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LETTER TO THE EDITOR

A FURTHER DISCUSSION OF "PARTICLE DRAG IN A DILUTE TURBULENT TWO-PHASE SUSPENSION FLOW"

In a recent Letter to the Editor, Gore & Crowe (1990) raised some questions concerning the validity of the assumptions used in the study of particle drag in a turbulent pipe flow by this author, Lee (1987a). These are legitimate questions and are hereby addressed as follows.

1. TIME (OR DISTANCE) REQUIRED FOR PARTICLE ACCELERATION (AERODYNAMIC RESPONSE TIME)

The basic assumption underlying the equation used to deduce the particle drag coefficient from measurements of particle and gas velocities,

$$C_D = \frac{A}{3}\frac{\rho_p}{\rho_g}\frac{d_p g}{U_R^2}, \tag{1}$$

is that the particle acceleration is zero. The use of a simple particle aerodynamic response time, $\tau_A = \rho_p d_p^2/18\mu$, to estimate the validity of the assumption underlying [1], in the view of this author, represents an over-simplification of the actual experimental situation. In the experiments of Lee & Durst (1982) and Tsuji *et al.* (1984), particles are collected from the exhaust by a cyclone separator and are then fed back into the flow at the throat of a Venturi Orifice placed before the entrance to the pipe. In much of this region, the local air velocity is raised to a very high level and much of the particle acceleration can be expected to have taken place in the Venturi passage and the immediate entrance region of the pipe. Therefore [1] can be considered reasonable.

2. EFFECT ON PARTICLE VELOCITY DUE TO PARTICLE–WALL COLLISIONS

The Discussion stated that:

> "The gas velocity in the axial direction is constant in a fully developed flow but particles will lose momentum due to collisions with the wall and will be reaccelerated toward the free stream velocity. Thus, particle–wall collisions lead to a situation in which the particles are continually undergoing acceleration with respect to the mean flow."

The actual fact is that for large particles, Lee & Durst (1982) (glass particles) and Tsuji *et al.* (1984) (plastic particles), experimental results show clearly that, at the measuring station at least, there is a sizable radial particle-free zone at the pipe wall, about 10 and 8% of the pipe radius for the heavier (glass) particles of 800 and 400 μm, respectively, of Lee & Durst (1982). The same trend also shows up in the results for large-size lighter (plastic) particles of Tsuji *et al.* (1982). It is reasonable to expect that this particle-free zone probably exists for much of the length of the pipe, with the probable exception of the very entrance region. Since there are no particles found in this particle-free zone, there could be no particle–wall collisions. An explanation can be provided for the formation of the particle-free zone by a particle transport theory, Lee (1987b, 1989). For large particles, the dominant forces which govern the transverse transport of particles are the lift force (in the present case, acting toward the pipe axis) and the drag (opposing the particle movement toward the pipe axis). The lift force depends on, among the other things, the ambient velocity gradient which is highest near the wall, thus is primarily responsible for producing the particle-free zone. The effective thickness of this region of large particle transverse migration is estimated to be on the order of one half of the pipe radius in the experiments with large particles (400 and 800 μm) of Lee & Durst (1982). Therefore, the dynamic behavior of large particles near the pipe axis in this case can be assumed to be essentially unaffected by the actions in the near-wall region.

For small particles, Lee & Durst (1982) (glass particles) and Tsuji *et al.* (1984) (plastic particles), experimental results show the existence of a sizable slip-velocity reversal zone near the pipe wall, about 20 and 10% of the pipe radius for the heavier (glass) particles of 100 and 200 μm, respectively, Lee & Durst (1982). The same trend also shows up in the results for small-size lighter (plastic) particles of Tsuji *et al.* (1984). An explanation can also be provided for this observed behavior by the same particle transport theory, Lee (1987b, 1989). For small particles, the dominant forces which govern the transverse transport of particles are the turbulent diffusion force (pushing the particles toward the wall) (Lee & Wiesler 1987c) and the drag force (opposing the direction of the particle movement). Therefore, if a small particle away from the near-wall region is pushed outward toward the wall by the diffusion force and can overcome the drag resistance in the transverse direction on the way, it will collide with the wall and will get bounced back. On the way back, it will be further slowed down in the transverse direction by the drag resistance. In the meantime, in the near-wall region the longitudinal fluid velocity is low and goes to zero at the wall. During the rendezvous with the pipe wall, the small particle will lose its momentum in the longitudinal direction, but its longitudinal velocity is always higher than the local fluid longitudinal velocity. This explains the formation of the slip-velocity reversal region and gives some insight to the dynamics of small particle behavior in this situation. The loss of longitudinal momentum of the particles there is due mainly to its interaction with the slow-moving fluid near the wall rather than its collision with wall itself as pointed out in the Discussion. In the experiments with small particles (100 and 200 μm) of Lee & Durst (1982), this transverse region is estimated to be about half of the pipe radius. Therefore, the dynamic behavior of small particles near the pipe axis in the case can be assumed to be essentially uneffected by actions in the near-wall region as well.

Modaress *et al.* (1984) measured the air and particle velocities in a downward flow of a two-phase suspension near the exit of a circular pipe of 2 cm dia and 1.8 m length, and found the particles lagging behind the air. The difference in the flow direction [upward flow for Lee & Durst (1982) and Tsuji *et al.* (1984) and downward flow for Modaress *et al.* (1984)] for small particles (for instance 200 μm) is not expected to affect the transverse migrational behavior of particles. The main important difference lies in the size of the pipe [for instance, 4.19 cm for Lee & Durst (1982) and 2.0 cm for Modaress *et al.* (1984)]. For a pipe of smaller diameter, it can be expected that this intense particle fluid interaction region near the wall would probably overlap with the region around the pipe axis. Thus, the measured particle velocity in this case may very well lag behind the air velocity near the pipe axis for the reasons stated above.

3. ON THE DETERMINATION OF PARTICLE DRAG

3.1. *The standard drag curve for a sphere*

The standard drag curve (C_D–Re) has been formulated basically from drag measurements on a single stationary sphere which is placed in a quiescent (very low turbulence) ambient flow. In the present case of a turbulent flow of a two-phase suspension, the flow around a particle in the suspension is far from being quiescent. Torobin & Gauvin (1960) studied the effects of free-stream turbulence on the drag coefficient of fairly large spheres of different densities and diameters staying stationary or moving in steady motion in an upward concurrent turbulent flow wind tunnel in which a novel arrangement of orifice grids in series was employed to create a flow with a flat central mean velocity profile and a random energy spectrum for the entire particle trajectory. In general, for a stationary sphere, the presence of significant free-stream turbulence causes the particle drag coefficient to drop noticeably below the standard drag curve. Furthermore, it is important to note that the drop in the apparent drag coefficient for a moving sphere under the identical flow conditions is even far more serious. This can be contributed to the difference in the turbulence intensities felt by a stationary sphere and by a moving sphere in the same turbulent ambient flow. A stationary sphere feels the turbulence intensity of the flow relative to the velocity of the flow which is defined with respect to a stationary frame of reference. However, a moving sphere which is passively following the fluid flow feels the turbulence intensity of the flow relative to the slip velocity of the flow which is defined with respect to a frame of reference moving with the sphere. Therefore, a moving sphere feels a greatly enlarged turbulence intensity in the same turbulent flow. At very low turbulence intensity, the values of the drag coefficient for either a stationary or a moving sphere were found to coincide with those obtained in a laminar flow. At sufficiently higher turbulence intensities, there appeared a characteristic sharp drop in the drag coefficient of at least an order of magnitude. In the present situation of the upward turbulent flow of a two-phase suspension through a vertical pipe, it would be of interest to examine the turbulence intensity which is felt by a moving particle in the suspension. Take, for instance, the case of 800 μm glass particles in the experiments of Lee & Durst (1982) in which, along the pipe axis $\bar{U}/U_0 = 1$, $\bar{U}_p/U_0 = 0.25$, $\sqrt{\bar{u}^2}/U_0 = 0.115$, $\sqrt{\bar{u}_p^2}/U_0 = 0.075$, where U_0 = mean centerline velocity of air = 5.66 m/s, $\bar{U}$ and $\bar{U}_p$ = mean fluid and particle velocities, respectively, u' and u'_p = turbulent fluctuating velocities of fluid and particle, respectively. In terms of the slip velocity of the particle, $U_R = U_0 - \bar{U}_p$, and considering only the fluctuating velocity of the fluid alone, the turbulence intensity which is felt by a moving particle would be $\sqrt{\bar{u}'^2}/U_R = 0.15$. If the fluctuating velocity of the particle velocity is also included, an estimate of the turbulence intensity which is felt by a moving particle leads to a very high value of around 0.25, which far exceeds even the turbulence intensity levels covered by the experiments of Torobin & Gauvin (1960). An analysis of the data of Tsuji *et al.* (1984) produces similar results. Therefore, from a philosophical point of view, the drag coefficients which are properly deducible from the experiments of both Lee & Durst (1982) and Tsuji *et al.* (1984) should be expected, in most cases, to be far below those predicted by the standard drag curve. A preliminary examination on this point, as the discussors have correctly pointed out, was at best inconclusive in view of the wide spread of results. It was the intention on the part of this author to find a rational way of piercing through the seemingly chaotic situation on the surface to arrive at a more realistic determination of the particle drag in a turbulent suspension flow by a careful examination of the various elements of these aforementioned experiments.

3.2. Analyses of experimental results

The turbulent flow of a two-phase suspension in a pipe is an extremely complex problem, which until fairly recently remained unattainable for local detailed dynamic measurements. Measurements by Lee & Durst (1982) and Tsuji *et al.* (1984) were at best the first attempts in this effort and unavoidably carried with them a great deal of uncertainties in their results due to the inherent uncertainties of the various components in their experimental procedures. Unlike the similar uncertainties faced in the measurements of a more conventional flow, such as the flow of a single-phase fluid, the uncertainties faced here are caused by stretching the realm of capabilities of the technologies of the various experimental components, many of which were newly conceived then, to an extreme extent. These experimental components include flow establishment, LDA optics, electronics and data processing and analyzing, which are arranged in series in the experimental procedure. The two sets of experiments, Lee & Durst (1982) and Tsuji *et al.* (1984), adopted quite different approaches to almost all of these experimental components. The uncertainties in the final measurements are the results of accumulation and mutual amplification of the exaggerated uncertainties of the experimental components which are arranged in series. Therefore, the final measurements cannot be taken for granted at their face values without a certain rational probing of the flow under investigation. One of the strategies is to examine the "consistency" of the experimental data.

The parameters which characterize a two-phase suspension flow in a pipe include the particle size, the particle-to-fluid intrinsic density ratio, the characteristic fluid velocity, the particle mass flux etc. In a hypothetical situation, suppose one can hold all the parameters the same with the exception of one, say the particle size, in a series of tests in which the centerline particle velocity is measured. Although the result of each individual test carries with it the inherent uncertainties discused above, the consistency of the general trend of the dependence of the centerline particle velocity on the particle size for all tests in the series would suggest a correction on the measured centerline particle velocity for certain particle sizes. However, in the present case, there are always several parameters which are varied at the same time. Therefore, the procedure for consistency correction on the measured centerline particle velocity would require an iteration based on the individual variations of the parameters involved. Figure 1 of Lee (1978a) shows the results of such a procedure for consistency correction. While this procedure could not be expected to eliminate most of the inherent experimental uncertainties, it would bring us closer to focusing on the underlying main feature of this complex flow which is hidden behind a mess of widely scattered experimental data.

It was an apparent oversight on the part of this author to have neglected a detailed explanation of the aforementioned points in Lee (1987a). Nevertheless, a short account of this explanation was recently conveyed to one of the authors of the discussion, Crowe (1989).

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