Particulate Science and Technology: An International Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/upst20

PARTICLE DISPERSION BY COHERENT STRUCTURES IN FREE SHEAR FLOWS

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Published online: 29 Oct 2007.

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ABSTRACT

The dispersion of particles in turbulent flows is poorly understood. Previous approaches to this problem have been found to be inadequate for nonisotropic turbulent flows. An approach involving a new physical concept is presented. This approach assumes that coherent vortex structures control the particle dispersion process in free shear flows. A simple computational model employing Stuart's vortices is used to simulate particle motion in a two-dimensional free shear layer. The results of this simulation are in reasonable agreement with previous experiments. For the first time, experimental observations indicating particle dispersion rates greater than fluid dispersion rates in free shear flows can be plausibly explained.

INTRODUCTION

The dispersion of particles due to turbulence in a liquid or gas is an important process in many chemical and energy-related industries. A power plant fired by pulverized coal relies on the dispersion of particles in the feed jets to provide a well mixed particle-gas suspension for efficient combustion. The removal of fly ash from a power plant effluent by electrostatic precipitation is also dependent on particle-gas mixing. In this situation, excessive particle-gas mixing can keep particles in suspension and degrade collection efficiency. In some currently proposed concepts for coal gasification systems, the control of particle-gas mixing is essential. For example, proper operation of a coal gasification system in which heat is transferred by radiation from hot combustion products to a coflowing, coal-laden steam flow depends on minimizing the dispersion of particles into the combustion products and minimizing the mixing of combustion products (contaminants) into the coal-steam mixture.

Particulate Science and Technology 3:149–158, 1985

Liquid-fueled gas combustors are another application where turbulent particle dispersion is of crucial importance. In some combustion chambers the fuel droplets are dispersed into turbulent shear regions downstream of bluff bodies. The dispersal of the droplets caused by the turbulence in these regions is an important factor in the stability and performance of these combustors.

The traditional approach to predicting particle dispersion in turbulence is to regard the process as a Fickian diffusion process and to quantify the mass transfer of particulates by a diffusion coefficient and particle concentration gradient. This model may be adequate for near-isotropic flow fields such as the turbulent flow field generated by a grid. However, the majority of particle mixing and dispersion problems involve shear-driven turbulent flows in which the mean velocity gradient produces nonisotropic, large-scale turbulent structures. These large-scale turbulent structures are undoubtedly instrumental in the mechanics of the particle dispersion process. In fact, there is reason to believe that the large scale structures can promote unexpectedly large particle dispersion effects.

Large scale turbulent structures have been clearly identified by numerous investigators in free shear flows such as plane mixing layers, jets and wakes. For the plane mixing layer, a quasi two-dimensional vortex structure has been identified as the dominant large-scale feature [1,2]. Pairing interactions between these large scale structures are primarily responsible for the entrainment and growth of this turbulent flow. The connection between these vortex structures and particle dispersion, however, is poorly understood.

This paper introduces a new approach for predicting particle dispersion in free shear layers. This approach assumes that large scale structures control the particle dispersion process in these flows. A simple numerical model is used to illustrate this concept.

PARTICLE DISPERSION MODELS

The traditional approach to modeling particle dispersion is to regard the particles as a gaseous species and use Fick's law. Thus, the particle diffusion velocity is represented as

$$\vec{v}_D = D_{eff} \nabla c_p$$

where D_{eff} is the effective diffusion coefficient and c_p is the concentration of the particulate phase. Experimental data from turbulent flows for D_{eff} show a spread of over two orders of magnitude. This discrepancy suggests that the Fickian model is inadequate to represent the physics of the dispersion process.

Another approach to modeling the dispersion process is to treat the turbulent flow as a random field and integrate the particle motion equations through the field to obtain the dispersion. This is known as the Monte Carlo approach. Application of this model has resulted in reasonably good comparison with experimental data for near-isotropic homogeneous fields. Chen [3] used the model to predict the particle dispersion in the classic experiments by Synder and Lumley [4]. These experiments were carried out in the turbulent flow field downstream of a screen. Particles consisting of hollow glass beads, corn, pollen, and copper were tracked photographically in this turbulent field. The experimental and predicted results are shown in figure 1. The model adequately predicts the crossing trajectory effect; the decrease in particle dispersion rate owing to a relative velocity between the particles and the mean velocity field.

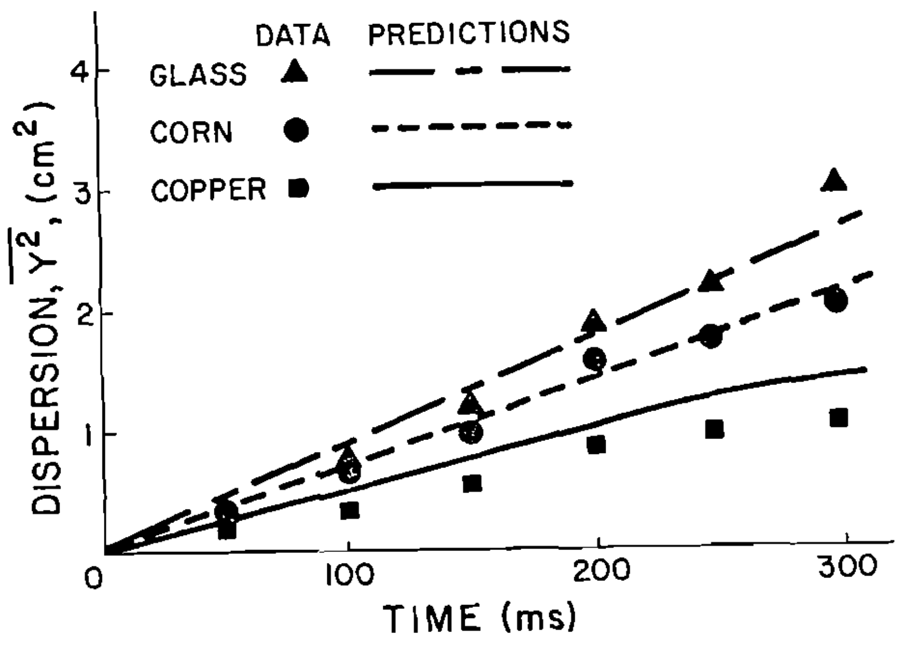

Figure 1. Comparison of Monte-Carlo model with Synder and Lumley's data

The success of the Monte Carlo method, however, does not extend to non-isotropic turbulent flows. Chen [3] applied the Monte Carlo method to particle dispersion in a fully developed turbulent pipe flow as measured by Arnason [5]. Chen's results showed poor agreement. Chen's results again predicted that the larger particles would disperse less. Arnason's experimental results, however, displayed the opposite trend. The larger particles dispersed faster than the smaller particles. This trend cannot be explained by assuming that the controlling turbulent field is isotropic.

Turbulent flows of most interest in particle mixing problems are typically driven by nonisotropic mean velocity gradients. The plane mixing layer is an example of a flow of this type in which large scale coherent structures occur. A visualization of this flow is shown in figure 2. Organized vortices generated by the mean shear combine to form even larger vortices. This flow field is very non-isotropic and obviously not describable simply as a mean velocity plus a random velocity component. Particles subjected to this flow will be affected more by the "ordered" motion of the larger vortices than the random smaller scale flow fluctuations about the fluid path. If the particles are very small, they will approximately follow the large scale structure and therefore the particle dispersion rate will approximate the spreading rate of the mixing layer. On the other hand, very large particles will pass through the vortices with nearly rectilinear trajectories and will be dispersed little by the turbulent field. A certain size particle, however, may be caught up in

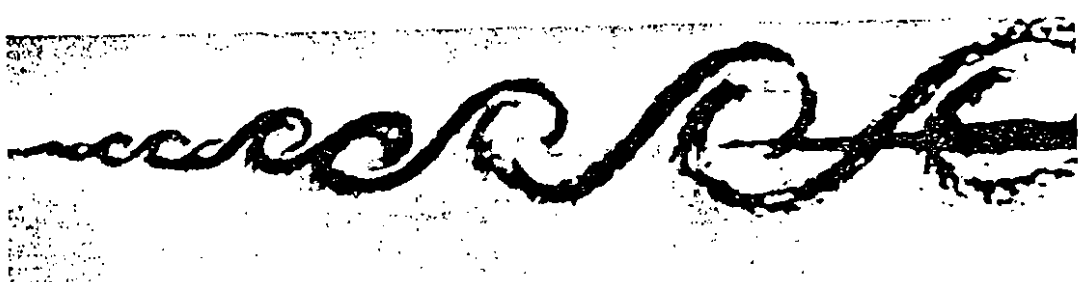

Figure 2. Shadowgraph visualization of coherent structures in a turbulent mixing layer. (Roshko, A., 1976, AIAA Journal, 14, 1349-1357)

the vortex and flung beyond the fluid mixing layer. This concept may explain the observation that, in some cases, particles are able to mix faster than the fluid.

A method to quantify the above argument is to compare the response time of a particle to a time characteristic of the vortex motion. The response time of a particle is the time required for a particle released from rest in a constant velocity flow to achieve 63 percent of the free stream velocity. For Stokes drag, the response time is given by

$$\tau_A = (\rho_p d_p^2)/18\mu$$

where ρ_p is the material density of the particle, d_p, the particle diameter and μ is the dynamic viscosity. This time is a measure of the responsiveness of the particle to changes in fluid velocity.

A time characteristic of the large scale turbulent structures is

$$\tau_F = \delta/\Delta U$$

where ΔU is the velocity difference between the two streams and δ is the width of mixing layer (or equivalently the average width of the large scale structures). If $\tau_A/\tau_F << 1$, the particle will remain in velocity equilibrium with the fluid and the particle should disperse at the same rate as the mixing layer grows. If $\tau_A/\tau_F >> 1$, the particles should be unaffected by the flow field and exhibit little dispersion. For an intermediate time ratio, $\tau_A/\tau_F \sim 1$, the particle can be captured by the vortices and flung beyond the fluid mixing region, thereby yielding a dispersion profile which grows faster than that of the fluid.

In order to evaluate the feasibility of this model, we gathered data available in the literature for particle dispersion in round and planar particle-laden free jets and plotted the data as a function of the time ratio. The data are presented in figure 3. The ordinate is the measured particle dispersion coefficient divided by the effective dispersion coefficient of the gas as evaluated by the measured spreading rate of the jet. The length scale used is the local width of the jet where the measurements were taken. The data represent a wide range of conditions. The data by Yuu et al. [6] were obtained from measurement of fly ash in a round air jet. Goldschmidt and Eskinazi [7] measured the diffusion of safflower oil droplets in a plane jet by using a clever application of hot-wire anemometry. Lilley [8] experimented with a plane jet and used dry magnesium powder. Memmot and Smoot [9] worked with a round jet and used pulverized coal for particles. The data, although exhibiting considerable scatter show the expected trend. At small values of τ_A/τ_F, the particles disperse as the jet spreads. At larger values of τ_A/τ_F, the particles show little mixing. However, the data suggest, at time ratios between 0.01 and 0.1, that the particles can mix considerably faster than the

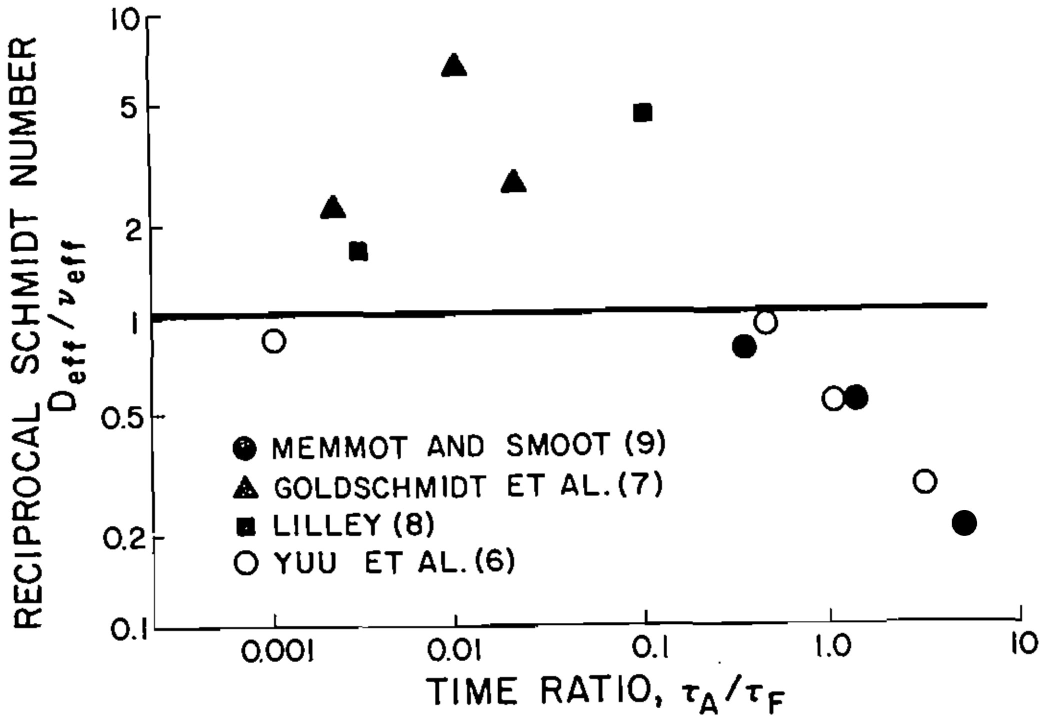

Figure 3. Experimental data for particle dispersion in planar and axisymmetric jets

fluid. This experimental observation provides significant support for the proposed model.

NUMERICAL SIMULATION

In order to investigate further the validity of the proposed particle dispersion model, a series of calculation were performed with a flow field approximating the large scale vortex structure in a mixing layer. This flow field, identified by Stuart [10], consists of a vortex street with constant diameter vortices with a distributed vorticity. The vortices in this field are noninteracting. The velocity components of the flow are given by

$$u = C + D\,\sinh(y)/[\cosh(y) + \alpha\cos(x-Ct)]$$

$$v = D\alpha\sin(x-Ct)/[\cosh(y) + \alpha\cos(x-Ct)]$$

where C, D, and α are adjustable parameters. The value of C for modeling a shear layer is the average velocity between the two layers $(U_2 + U_1)/2$. The value of D is $(U_2 - U_1)/2$. The value of α is related to the distribution of vorticity. Fitting the above equation with data for turbulent shear layers suggests that the most appropriate value for $\alpha = -0.25$. For purposes of this calculation, the values for C and D were taken as 1.0 and 0.5 respectively. The streamlines corresponding to the flow field are shown in Fig. 4. One must note that this is only an approximate simulation of the shear layer since vortex pairing is not modeled.

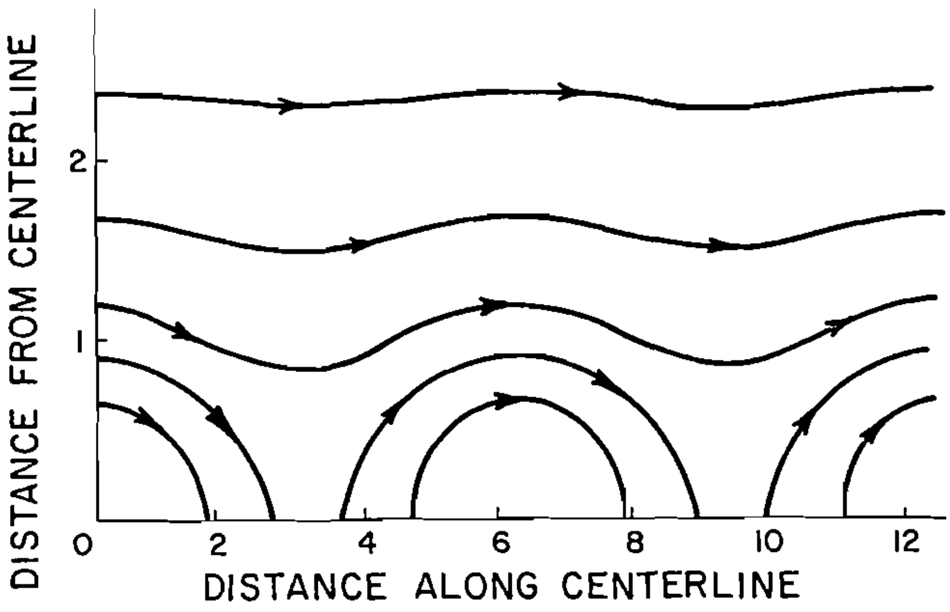

Figure 4. Streamlines for Stuart's vortices

The calculations are now carried out by starting the particles at various locations in the vortex pattern and integrating the particle equation of motion to find the particle trajectory in the flow field. The equation of particle motion is given by

$$\frac{d\vec{V}_p}{dt} = \frac{f}{\tau_A}(\vec{U}-\vec{V}_p)$$

Where $\vec{V}_p$ is the particle velocity and $\vec{U}$ is the gas velocity. The factor f accounts for the deviation of the drag coefficient from Stokes drag and is well-represented for Reynolds number less then 1000 by

$$f = 1 + 0.15\ Re^{2/3}$$

where the Reynolds number is defined by

$$Re = |\vec{U} - \vec{V}_p| d_p/\nu$$

and ν is the kinematic viscosity of the fluid. The contributions of virtual mass, pressure gradient, and the Basset force to particle drag have been neglected.

To smooth out the effect of initial position on the particle dispersion, the trajectory calculations were performed using a grid of initial positions. One hundred equally-spaced horizontal locations between vortex centers and four vertical locations at 0, 25, 50 and 75 percent of the vortex radius were chosen as starting positions. The particle dispersion was quantified by recording the maximum lateral displacement of each particle from its starting position. The dispersion for each size particle was then determined by averaging the maximum dispersions from the 400 trajectories.

The results of the particle dispersion computations for various size particles are shown in figure 5. The horizontal axis is scaled using a nondimensional ratio of the particle aerodynamic response time, τ_A, to the fluid time scale τ_F. Larger particles correspond to increasing time scale ratios. The vertical axis of the figure is scaled using a nondimensional ratio of the maximum particle displacement to an effective diameter of Stuart's vortices. As hypothesized from the physical model, the particle displacement maximizes at an intermediate value of time scale ratio.

The numerical results show the general trend suggested by the physical model, but predict a smaller dispersion ratio than that found experimentally. A more accurate representation of the flow field is needed to achieve a more

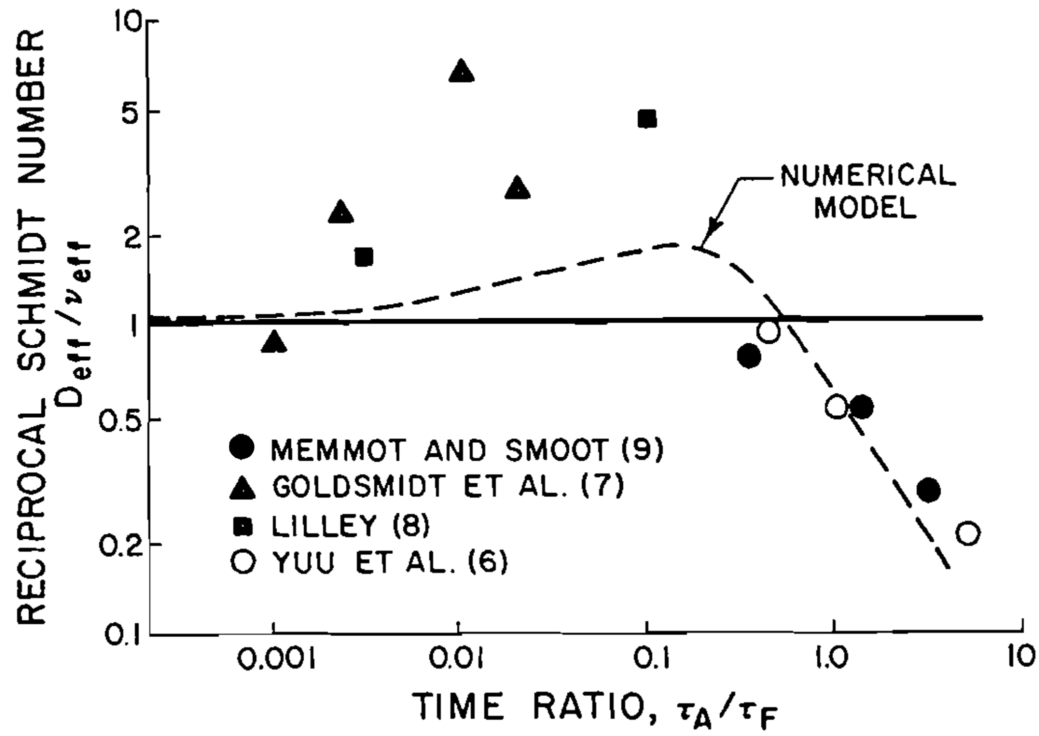

Figure 5. Comparison of numerical predictions with experimental data for particle dispersion.

meaningful comparison with the data and assessment of the physical model. At the present time, calculations are being performed with a pseudo-spectral method adapted by Riley and Metcalfe [11] which simulates vortex motion and pairing in a free shear layer. In addition to the more descriptive numerical models, better experimental data are needed to evaluate the validity of the model. An experimental program to provide this data is being pursued in our laboratory.

The data and analysis presented in this paper refer specifically to gas-solid flows. There appears to be no data available in the literature for solid-liquid flows. The analysis presented here could be extended to solid-liquid flows by the inclusion of virtual mass, pressure gradient and Basset force in the particle trajectory equation. The authors feel that the trends would be similar because the controlling mechanism for dispersion is the presence of large scale structures.

Should this physical model prove valid, the ramifications to engineering design are significant. Particle dispersions could be intensified or minimized by modification of the large scale structure in the turbulent mixing region. This could be accomplished by tayloring upstream conditions or by applying a spring field to the flow such as an acoustic source. The capability to control particle dispersion would lead to radical design changes in many combustion and gas cleanup systems.

CONCLUSION

It is hypothesized that particle dispersion in turbulent free shear flows is dependent on the ratio of the particle response time to a fluid motion time associated with the coherent structures. Previous experimental data appear to support this idea. Particle trajectory calculations based on a simple simulated field for the organized motion give further support to this idea. An investigation of this concept involving sophisticated numerical simulation techniques in conjunction with an experimental study is now being carried out.

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