

## PARTICLE TURBULENCE INTERACTION

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The interaction between the carrier and the dispersed phases is bi-directional: the carrier-phase turbulence influences the dispersion and preferential accumulation of particles and bubbles, and particles and bubbles in turn modulate the fluid turbulence. At the level of a single particle, the effect of freestream turbulence is to modify the drag force compared to that in a steady uniform flow. On the other hand, the particle can modify freestream turbulence by the formation of a wake, periodic shedding of vortices, and wake turbulence. The collective effect of a distribution of particles can further modify the effective drag force on a particle due to the screening effect and thereby influence the mean settling and dispersion characteristics. Similarly, the collective effect of the dispersion of particles will determine the attenuation or augmentation of the turbulence intensity. Thus, many of the mechanisms of multiphase flow turbulence are quite distinct from those that have been well established in single-phase turbulence and therefore deserve detailed investigation.

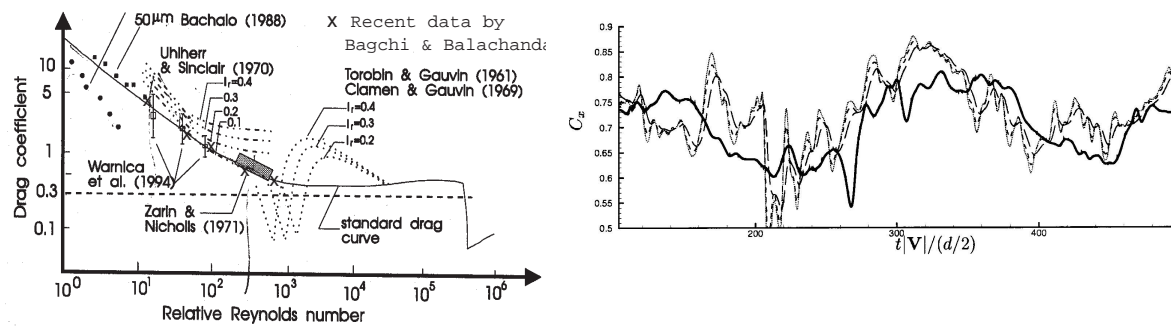
Here we present results from fully-resolved direct numerical simulations (DNS) of turbulent multiphase flow. In addition to resolving the wide range of length and time scales associated with turbulence, which would exist even in the absence of the particles, we now need to resolve all the length scales associated with the particles and the small-scale flow features generated by them. Thus, direct numerical simulations of multiphase flow turbulence pose greater challenge than the DNS of corresponding single-phase turbulence. Here we plan to present results for the interaction of a single spherical with ambient turbulence. We will consider the cases of both isotropic freestream turbulence and wall-bounded channel flow turbulence.

For the case of isotropic turbulence the particle Reynolds number is varied from about 50 to 600, and the particle diameter is about 1.5 to 10 times the Kolmogorov scale of the undisturbed turbulent flow. The Taylor microscale of the freestream turbulent flow is 164 and the relative intensity of freestream turbulence to mean crossflow is varies from 10% to 25%. The DNS technique employed here resolves both the smallest scales in freestream turbulence and the thin shear layers and complex vortical structures associated the particle wake. The present DNS study is similar to the experimental study by Wu & Faeth (1994a, 1994b), and agreement between the DNS results and the experimental measurement are presented.

Figure 1a summarizes the drag coefficient for a sphere in the presence of freestream isotropic turbulence compiled from many different experimental measurements. Also plotted for reference as the solid line is the standard Schiller-Neumann drag law corresponding to a turbulence-free uniform flow. The scatter in the experimental data clearly illustrates the large discrepancy between the different results. Also plotted in the figure are the DNS results which show that freestream isotropic turbulence does not have a substantial and systematic effect on the time-averaged mean drag on the particle. Standard drag correlation based on instantaneous relative velocity between the particle and the undisturbed fluid velocity at the center of the particle results in a reasonable prediction of the mean drag. However, the accuracy of prediction of the instantaneous drag decreases with increasing particle size. For the smaller particles, the low frequency oscillations in the DNS drag are well captured by the standard drag, but for the larger particles significant differences exist even for the low frequency components. Inclusion of the added-mass and history terms, computed based on the undisturbed ambient flow at the center of the particle, does not improve the prediction of instantaneous forces. Fluctuations in the drag and lift forces are shown to scale with the mean drag as well as the freestream turbulence intensity (see figure 1b).

The effect of freestream turbulence on the mean and instantaneous wake structure is studied. The mean wake in a turbulent flow shows reduced velocity deficit and a flatter profile. However, the mean wake in a turbulent flow behaves like a self-preserving laminar wake. At low Reynolds numbers the wake in a turbulent flow oscillates strongly without any vortex shedding, but at higher Reynolds numbers vortex shedding starts. The nature of the vortices are very different from that in a uniform flow. Increasing the freestream turbulence intensity suppresses the process of vortex shedding, and only marginally increases the wake oscillation. The modulation of freestream turbulence in the wake is studied in terms of the distribution of the kinetic energy and RMS of velocity fluctuation. The freestream energy lost in the wake is recovered faster in a turbulent flow than in a uniform flow. The energy of the velocity fluctuation is enhanced in the wake at low freestream intensities, and is damped or marginally increased at higher intensities. The fluctuation energy is not equi-partitioned among the streamwise and cross-stream components. The RMS of the streamwise fluctuation is always enhanced, whereas the RMS of the cross-stream fluctuation is enhanced only at low freestream intensities, and damped at higher intensities.

We are currently extending the above results in several significant ways. For a given ambient turbulent flow, the particle Reynolds number can be expressed in terms of the other two parameters: the relative turbulence intensity and the ratio of particle diameter to freestream turbulence. Here we explore in greater detail the independent role of these different parameters on turbulence modulation. The above DNS approach is also being used to address the influence of freestream turbulence on the mean settling (or rise) velocity of heavier-than-fluid particles (or lighter-than-fluid bubbles). Unlike the earlier simulations, here the particle is allowed to freely move in response to hydrodynamic forces acting on it.



**Figure 1.** (a) Data on the effect of freestream turbulence on mean drag coefficient for varying  $Re$  obtained from several different experiments. Shown in the plot is the standard drag curve valid for a rigid sphere in a turbulence-free uniform cross-flow. Also shown are the recent DNS results of Bagchi & Balachand (2003b). (b) Time variation in the streamwise component of the drag coefficient due to freestream turbulence. For the case shown here the ratio of particle diameter to Kolmogorov scale is 4, turbulence intensity is 10% and  $Re = 261$ . Thick solid line: DNS result, thin solid line: standard drag law (SDL), dash line: SDL plus added-mass force, dash-dot line: SDL plus added-mass and Basset history force.

We are also in the process of investigating the interaction of a single isolated particle with wall turbulence. We consider the case of a spherical particle embedded in a channel formed between two parallel plates. Inflow to the computational domain is specified as a fully developed turbulent channel flow (at a specified Reynolds number based on friction velocity) obtained from an auxiliary turbulent channel flow simulation. The computational grid for the present simulation is chosen such that it resolves all the scales of the turbulent inflow across the entire width of the channel as well as the unsteady boundary layers, shear layers and the wake behind the particle. A high accuracy spectral element numerical methodology is used for simulating the turbulent flow around the sphere within the channel. Of particular interest is the interaction of the turbulent wake with the nearby wall. The key parameters of the problem are the relative size of the particle compared to the channel height, and the relative distance of the particle center from the nearby wall. We plan to vary these two parameters and accordingly the particle Reynolds number.

As with the isotropic turbulence, we plan to first study the effect of wall turbulence on the mean and fluctuating components of drag on the particle. The asymmetric effect of the nearby wall is to introduce a lift force on the particle. We will also investigate the effect of wall turbulence on the mean and fluctuating components of the lift force. We will then study the effect of the particle on the wall turbulence by focusing attention on the wake region downstream of the particle. The back-effect of the particle on the structure of turbulence will be first investigated in terms of interaction between wall-vortical wake-vortical structures. The turbulence statistics in the wake region will be compared with the undisturbed channel flow statistics to assess the influence of the particle. Particular attention will be focused on the effect of the particle on modifying the mean drag on the nearby flat plate.

## References

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