EVOLUTION OF TWO-WAY COUPLED PARTICLE-LADEN MIXING LAYER AND JET

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ABSTRACT

Shear flows provide a means to rapidly mix and disperse discrete solid particles and droplets in natural and industrial processes. Particles at moderate mass loading can also alter the gas shear flows. To better understand these phenomena, we have performed direct numerical simulations of particle-laden mixing layers and jets. The objective of this paper is to provide an overview of our recent studies on two-way coupled particle-laden free shear flows. Results on linear instability and nonlinear evolution of gas shear flows under two-way coupling are discussed. Most of the results are based on simulations of temporally evolving, three-dimensional particle-laden flows, preliminary results on spatially evolving jet are also discussed.

INTRODUCTION

Particle-laden two-phase flows are encountered in a wide range of industrial applications under various flow configurations. Examples are jet propulsion, spray combustion, spray coating, and pulverized coal combustion. The mixing of small solid particles or liquid droplets with the gas phase determines the efficiency and stability of the particular process, e.g., droplet vaporization and mixing or contaminant removal. In these and other examples it is desirable to achieve a specific particle concentration profile. Therefore, the ability to predict and control particle dispersion in mixing layer and jet flows is important to developing and improving designs of industrial equipment.

Most of the studies in the past have focused on the turbulent dispersion of particles in dilute flows (e.g., see Shirolkar et al., 1996 for a review). Moderate mass loadings of particles can also alter the fluid flow, which is known as the flow modulation (or turbulence modulation if the carrier flow is turbulent). In gas-solid flows, three qualitatively different flow regimes can be defined, depending on the level of particulate volume fraction and mass loading (Elghobashi, 1994). First, at very low volume fraction and mass loading, the particles do not affect the surrounding flow and there is no flow modulation. This is known as the one-way coupling regime. In the second regime, the particulate volume fraction is very low due to small particle sizes, but the mass loading is on the order of one because of the high particle to fluid density ratio. In this case, particles can significantly change the carrier-flow characteristics, but particle-particle interactions are often neglected. This is called the two-way coupling regime. Finally, in the dense flow regime, both the volume fraction and mass concentration are high so that particle-particle collisions have to be considered. In this paper, we are concerned with particle-laden free shear fflows (i.e., mixing layer and jet) which are volumetrically dilute, but have a large mass loading (the second regime).

Turbulence or flow modulation by particles has been known for several decades. Early experimental observations (Torobin and Gauvin, 1961) showed that the presence of particles changes the wall drag in pipes as well as rates of heat transfer and chemical reaction which cannot be explained unless the fluid turbulence is modified by particles. Since then, the issue of whether turbulence in the carrier flow is enhanced or reduced by the dispersed particles has been a subject of many experimental studies as experimental techniques are advanced. The survey by Gore and Crowe (1991) showed that a range of effects may be observed depending on the particle size and volumetric loading of particles. Recently, several theoretical models have been developed to predict the direction and level of turbulence modification (Yuan and Michaelides 1992, Hwang and Shen, 1993; Yarin and Hetsroni 1994, Crowe 2000).

With the development of modern computers, direct numerical simulations (DNS) provide an alternative tool for studying turbulence modulation by particles. For example, Squires and Eaton (1990) reported that the particles enhance the turbulent kinetic energy at high wavenumbers while decreasing the turbulent kinetic energy at low wavenumbers in forced isotropic, stationary turbulence. Similar “pivoting” phenomenon has been observed in Elghobashi & Truesdell (1993) and Sundaram & Collins (1999).

These numerical studies provide useful insight to turbulence modulation, although the point-force representation used has been questioned (Ooms and Jansen 2000, Maxey *et al.* 1997).

The problem of turbulence modulation in free shear flows may consist two facets: the instability and the nonlinear evolution of the flows. Shear flows usually develop from linear instabilities and as such the study of instability of the particle-laden jet would be the first step towards a better understanding of two-way coupled evolution of two-phase flows. Studies of instability of particle-laden shear flows have primarily focused on the *inviscid* mixing layer and jet (Michael 1965, Yang et al. 1990, Wen and Evans 1994, Sykes and Lyell 1994, Parthasarathy 1995, Dimas and Kiger 1998) with limited study of the viscous two-phase shear flows (Saffman 1962, Tong and Wang 1999, DeSpirito and Wang 2001a). There are very few studies on the nonlinear evolution of two-way coupled particle laden shear flows due to the experimental/numerical difficulties in characterizing these flows. The few studies reported in the literature have not yet established a general description of the flow evolution under two-way coupling (Ramanujachari and Natarajan 1993, Aggarwal et al. 1996, Davidson 1998, Ling et al. 2000).

In this paper, we provide an overview of our recent DNS studies on two-way coupled particle-laden free shear flows. Results on linear instability and nonlinear evolution of gas shear flows in the presence of particles are outlined. Most of the results are based on simulations of temporally evolving, particle-laden flows; preliminary results on spatially evolving jet are also reported.

NUMERICAL METHOD

We consider a gas-particle system in which the particle volume concentration, ε, is low but the mass loading, Z, is on the order of one. The latter is due to the assumption that the particle density, ρ_p, is much larger than the fluid density, ρ_f. As such, the flow modulation by the particles may be significant. Also, because of the large density ratio, the effects of virtual mass, Basset history forces, etc., are neglected. The particles are of uniform size with a diameter much smaller than any characteristic length scales in the carrier gas flow. The particle Reynolds numbers are in the Stokes flow regime so that linear Stokes drag is assumed. The effects of particle/particle interactions and the effect of the particle volume fraction in the continuous-phase governing equations are neglected, both due to the low particle volume concentration.

The numerical method involves solving the carrier flow equations and the equations for the particulate phase. The carrier flow equations are the incompressible Navier-Stokes equations with an additional forcing term due to the presence of the particles (Saffman 1962). For the particulate phase, two different approaches may be used. In the Lagrangian approach, the equation of motion for each particle is solved. An alternative approach is to treat the particulate phase as a continuum medium and the governing equations for particle concentration and momentum fields are developed and solved (The continuum approach). The two approaches have been shown to give similar results (Tong and Wang 1997). In this paper, we will only show results based on the continuum approach. For discussions regarding the comparison of the two approaches, the readers are referred to Slater and Young (1998) and Tong and Wang (1997).

The numerical method for the temporally evolving particle-laden mixing layer has been presented in Tong and Wang (1999) and that for the temporally evolving jet is described in DeSpirito and Wang (2001a).

Most past numerical studies of particle-laden free shear flows were based on a temporal formulation of the governing equations to reduce the computational cost and fit within the framework of the spectral methods that were used. Although the temporal formulation provides very useful results, a drawback of the method is that there are uncertainties in comparing the results to those of a spatially evolving flow. A spatially evolving flow is more representative of flows studied in the laboratory, and can therefore be compared more directly with experimental data.

A finite difference method used previously to study the temporally evolving, particle-laden jet was extended to study the spatially evolving jet. The method is similar to that of DeSpirito and Wang (2001a) except that the periodicity in the mean flow (z) direction is not employed. Instead of Fourier representation, we applied cosine-series represenation in z direction in the Poisson solver (Salvetti et al. 1996). The inlet boundary conditions are specified using the same velocity and concentration profiles as in DeSpirito and Wang (2001b). A radiation outflow boundary condition (Salvetti et al. 1996) is adopted to minimize the numerical artifacts at the boundary. Stress-free boundary conditions are imposed at large radial distance.

RESULTS

Linear Instability

To understand how the addition of solid particles affects the stability of the gas flow, we performed numerical simulations (Tong and Wang, 1999;

DeSpirito and Wang, 2001a) to obtain results equivalent to solving the Orr-Sommerfeld equation of a dusty gas mixing layer first derived by Saffman (1962). The growth rate of a viscous particle-laden mixing layer depends on the wavenumber, flow Reynolds number, Stokes number, and bulk particulate mass loading. The jet flow stability is complicated by a variable wave (or phase) velocity and an additional curvature parameter, i.e., the ratio of jet radius to shear layer thickness.

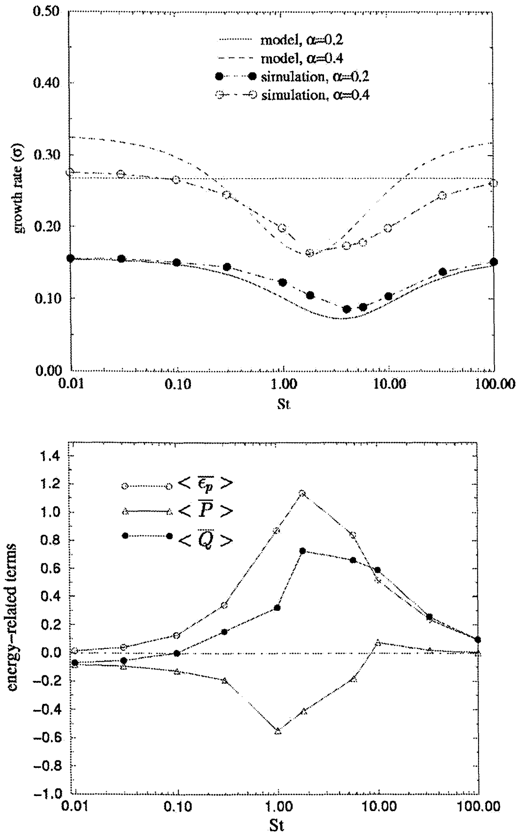


Figure 1: *Growth rate (top) as a function of particle Stokes number, showing that the addition of particles usually stabilizes the flow for intermediate Stokes numbers, but can also destabilize the flow at small Stokes number. An alternative explanation is given in terms of the interphase energy transfer budgets (bottom):* $<\overline{\varepsilon}_p>$ = *particle dissipation;* $<\overline{P}>$ = *the rate of work transferred to the particle phase; and* $<\overline{Q}>$ = *the rate of work provided by the gas phase.*

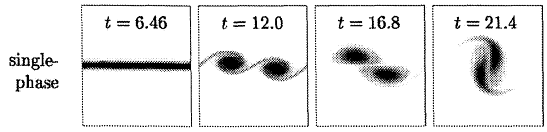
In addition to the stabilizing effect of particles on the gas flow at intermediate and large Stokes number, a destabilizing influence at small Stokes number is also observed at finite flow Reynolds number (Figure 1a). The fact that the addition of particles can destabilize the gas flow in the absence of gravity has been shown to follow the original speculation of Saffman (1962). Physically, the increase of effective inertia of the fluid-particle mixture causes a destabilization effect while the enhanced viscous dissipation around particles gives a stabilization effect.

These qualitatively different effects have been shown to be directly related to the direction of interphase energy transfer (Figure 1b). Results at arbitrary mass loading, Stokes number, and wavenumber show that for a given mass loading and wavenumber, there is an intermediate Stokes number which corresponds to a maximum flow stability. We have shown that this Stokes number is on the order of one, and depends on the wavenumber. An analytical model for predicting the growth rate in a viscous, particle-laden gas mixing layer is proposed in Tong and Wang (1999) and compared with the simulation results. The efficient damping by the particulate phase at the intermediate Stokes number can reduce the dispersion enhancement discovered previously under one-way coupling. For the case of the particle-laden jet, we also found that the addition of particles increases the wave velocity at high wavenumbers but decreases the wave velocity at low wavenumbers (DeSpirito and Wang, 2001a).

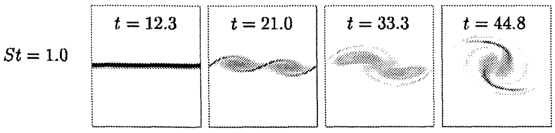
Nonlinear Evolution

Next we discuss nonlinear flow modulation by the addition of particles, initially uniformly distributed *throughout the flow*, in a temporally evolving mixing layer. Qualitatively, the particle-laden mixing layer, like the single-phase mixing layer, undergoes the familiar rollup and subsequent vortex pairing. There are, however, several quantitative as well as qualitative differences. For most parametric settings, both the time scales and length scales for the rollup and pairing are larger due to the enhanced linear stability and shifting of the most unstable wavenumber. The size of the vortices scales roughly with the wavelength and time scales of the linear instability. The coupling term acts as a forcing to the fluid vorticity equation, which introduces a memory effect that alters the structure of the rollup vortices. At intermediate Stokes number, this forcing can rupture the vortices, leading to a qualitatively different vortex structure (Figure 2).

We have also studied the flow modulation in an axisymmetric jet due to addition of particles uniformly distributed *at the shear layer interface* (DeSpirito and Wang, 2001b). Figure 3 shows the flow vorticity and particle concentration contours for *St* =1.0 under both one-way and two-way couplings. The effect of the particles on the flow is observed as early as t = 4.0. Under two-way coupling, the intensity of vortex ring roll-up is stronger, leading to enhanced spreading of the jet interface. The vorticity inside the ring is more nonuniformly distributed, similar to the vortex rupture observed in the mixing layer simulation. The enhanced spreading of the jet shear layer can also be shown by comparing the jet



(a) One-way coupling



(b) Two-way coupling

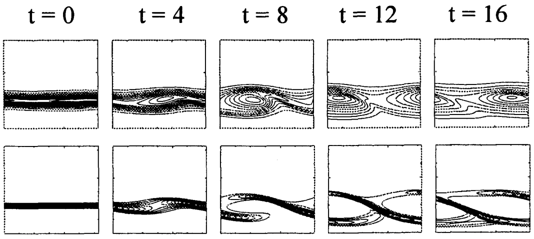
Figure 2: *Nonlinear evolution of vortical structures in particle-laden mixing layer under (a) one-way and (b) two-way coupling, showing that the addition of particles can rupture the vortical structure.*

vorticity thickness. This result indicates that the nonlinearity may actually enhance the jet shear layer growth rate at intermediate Stokes number for this localized particle seeding. The two-way coupled case shows a localization of the particle concentration near the jet shear layer interface for intermediate and large Stokes number, leading to reduced dispersion. As the same time, enhanced mixing of the particles inside the vortex rings has been observed.

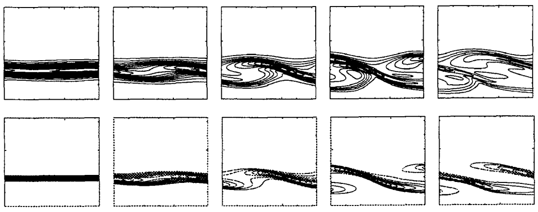
The level of accumulation and mixing in the particle-laden jet are quantified by the normalized mean concentration profiles for one-way and two-way coupled cases in Figure 4, for three Stokes numbers at different times. At intermediate and large Stokes number, there is an increase in mixing (flattening of the concentration profile) and a reduction in dispersion in the two-way coupled case. For low Stokes number, there is a broadening of the concentration profile, with an accumulation of particles in the jet core region leading to larger dispersion.

Spatially Evolving Jet

Here we present some preliminary results on the spatially evolving, axisymmetric particle-laden jet. Initially, the fluid is static everywhere, and a jet is issued from the inlet starting at $t = 0$. As the jet moves downstream, the jet interface becomes unstable and vortices are generated through roll-up of the interface shear layer. The vortices subsequently pinch off from the interface and merge to form large vortices (e.g., Figure 6). By t=100, the jet flow is established everywhere in the domain. The particulate phase is then added at t=100 to the simulation with a fixed nonzero inlet concentration profile at the interface (Figure 6). The jet flow Reynolds number based on the jet diameter D is 5000 and the particle Stokes number is 1.0. The domain size used is 2.5D by 20D. 148 nonuniform cells are used in the r direction and 1024 uniform cells in the z direction.



(a) One-way coupling



(b) Two-way coupling

Figure 3: *Vorticity (top pane) and particle concentration (bottom pane) contours for particle-laden axisymmetric jet under (a) one-way and (b) two way coupling, showing modulation of vortical structure by the addition of particles. In each display, the times in the simulations from left to right are t = 0, 4, 8, 12, and 16, respectively.*

Figure 5 shows the time history of the z-component fluid velocity and particle concentration at a point close to the outlet under one-way coupling. The quasi-periodic flow for both phases is established after t=200. A single-time snapshot of the flow vorticity and particle concentration at t=200 is provided in Figure 6, showing how the flow vortical structure disperses the particles in the radial direction and concentrates particles in selected regions.

When the two-way coupling term is included with a loading ratio on the order of one (the mass flow rate of particles to that of the fluid), the shear layer instability is inhibited as the particles are moved through the computational domain, and a steady laminar jet is gradually established after t=200 (Figures 7 and 8). This indicates a strong stabilization effect of the particles on the jet. This stabilization effect has been observed in temporally evolving jet (DeSpirit and Wang 2001a). We will

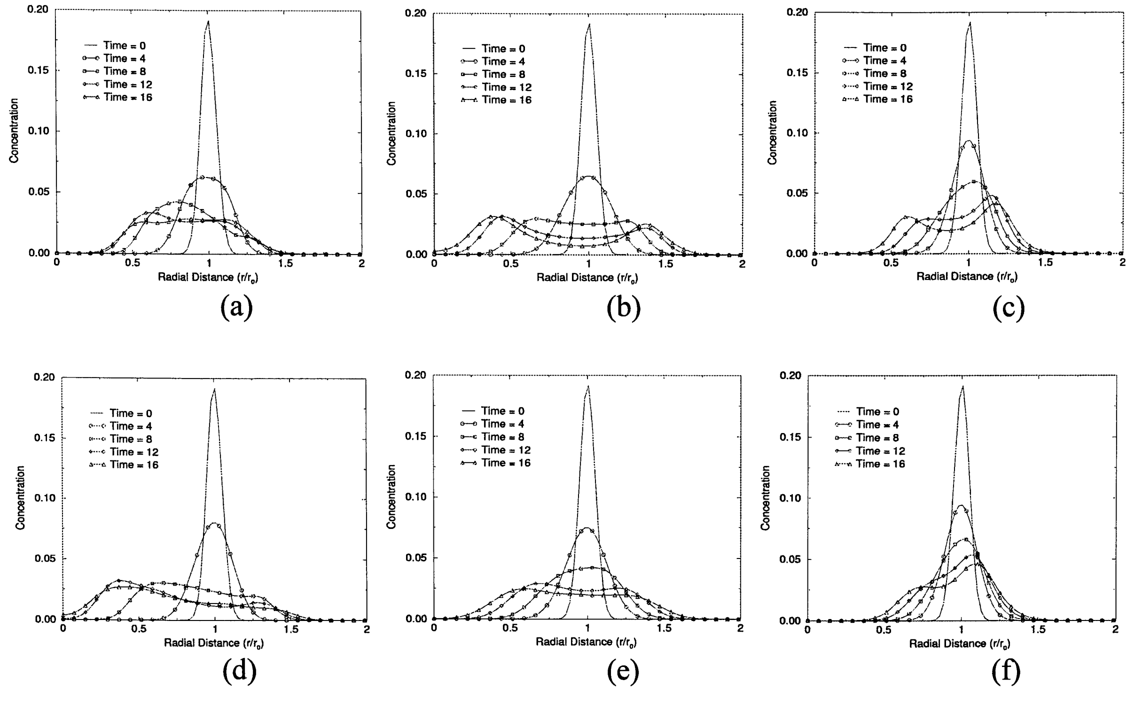


Figure 4: *Normalized mean particle concentration profiles for one-way coupled (a-c) and two-way coupled (d-f) axisymmetric jet for (a, c) St = 0.1, (b, e) St = 1.0, and (c, f) St = 10.0.*

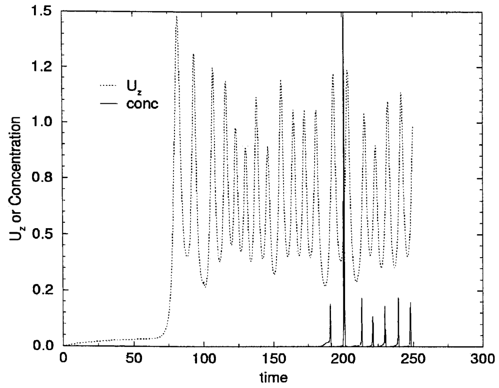


Figure 5: *Time history of z-component fluid velocity and particle concentration at a point* $r = r_0$, $z = 40 r_0$ *for one-way coupled spatially-evolving jet.*

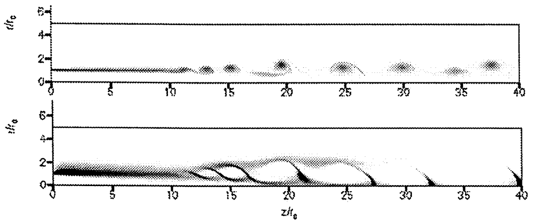


Figure 6: *Visualization of fluid vorticity (top) and particle concentration (bottom) at* $t = 200$ *for one-way coupled spatially-evolving jet.*

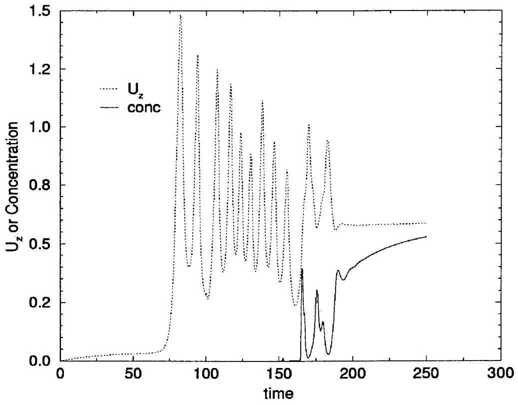


Figure 7: *Time history of z-component fluid velocity and particle concentration at a point* $r = r_0$, $z = 40 r_0$ *for two-way coupled spatially-evolving jet.*

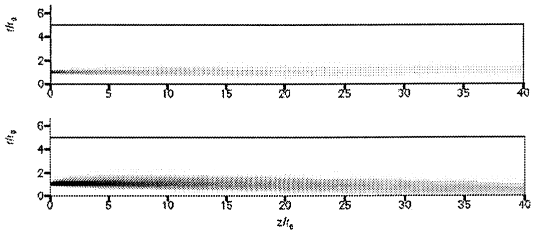


Figure 8: *Visualization of fluid vorticity (top) and particle concentration (bottom) at* $t = 200$ *for two-way coupled spatially-evolving jet.*

study carefully the accuracy of the numerical simulation and the parametric region for a stabilized jet in terms of flow Reynolds number, Stokes number, and mass loading.

SUMMARY

We have observed that the addition of solid particles can alter both the instability of the gas shear flows and the structure of the flow. The linear instability of temporally evolving two-phase mixing layer and jet has been quantitatively studied, while the spatially evolving case requires a separate investigation. The results obtained to date on the nonlinear flow evolution and particle transport/mixing under two-way coupling show a number of interesting phenomena that require quantitative physical explanation. We plan to validate the spatially evolving jet code by comparing the simulation results with available experimental data.

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