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LETTER TO THE EDITOR

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

Several papers have appeared in the literature on the flow of gas–particle mixtures in vertical pipes. These papers have addressed the effects of particles on gas turbulence as well as the dispersion of particles due to turbulence. Among these investigations, Lee (1987) has studied particle drag coefficients in turbulent pipe flows. This letter addresses the errors associated with the particle drag coefficients given in Lee (1987).

The equation used by Lee (1987) to reduce the particle drag coefficient from measurements of particle and gas velocity was

$$C_D = \frac{A}{3}\frac{\rho_P}{\rho_G}\frac{d_p g}{U_R^2}, \qquad [1]$$

where U_R is the magnitude of the relative velocity. This expression is obtained by equating the drag force and weight for the case in which the gravitational vector has the opposite sense of the relative velocity vector between the particle and the fluid. Lee applied this equation to the data reported by Tsuji *et al.* (1984) and Lee & Durst (1982) for particles being conveyed upward in fully developed pipe flow. The data used to evaluate the drag coefficients from both experiments were the gas and particle velocities at the pipe centerline.

The basic assumption underlying [1], besides the insignificance of the pressure gradient effect, is that the particle acceleration is zero. 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 effect of walls on particle velocities is very evident in the work of Moddaress *et al.* (1984) who investigated the effects of particles on the gas flow field of a free jet. The gas–particle jet was formed by 200 μm particles issuing downward from a vertical pipe 2 cm dia and 1.8 m length. To establish the initial conditions for the particle field the particle velocities were measured 2 mm downstream from the pipe exit. These velocities are very near those in the pipe because of the proximity of the measurement location to the pipe exit. The gas velocity in the pipe was 12 m/s. With no wall collisions the velocity of a particle (of density and size used in their experiment) starting from rest in a 12 m/s downward gas flow will exceed the gas velocity in a 1.8 m distance. The data revealed, however, that the particle velocity was 10 m/s which was less than the gas velocity, which implies the significance of particle–wall collisions. Applying [1] to these data correctly accounting for the sign of the relative velocity would yield negative drag coefficients.

A measure of the time required for particle acceleration is the aerodynamic response time defined as

$$\tau_A = \frac{\rho_P d_P^2}{18\mu}. \qquad [2]$$

The aerodynamic response time for the 500 μm particles used in the experiment of Tsuji *et al.* was 0.8 s. An estimate of the distance required for a particle to complete its acceleration after a wall collision is $\tau_A \bar{U}$, where $\bar{U}$ is the average particle velocity. Taking an average velocity of 10 m/s, a distance of 8 m would be required top accelerate a 500 μm particle which exceeds the length of the test section. Thus, it is reasonable to expect that the particles are continually colliding with the walls and accelerating in the tube and that the assumption of no acceleration is invalid.

Table 1. Comparison of centerline relative velocities

Partical diameter (μm)	Mass ratio	Velocities used by Lee (1987) (m/s)	Actual velocities (m/s)
200	4.2	1.46	0.6
200	2.1	3.48	1.3
200	1.0	3.31	1.4
500	3.6	3.27	2.0
500	2.0	4.54	2.7
500	1.1	5.82	3.45
3000	3.0	10.60	10.7
3000	2.2	11.1	11.2
3000	1.2	11.8	11.9

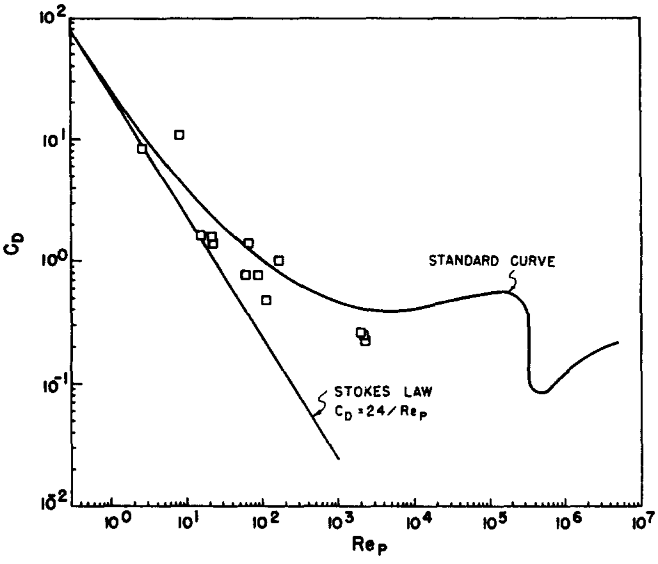

Figure 1. Corrected drag coefficients using [1].

There are not enough data to evaluate particle acceleration and recalculate the drag coefficient. Including particle acceleration would yield higher drag coefficients but the magnitude of the effect is uncertain.

The large discrepancy between the standard drag curve and drag coefficients reduced by Lee (1987) prompted a check of the values used in reducing the drag coefficient. Table 1 provides the values for centerline relative velocities as used by Lee (and reported in this paper) and those read by the current authors [and confirmed by Tsuji (1988)].

Reducing Tsuji's data using these values and [1] yields the drag coefficients shown in figure 1. One notes that the data cluster around the standard drag curve with a tendency to lie below the curve. This tendency is possibly due to the effect of excluding particle acceleration in the particle motion equation.

The effect of turbulence on the particle drag coefficient and its measurement remains an open question in gas–solid flows. The most practical approach for selecting a particle drag coefficient still appears to be the standard drag curve with the correlations suggested by Torobin & Gauvin (see Clift *et al.* 1978) to account for turbulence effects.

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