Coupling Effects in Multiphase Free Shear Flows

T.R. Troutt, C.T. Crowe, and J.N. Chung
Washington State University

ABSTRACT

The primary goal of this research program is to examine the effects of two-way multiphase coupling on the development of organized vortex structures in free shear flows and the resultant multiphase dispersion. Previous research studies have determined that one-way coupled particle dispersion in free shear flows is strongly dependent on the vortex structures present in these flows and their interactions as well as the ratio of the particle aerodynamic response time to the time scale of the dominant vortex structures. Current research efforts are directed towards exploring the effects that two-way momentum, mass and energy coupling have on the multiphase dispersion processes previously uncovered. These efforts involve analytical, numerical and experimental investigations. Recent analytical and numerical results indicate that momentum coupling effects can significantly alter the global stability and potentially the large scale features of the multiphase flow field. These multiphase coupling effects may have significant importance with regard to predicting the performance of many energy conversion systems.

INTRODUCTION

Multiphase mixing in turbulent flows is a key element in many practical energy conversion, chemical mixing and pollutant dispersal problems. Numerous important technological and environmental processes could be better addressed with improvements in understanding in this area. Progress in developing understanding of this field, however, has traditionally been difficult because of the complexities involved with the turbulent flows employed to provide the mixing mechanisms. To address this problem from a new perspective several years ago this research group initiated an ongoing investigation concerning the potential connections between organized turbulent vortex structures and the particle dispersion process.

Organized vortex structures in single phase free shear flows have been studied extensively in the recent past Ho and Huerre[1] because of their apparent importance in the global flow development. However, the relationship between organized vortex structures and the particle dispersion process was largely unknown. A simple physical concept which identified the Stokes number, a time scale ratio between the particle aerodynamic response time and the characteristic organized vortex motion time, as a controlling parameter for the particulate dispersion process was used to initially guide this new approach Crowe, Gore and Troutt[2], Chung and Troutt[3], Crowe, Chung and Troutt[4]. The Stokes number can in fact be shown to be the controlling parameter in the particle motion equation for situations where the particle material density is much greater than the local fluid density and the particle Reynolds number is small Chung and Troutt[3].

To emphasize the role organized vortex motions play in the particle dispersion process this research program has focused on free shear flows such as mixing layers, jets and wakes since the organized vortex structures in these single phase flows are probably the most clearly characterized and understood Ho and Huerre[1]. Although these flows do exhibit instantaneous, three dimensional, small scale structures, their primary global development is closely tied to the large scale, quasi two-dimensional structures Browand and Troutt[5].

The overall results from these analytical, experimental and numerical research efforts concerning particle dispersion in free shear flows have yielded several interesting insights into the dispersion process and its connection to the organized vortex development. These findings can be summarized as follows:

a) The qualitative and quantitative character of the particle dispersion patterns in mixing layers, jets and wakes are strongly dependent on Stokes number and can be instantaneously highly anisotropic and nonhomogeneous Crow, Chung and Troutt[4]; Chung and Troutt[3]; Tang *et al.*[7].
b) For mixing layers a stretching and folding operation associated with vortex structure development and pairing appears to be a dominant intermediate Stokes number particle dispersion mechanism Wen[8].
c) For wakes where vortex pairings rarely occur, the dispersion process focuses intermediate Stokes numbers particles into extremely thin sheet-like regions near the boundaries of the vortex structures Tang[7].

The previous results have addressed primarily flows for which the effects of the particles on the flow were neglected, one-way coupling. Of considerable scientific and technological interest is the more complex situation where two-way coupling effects between the particles and the flow exist. This situation has been initially addressed quite recently by our group using stability analysis involving momentum two-way coupling effects Yang *et al.*[9], and Yang *et al.*[10]. The present research program addresses the two-way coupling situation involving mass, momentum and energy coupling between the flow and particles or droplets. This type of coupling is of high technological interest and has the potential for greatly affecting the resultant flows.

<u>Analytic Procedure for Implementing Coupling Effects</u>

One objective of the present research is to extend the existing modeling effort to include compressibility effects and energy coupling. This development can be viewed as a logical precursor to including heat release due to chemical reaction and the analysis of multiphase combustion in large scale turbulent structures. The technique is an extension of that reported by Ghoniem *et al.*[11] for compressible reacting flows using the discrete vortex method together with transport elements.

The velocity field in the model is decomposed into three parts; the field corresponding to the basic potential flow, the velocity induced by the vortices in the field and the field produced by the mass release from the droplets. Including compressibility effects leads to a change in the strength of the mass sources and also affects the circulation of the discrete vortices.

The continuity equation for the gas phase of a droplet-laden flow with void fraction near unity is

$$\nabla \cdot \vec{u} = \frac{S_m}{\rho} - \frac{1}{\rho}\frac{D_\rho}{Dt}$$

where S_m is the mass source per unit volume due to droplet evaporation or condensation. For low Mach numbers, one can make the assumption that the pressure level is constant so, for an ideal gas, the continuity equation becomes continuity equation becomes

$$\nabla \cdot \vec{u} = \frac{S_m}{\rho} + \frac{1}{T}\frac{DT}{Dt}$$

where T is the local temperature. The right side of this equation represents the strength of the mass source term associated with each droplet. The last term represents the local expansion of the flow due to local heating or cooling.

The momentum equation for the gas phase of a dispersed phase flow at high Reynolds number and void fraction near unity is

$$\frac{D\vec{u}}{Dt} = \frac{-1}{\rho}\nabla p + \frac{1}{\rho}\left[\left(\frac{f\rho_d'}{\tau_A} + S_m\right)(\vec{v} - \vec{u})\right]$$

where f is the ratio of the drag coefficient to Stokes drag, τ_A is the aerodynamic response time of the droplet, ρ_d' is the bulk density of the droplets and $\vec{v}$ is the velocity of the droplet phase. It is assumed that the viscosity is important only in the immediate neighborhood of the droplets. The last term in the above equation is due to momentum coupling and is calculated from the droplet trajectories. For convenience this term is simplified to $\vec{C}$ so the equation can be rewritten more simply as

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\vec{C}$$

Taking the curl of the momentum equation and limiting the solution to two-dimensional flows yields

$$\frac{D\vec{\omega}}{Dt} - \frac{\vec{\omega}}{\rho}\frac{D\rho}{Dt} = \frac{1}{\rho}\nabla\rho \times \left(\frac{\nabla p}{\rho} - \frac{\vec{C}}{\rho}\right) + \frac{1}{\rho}\nabla \times \vec{C}$$

In the discrete vortex approach the flow field is subdivided into material elements with circulation Γ. Since the mass of a material element is constant, the derivative of the density can be related to the area change of the element (in planar flow) by

$$\frac{1}{\rho}\frac{D\rho}{Dt} = -\frac{1}{A}\frac{DA}{Dt}$$

Substituting this expression into the vorticity equation and using the momentum equation leads to

$$\frac{D(\omega A)}{Dt} = -\frac{A}{\rho}\nabla\rho \times \frac{D\vec{u}}{Dt} + \frac{A}{\rho}\nabla \times \vec{C}$$

The product of the vorticity and the area is the circulation of the vortex. If low Mach number is assumed the density variation is associated with the temperature change only and the expression for the change in circulation of each discrete vortex is

$$\frac{D\Gamma}{Dt} = \frac{(A\rho)_0}{\rho}\frac{\nabla T}{T} \times \frac{D\vec{u}}{Dt} + \frac{A}{\rho}\nabla \times \vec{C}$$

where $(A\rho)_0$ is the initial cross-sectional area times the density of the material element. This product, which is proportional to the mass of the element, remains constant. The first term on the right side is the effect of density change on the vortex strength and the last term is that due to multiphase coupling. The coupling term is to be evaluated in the same manner used previously for the mass and momentum coupling. That is, the droplet trajectories provide locations and properties of the droplets in the field. The properties are area-averaged to nodal points on a grid and the coupling term is evaluated and distributed to each vortex in the cell. To calculate the change in circulation, the temperature and density fields are needed. These are obtained from the transport-element method introduced by Ghoniem *et al.*[11]

Numerical Results

Numerical simulation results for momentum coupling effects in a temporally developing free shear layer have been recently computed over a range of particle concentration levels. For base flow comparison purposes Figure 1 presents the time development of the flow structures for a one-way coupling situation.

The time evolution of the vortex structures in the free shear layer for a two-way momentum coupled situation at a particle mass concentration ratio of 0.3 is shown in Figure 2. Although the flow develops in a qualitative similar fashion the vortex pairing process shows little change and the lateral flow dispersion process is only slightly inhibited. At higher particle concentration levels the flow development is slowed significantly. A comparison between flow vortex structure development at similar times for the non-coupled and momentum coupled flow at a concentration level of 3.0 is shown in Figure 3.

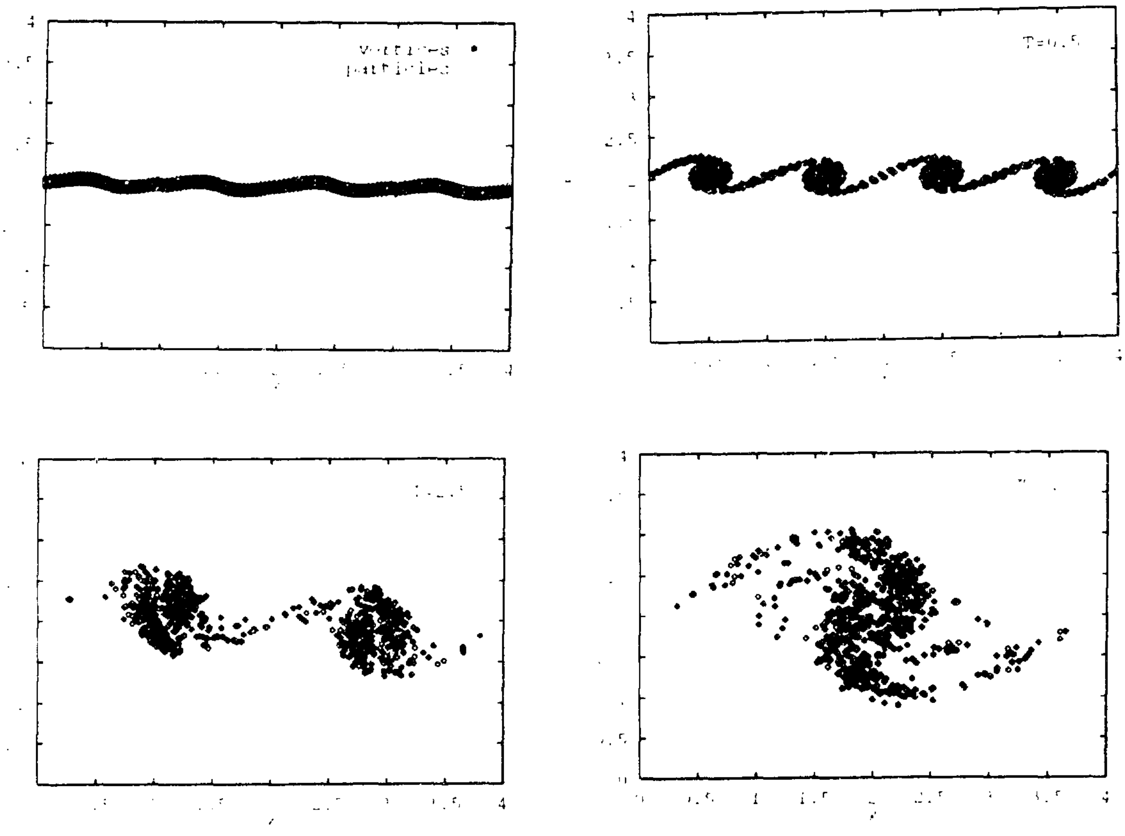


Figure 1. Time development of flow structures one-way coupling

A quantitative evaluation of the effect of momentum coupling on rate of growth of the free shear layer is presented in Figure 4. This figure compares the momentum thickness of the shear layer as a function of time for three different particle concentration levels. The significant change in the development of the free shear layer at the high concentration level is quite apparent.

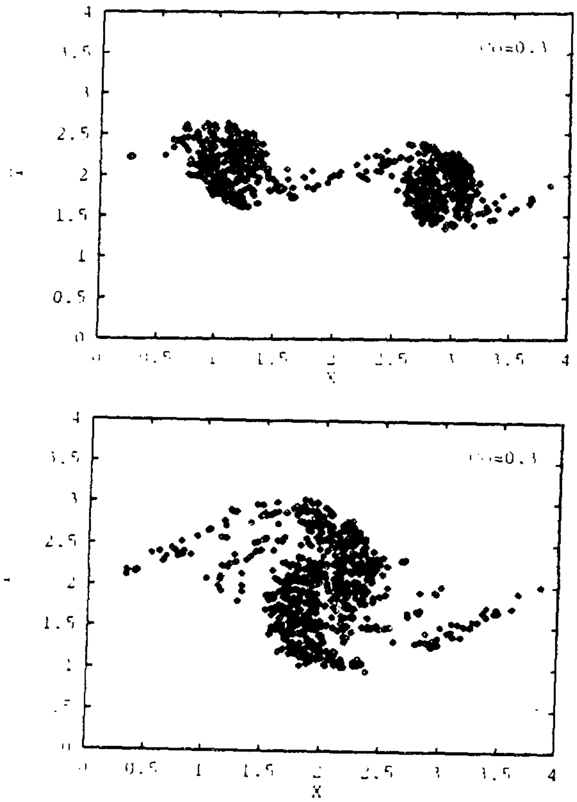


Figure 2. Time development of flow structures two-way momentum coupling, particle mass concentration = 0.3

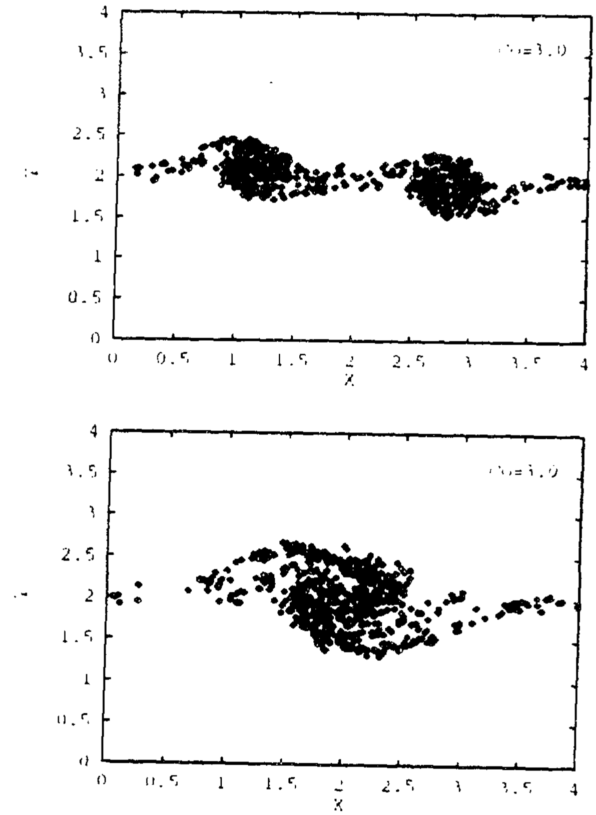


Figure 3. Time development of flow structures two-way momentum coupling, particle mass concentration = 3.0

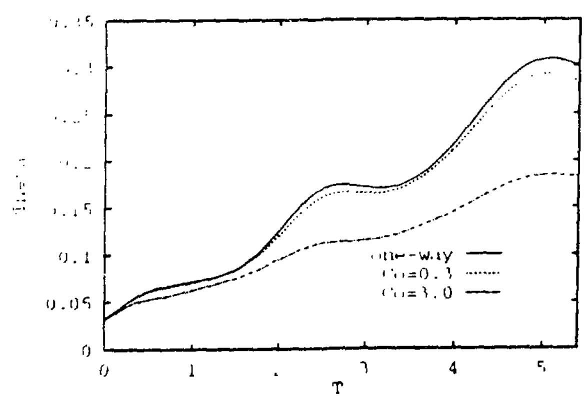


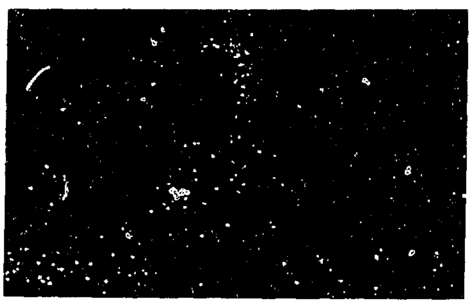
Figure 4. Development of momentum thickness for different mass particle concentration levels.

Experimental Research Program

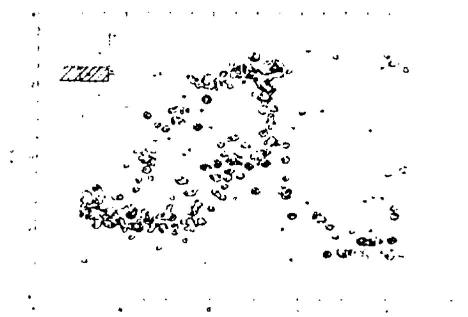
Currently experiments concerning vaporizing droplet dispersion are being carried out in a recently installed heated wind tunnel. The flow configuration involves a heated two-dimensional plane wake into which lower temperature liquid H_2O droplets are injected. the temperature of the air stream is adjustable between T=100°C to 400°C. the vaporizing droplets then release both mass and energy into the wake flow creating the potential for significant two-way coupling effects between the droplets and the wake flow.

Two major experimental techniques are being pursued in conjunction with this research. Global multiphase flow information will be obtained by employing laser light sheet visualization techniques with digital particle image position and velocity analysis. Local point multiphase flow information involving droplet size and velocity will be obtained using phase doppler anemonetry techniques. Both of these major experimental techniques are presently being carried out in this laboratory.

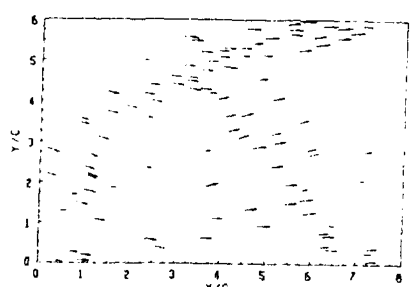
Figure 5 displays the results from a laser light sheet visualization of solid particles in a plane wake flow. After acquisition the image is then digitized and the spherical particles identified through shape analysis. Instantaneous particle locations and velocities using multiple light pulse control, can then be determined from the results. The results for particle concentration contours and velocities obtained from the image are also shown. Similar techniques are now being pursued for vaporizing droplets in the heated plane wake environment.



a) particle dispersion pattern



b) particle concentration contours



c) particle velocity vectors

Figure 5. Experimental results for particle dispersion in a plane wake flow St=0(1)

SUMMARY

An analytical, experimental and numerical investigation of the effects of two-way momentum, mass and energy coupling in multiphase free shear flows is underway. Stability results indicate that two-way momentum coupling effects decrease the amplification rate of disturbances in plane mixing layers and change the instability mode from absolute to convective in plane wakes. The magnitude of these effects increase with particle concentration levels in a nearly linear fashion.

Numerical results for a temporally developing free shear layer demonstrate that two-way momentum coupling effects slow the development of vortex structures and their subsequent pairing interactions. This slowdown effect in the vortex interactions causes decreases in the momentum thickness development of the free shear layer.

Experimental efforts using laser visualization techniques and phase doppler velocity and droplet sizing techniques are presently evaluating two-way coupling effects for comparison to the numerical results.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Department of Energy Grant No. DE-FG06-86ER-13576 under the direction of Dr. Oscar Manley, Dr. Daniel Frederick and Dr. Subhendu Datta. Equipment support from the National Science Foundation, Grants No. CBYT-8500618 and No. CBT-8806525, is also gratefully acknowledged.

REFERENCES

1. Ho, C.M. and Huerre, P., 1984. Perturbed Free Shear Layers, *Ann. Rev. Fluid Mech.*, **16**, 365-424.
2. Crowe, C T., Gore, R.A. and Troutt, T.R., 1985, Particle Dispersion by Coherent Structures in Free Shear Flows, Particle Science and Technology, Vol. 3, pp. 149-158, 1985.
3. Chung, J.N. and Troutt, T.R., 1988, Simulation of Particle Dispersion in an Axisymmetric Jet, *J. Fluid Mech.*, **86**, 199.
4. Crowe, C.T., Chung, J.N. and Troutt, T.R., 1989, Dispersion in Turbulent Shear Flows, *Progress in Energy and Combustion Sci.*, **14**, 171.
5. Browand, F.K. and Troutt, T.R., 1985, The Turbulent Mixing Layer: Geometry of Large Vortices, *J. Fluid Mech.*,**158**, 487.
6. Crowe, C.T., Chung, J.N. and Troutt, T.R., Particle Dispersion by Organized Turbulent Structures, 1992, Chp 18, Particulate and Two-Phase Flow Edit. M.C. Roco Butterworth-Heinemann Series in Chemical Engineering.
7. Tang, L., Wen, F., Yang, Y., Crowe, C.T., Chung, J.N, and Troutt, T.R., 1992, Self-organizing particle Dispersion Mechanism in a Plane Wake," *Phys. Fluids A*, **4**, 10, 2244.
8. Wen, F., Kamalu, N., Chung, J.N., Crowe, C.T. and Troutt, T.R., 1992, "Particle Dispersion in Plane Mixing Layers," ASME, *J. of Fluids Engin.*, **114**, 657-666.
9. Yang, Y., Chung, J.N., Troutt, T.R. and Crowe, C.T., 1990, "The Influence of Particles on the Spatial Stability of Two-Phase Mixing Layers," *Phys. Fluids A*, **2**(10), 1839-1845.
10. Yang, Y., Chung, J.N., Troutt, T.R. and Crowe, C.T., 1993, "The Effects of Particles on the Stability of a Two-Phase Wake Flow, *Int. J. Multiphase Flow*," **19**, 1, 137-149.
11. Ghoniem, A.F., Heidarinejad, G. and Krishnan, A., 1987, Turbulence-Combustion Interactions in a Reacting Shear Layer, Paper AIAA-87-1718, 23rd AIAA/SAE/ASME/ASEE Joint Propulsion Meeting, La Jolla, CA.