactions between the turbulent fluid and the particles. Titanium oxide powder (0–10 μm) was used as the flow tracer. The individual particles had a material density of 2650 kg m^{-3}. Microscopic examination showed that most of the particles were spherical. Two different size ranges, 30–60 μm and 80–150 μm, with

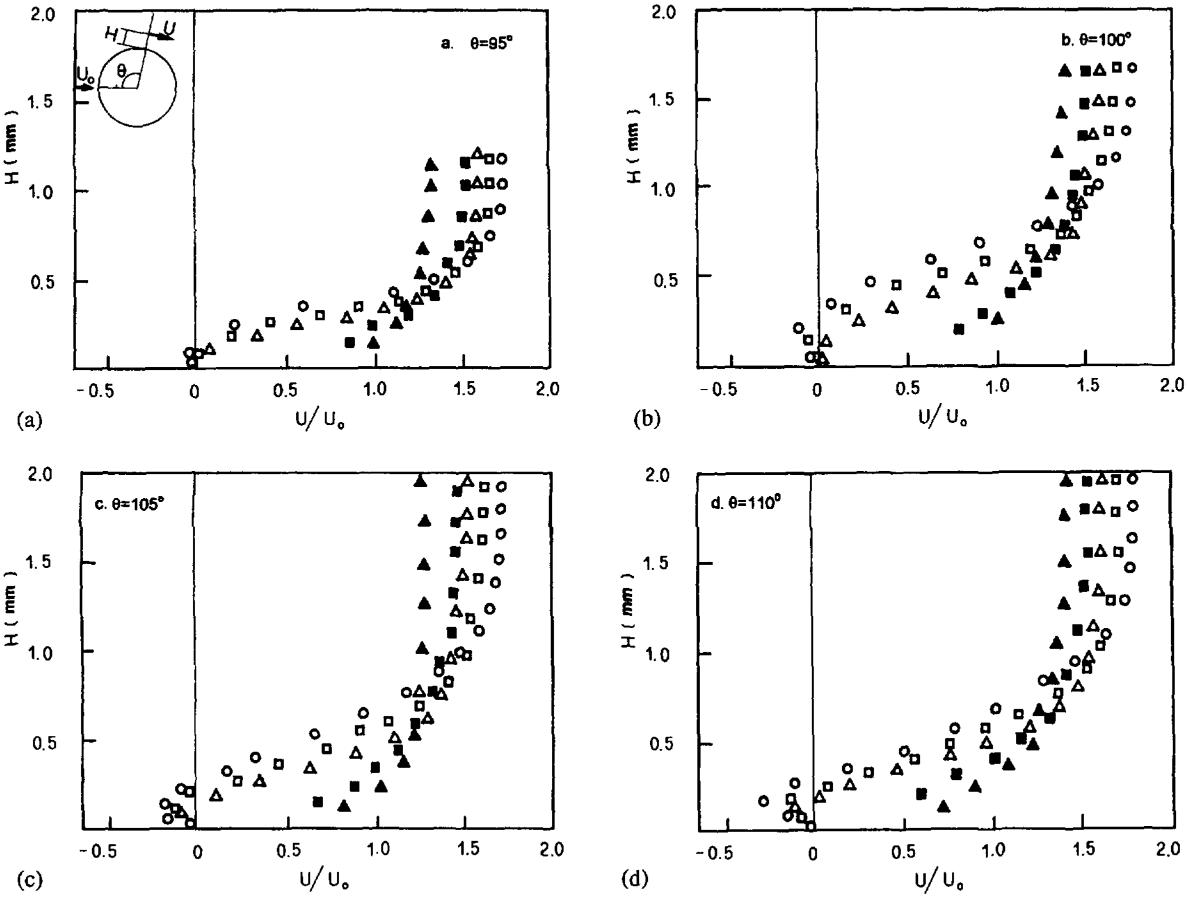

Fig. 2. Mean velocity profiles in the boundary layer (○, single-phase flow; □, two-phase flow, $d_p = 40$ μm; △, two-phase flow, $d_p = 120$ μm; open symbols, gas phase; filled symbols, particles): (a) 95°; (b) 100°; (c) 105°; (d) 110°.

mean diameters of 40 μm and 120 μm respectively, were used. Experiments were carried out for the two sizes at the same mass loading ratio of 0.25 and for unladen (air) flow with all other conditions unchanged. Considering the geometrical symmetry, boundary layer profiles of both mean and fluctuating velocity were only measured for the symmetrical section at 95° to 110° from the front stagnation point. At each measurement point, 20 000 samples were collected. The free stream velocity and turbulence intensity upstream of the cylinder for the unladen case were 14.4 m s^{-1} and 15% respectively from PDA measurements.

3.1. Particle response to the mean fluid velocity

Fig. 2 shows the boundary layer profiles of the time-averaged velocity U of the gas and particle phases for the single-phase (air) flow and the two-phase flow laden with two different sizes of particles. The results are normalized by the free stream velocity U_0. It can be seen from Fig. 2 that both gas and particle phases are accelerated to velocities in excess of the free stream velocity U_0. However, the particles lag behind the gas flow owing to their inertia in the outer region of the boundary layer. Due to their higher inertia, the larger particles ($d_p = 120$ μm) exhibit lower velocities than the smaller particles ($d_p = 40$ μm). On the other hand, particles of both sizes show greater velocities than the gas in the inner region of the boundary layer. Physically, the fluid velocities are reduced markedly in the region close to the wall due to the viscosity. This viscosity, together with the adverse pressure gradient along the tube wall, results in a flow reversal near the wall, i.e. the separation of the boundary layer. However, the particles, whose inertia tends to make them maintain their initial greater velocities, lose their velocities much more slowly than the gas. As a result, the particle phase shows greater velocities than the gas phase in the inner region of the boundary layer. Equally, Fig. 2 shows that the larger particles flow faster than the smaller particles near the wall. Because the particles take time to respond to the fluid flow reversal, we find from Fig. 2 that, compared with the gas flow, flow reversal occurs later for the particle phase. The smaller particles ($d_p = 40$ μm) follow the mean fluid velocity generally much more closely than the larger particles ($d_p = 120$ μm).

3.2. Modification of the mean fluid velocity by the particles

A comparison of the mean velocities for single-phase and two-phase flow shows that there is a minor decrease in the mean gas velocity for two-phase flow laden with the larger particles in the outer region of the boundary layer, but a minor increase in the inner region. However, this modification is

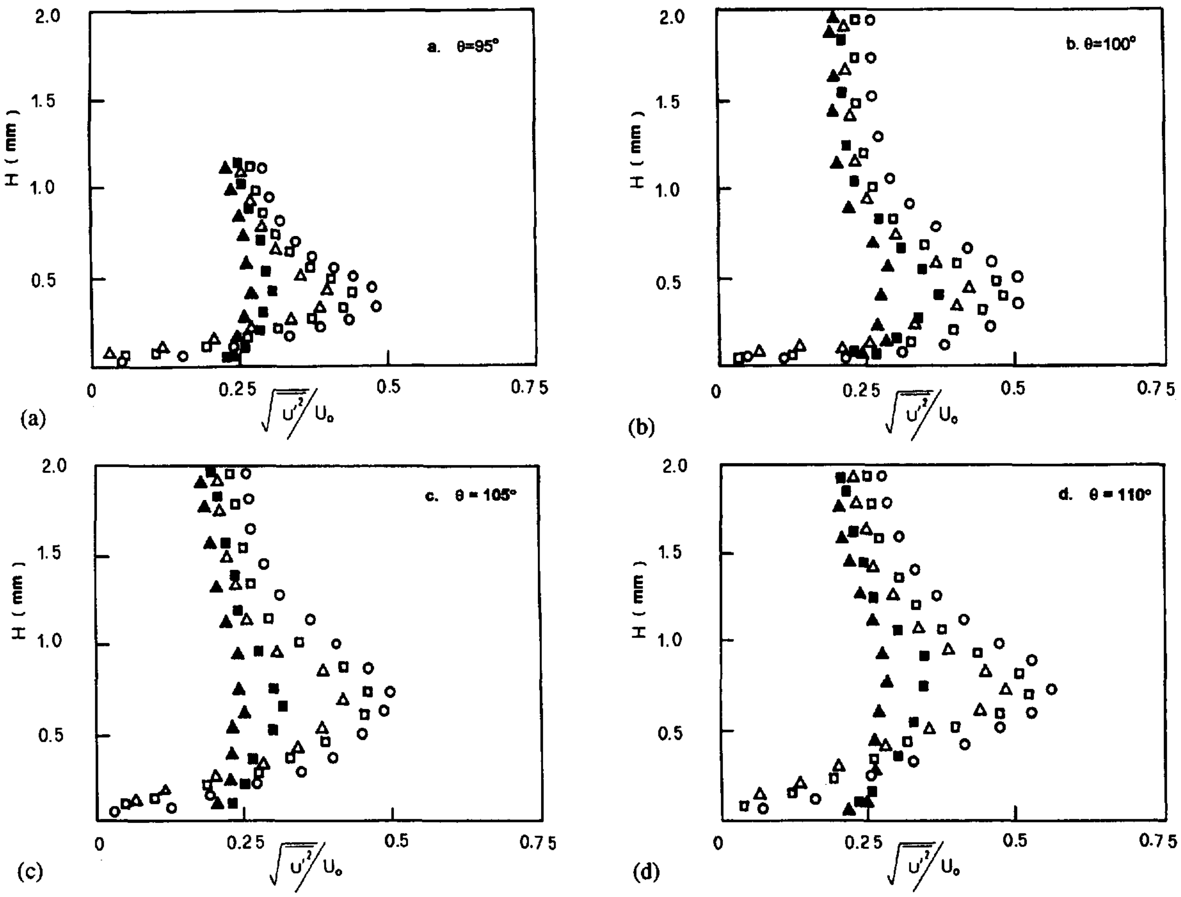

Fig. 3. Root-mean-square velocity profiles in the boundary layer (○, single-phase flow; □, two-phase flow, $d_p = 40$ μm; △, two-phase flow, $d_p = 120$ μm; open symbols, gas phase; filled symbols, particles): (a) 95°; (b) 100°; (c) 105°; (d) 110°.

less noticeable for the smaller particles. This change leads to a considerable reduction in the physical thickness of the boundary layer in two-phase flow. This indicates that a mass loading ratio of particles of as much as 0.25 may cause some modification of the mean fluid velocity. This distinct modification between the two regions is thought to arise from the momentum transfer between the gas and the particle phases. Particles lag behind the carrier (fluid) and obtain momentum from the latter in the outer region of the boundary layer; as a result, the mean fluid velocities are reduced and show lower values than that in single-phase flow. For comparison, the momentum transfer occurs in the opposite direction in the inner region of the boundary, since particles have greater velocities than the gas phase. Thus increases in the mean fluid velocity can be expected in two-phase flow. For the same reason, the flow reversal of the fluid is reduced in two-phase flow.

A careful examination of Fig. 2(a) shows that the boundary layer begins to separate from the wall at $\theta = 95°$ for single-phase flow, whereas the boundary layer separation is definitely delayed due to the presence of particles. Similarly, the momentum transferred from the particle phase to the air flow in the boundary layer region close to the wall contributes to this delay. The particle–wall interaction may also enhance the momentum exchange between the air flow close to the wall and thus delay the boundary layer separation.

3.3. Fluctuating velocities of fluid and particles

The measured root-mean-square (r.m.s.) velocities $\sqrt{\overline{u'^2}}$ of the gas and particle phases are shown in Fig. 3, where the results are also made non-dimensional by the free stream velocity U_0. For comparison, we plot the profiles of the r.m.s. velocities for the single-phase (air) flow, together with those for both two-phase flows, in the same figure. The particle velocity fluctuations are generally lower than the corresponding fluid turbulent velocity fluctuations for both the 40 μm and 120 μm diameter particles. It should be noted that the smaller particles ($d_p = 40$ μm) with a lesser Stokes time constant respond more readily to the velocity fluctuations of the gas phase, and exhibit much higher r.m.s. velocities than the larger particles ($d_p = 120$ μm). It can be seen from Fig. 3 that there is a peak located near the wall in profiles of the fluid turbulence intensity for both single-phase and two-phase flow. The maximum value becomes greater, accompanied by a more distant location of the peak from the wall, at an increasing angle θ from the front stagnation point. Although the velocity fluctuation profiles for two-phase flow are very similar to those for single-phase flow, the fluid turbulence intensity is consistently reduced by the presence of the particle phase. This result falls into the small particle ($d_p = 200$ μm) induced fluid turbulence attenuation previously documented by Tsuji et al. [12] and Rogers and Eaton [7].

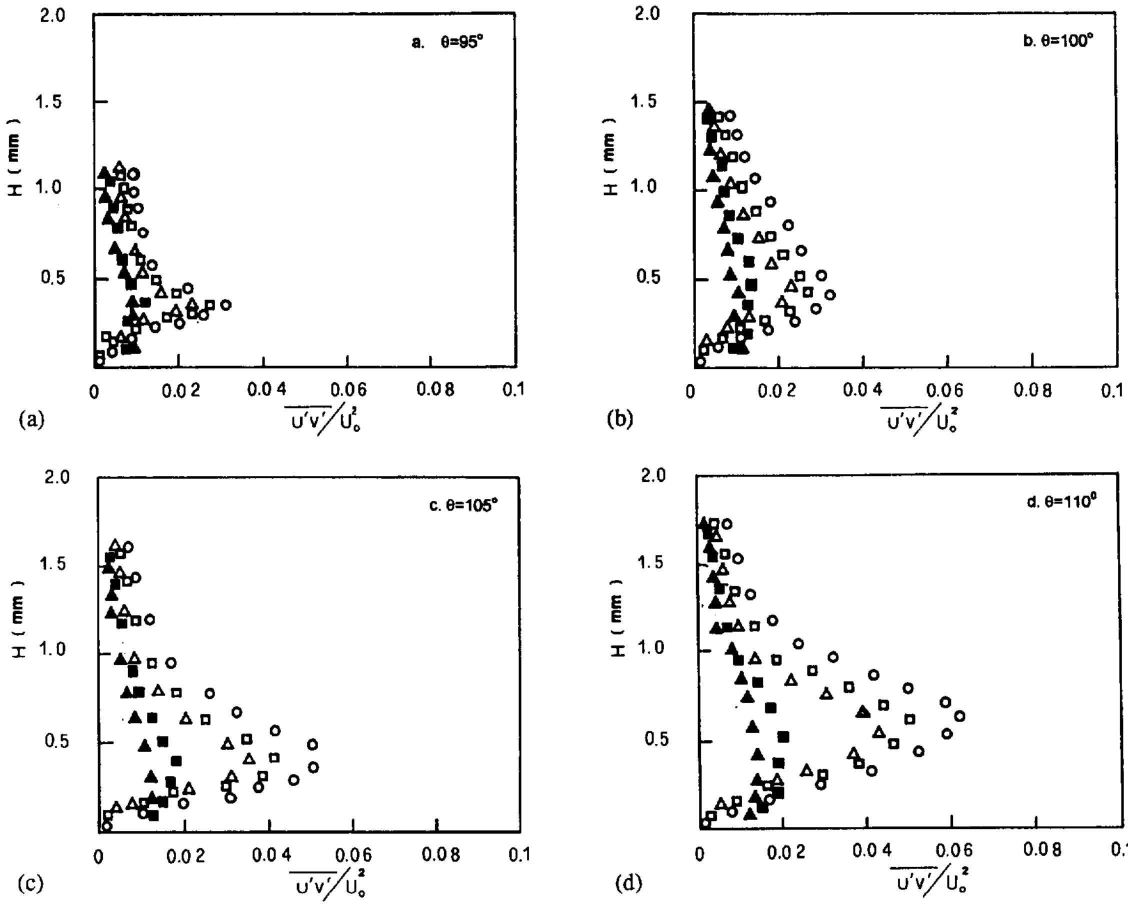

Fig. 4. Reynolds shear stress profiles in the boundary layer (○, single-phase flow; □, two-phase flow, $d_p = 40$ μm; △, two-phase flow, $d_p = 120$ μm; open symbols, gas phase; filled symbols, particles): (a) 95°; (b) 100°; (c) 105°; (d) 110°.

Fig. 4 shows the distribution of the normalized turbulent fluid shear stress $\overline{u'v'}/U_0^2$ and the measured values of the quantity for the particle phase. The distribution of $\overline{u'v'}/U_0^2$ shows the same trend as that of the velocity fluctuations $\sqrt{\overline{u'^2}}$: the maximum turbulent shear stress of the gas phase is located in the inner region of the boundary layer. The peak value increases and its location moves further from the wall as the angle θ increases. The turbulent shear stress of the particle phase is generally lower than that of the gas phase. While its peak location remains unchanged when laden with particles, the turbulent shear stress of the gas phase for both two-phase flows is slightly lower than its counterpart for single-phase flow. Similarly, it can also be seen that, at the same ratio of mass loading, the larger particles ($d_p = 120$ μm) appear to have a greater effect on the fluid turbulence intensity, both the velocity fluctuations (Fig. 3) and the shear stress (Fig. 4), than the smaller particles ($d_p = 40$ μm).

4. Conclusions

PDA measurements of the mean and r.m.s. velocities of the gas and particles in a particle-laden boundary layer over a tube have been carried out. The results from the present experiments can be summarized as follows:

1. particle flow lags behind the gas flow in the outer region of the boundary layer, but exceeds behind the gas flow in the inner region of the boundary layer;
2. the small particles ($d_p = 40$ μm) respond to the mean fluid velocities and fluid velocity fluctuations to a fairly good extent, whereas the larger particles ($d_p = 120$ μm) do not;
3. the mean fluid velocity profiles are modified by the presence of the particle phase at a mass loading ratio of 0.25; the presence of the particles reduces the fluid flow reversal, delays the fluid boundary layer separation and results in a thinner boundary layer than that of single-phase flow;
4. for the larger particles ($d_p = 120$ μm), attenuated fluid turbulence intensities are measured in the boundary layer; similar effects are also observed for the smaller particles ($d_p = 40$ μm), but to a lesser extent.

Acknowledgements

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References

[1] S.L. Soo, in R.L. Peskin and C.F. Chen (eds.), *Proceedings of Symposium on Single and Multi-Component Flow Processes, Engineering Res. Publ. No. 45,* Rutgers, New Brunswick, NJ, 1965, p. 1.

[2] S.L. Soo, *A.I.Ch.E. Conference Paper No. 36E, Dallas, TX, 1966.*

[3] R.E. Singleton, *Zeitschrift für Angewandte Mathematik un Physik, 16* (1965) 421.

[4] A.J. Grass, *Proc. Euromech., Tech. Univ. Denmark, Copenhagen, 48* (1974) 33.

[5] B.M. Sumer and R. Deigaard, *J. Fluid Mech., 109* (1981) 311–337.

[6] M. Rashidi, G. Hetsroni and S. Banerjee, *Int. J. Multiphase Flow, 16* (1990) 935–949.

[7] C.B. Rogers and J.K. Eaton, *Phys. Fluids A, 3* (1991) 928–937.

[8] S.L. Lee and F. Durst, *Int. J. Multiphase Flow, 8* (1982) 125–146.

[9] D.B. Murray, *Ph.D. Thesis,* University of Dublin, 1989.

[10] R.A. Gore and C.T. Crowe, *Int. J. Multiphase Flow, 15* (1989) 279–285.

[11] G. Hetsroni, *Int. J. Multiphase Flow, 15* (1989) 735–746.

[12] Y. Tsuji, Y. Morikawa and H. Shiomi, *J. Fluid Mech., 139* (1984) 417–434.