Particles and Turbulence

Turbulent flows of a single Newtonian fluid, even those of quite simple external geometry such as a fully-developed pipe flow, are very complex and their solution at high Reynolds numbers requires the use of empirical models to represent the unsteady motions. It is self-evident that the addition of particles to such a flow will result in;

1. complex unsteady motions of the particles that may result in non-uniform spatial distribution of the particles and, perhaps, particle segregation. It can also result in particle agglomeration or in particle fission, especially if the particles are bubbles or droplets.

2. modifications of the turbulence itself caused by the presence and motions of the particles. One can visualize that the turbulence could be damped by the presence of particles, or it could be enhanced by the wakes and other flow disturbances that the motion of the particles may introduce.

In the last twenty five years, a start has been made in the understanding of these complicated issues, though many aspects remain to be understood. The advent of laser Doppler velocimetry resulted in the first measurements of these effects; and the development of direct numerical simulation allowed the first calculations of these complex flows, albeit at rather low Reynolds numbers. Here we will be confined to a brief summary of these complex issues. The reader is referred to the early review of Hetsroni (1989) and the text by Crowe *et al.* (1998) for a summary of the current understanding.

To set the stage, recall that turbulence is conveniently characterized at any point in the flow by the Kolmogorov length and time scales, λ and τ, given by

$$\lambda = \left(\frac{\nu^3}{\epsilon}\right)^{\frac{1}{4}} \qquad \text{and} \qquad \tau = \left(\frac{\nu}{\epsilon}\right)^{\frac{1}{2}} \tag{Nca1}$$

where ν is the kinematic viscosity and ϵ is the mean rate of dissipation per unit mass of fluid. Since ϵ is proportional to U^3/ℓ where U and ℓ are the typical velocity and dimension of the flow, it follows that

$$\lambda/\ell \propto Re^{-\frac{3}{4}} \qquad \text{and} \qquad U\tau/\ell \propto Re^{-\frac{1}{2}} \tag{Nca2}$$

and the difficulties in resolving the flow either by measurement or by computation increase as Re increases.

Gore and Crowe (1989) collected data from a wide range of turbulent pipe and jet flows (all combinations of gas, liquid and solid flows, volume fractions from 2.5×10^{-6} to 0.2, density ratios from 0.001 to 7500, Reynolds numbers from 8000 to $100,000$) and constructed figure 1 which plots the fractional change in the turbulence intensity (defined as the rms fluctuating velocity) as a result of the introduction of the disperse phase against the ratio of the particle size to the turbulent length scale, D/ℓ_t. They judge that the most appropriate turbulent length scale, ℓ_t, is the size of the most energetic eddy. Single phase experiments indicate that ℓ_t is about 0.2 times the radius in a pipe flow and 0.039 times the distance from the exit in a jet flow. To explain figure 1 Gore and Crowe argue that when the particles are small compared with the turbulent length scale, they tend to follow the turbulent fluid motions and in doing so absorb energy from them thus reducing the turbulent energy. It appears that the turbulence reduction is a strong function of Stokes number, $St = m_p/6\pi R\mu\tau$, the ratio of the particle relaxation time, $m_p/6\pi R\mu$, to the Kolmogorov time scale, τ. A few experiments (Eaton 1994, Kulick *et al.* 1994) suggest that the maximum reduction occurs at St values of the order of unity though other features of the flow may also influence the effect. Of course, the change in the turbulence intensity also depends on the particle concentration. Figure 2 from

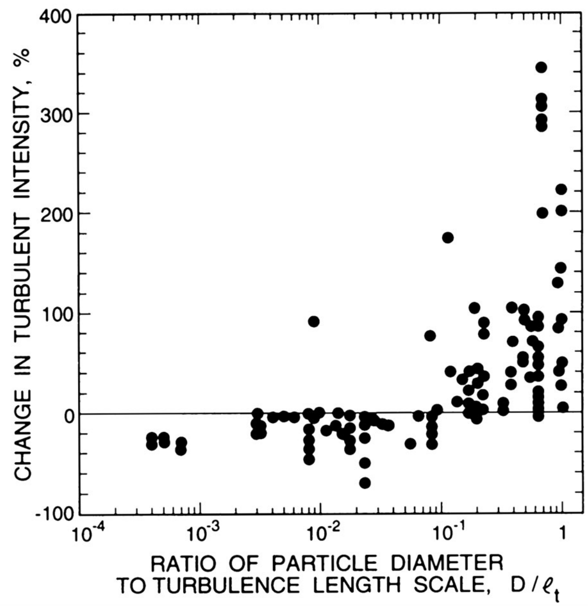

Figure 1: The percentage change in the turbulence intensity as a function of the ratio of particle size to turbulence length scale, D/ℓ_t, from a wide range of experiments. Adapted from Gore and Crowe (1989).

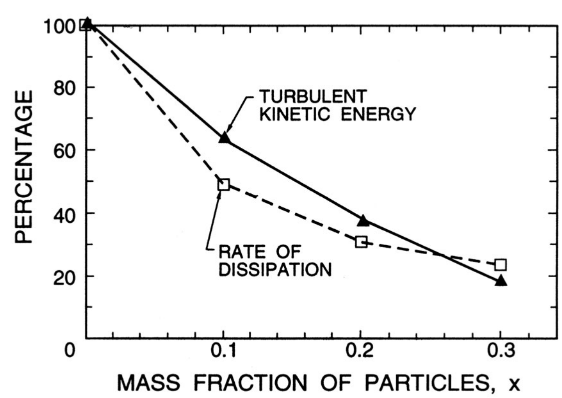

Figure 2: The percentage change in the turbulent kinetic energy and the rate of viscous dissipation with mass fraction for a channel flow of $150\mu m$ glass spheres suspended in air (from Paris and Eaton 2001).

Paris and Eaton (2001) shows one example of how the turbulent kinetic energy and the rate of viscous dissipation depend on the mass fraction of particles for a case in which D/ℓ_t is small.

On the other hand large particles do not follow the turbulent motions and the relative motion produces wakes that tend to add to the turbulence (see, for example, Parthasarathy and Faeth 1990). Under these circumstances, when the response times of the particles are comparable with or greater than the typical times associated with the fluid motion, the turbulent flow with particles is more complex due to the effects of relative motion. Particles in a gas tend to be centrifuged out of the more intense vortices and accumulate in the shear zones in between. Figure 3 is a photograph of a turbulent flow of a gas loaded with particles showing the accumulation of particles in shear zones between strong vortices. On the other hand, bubbles in a liquid flow tend to accumulate in the center of the vortices.

Analyses of turbulent flows with particles or bubbles are currently the subject of active research and many issues remain. The literature includes a number of heuristic and approximate quantitative analyses of the enhancement of turbulence due to particle relative motion. Examples are the work of Yuan and

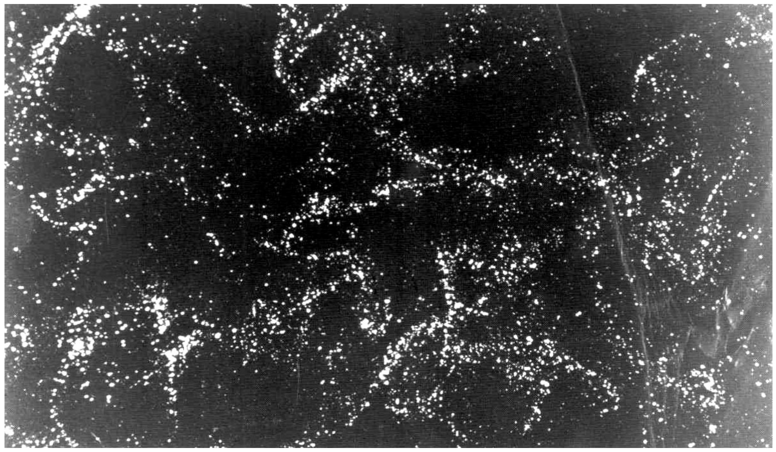

Figure 3: Image of the centerplane of a fully developed, turbulent channel flow of air loaded with $28\mu m$ particles. The area is $50mm$ by $30mm$. Reproduced from Fessler *et al.*(1994) with the authors' permission.

Michaelides (1992) and of Kenning and Crowe (1997). The latter relate the percentage change in the turbulence intensity due to the particle wakes; this yields a percentage change that is a function not only of D/ℓ_t but also of the mean relative motion and the density ratio. They show qualitative agreement with some of the data included in figure 1.

An alternative to these heuristic methodologies is the use of direct numerical simulations (DNS) to examine the details of the interaction between the turbulence and the particles or bubbles. Such simulations have been carried out both for solid particles (for example, Squires and Eaton 1990, Elghobashi and Truesdell 1993) and for bubbles (for example, Pan and Banarejee 1997). Because each individual simulation is so time consuming and leads to complex consequences, it is not possible, as yet, to draw general conclusions over a wide parameter range. However, the kinds of particle segregation mentioned above are readily apparent in the simulations.