MEASUREMENT TECHNIQUES FOR TURBULENT TWO-PHASE FLOW RESEARCH

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Invited Paper

ABSTRACT:

A review of the work conducted on particle interactions with turbulent flows provides a basis for the continued development of the diagnostics. Flow visualization techniques have provide insights to the global characteristics of the particle interaction with large scale eddies. Recent experiments conducted by a number of researchers in the field were reviewed. These data served to evaluate merits of the current theories and set a basis for future research. The development of particle size and velocity instrumentation has allowed the detailed probing of these flows and offers a potential for in-depth studies of particle interactions with the turbulent flows and the mechanisms of particle dispersion. Advances in the PDPA instrument and the data acquisition technology are described. Particle response correlations are given along with some experimental verifications using the Phase Doppler Particle Analyzer (PDPA) Examples of data obtained with the instrument are presented.

INTRODUCTION:

The behavior of a dispersed phases in a fluid, whether liquid or a solid particle in a gas, solid particles in a liquid, or bubbles in a liquid, is of importance to a broad range of practical applications. For example, direct fuel injection for spark and diesel ignition engines is an active area of research. Fuel is injected as a spray of liquid drops into a confined space and interacts with a highly unsteady turbulent flow. The process is characterized by the dispersion of the spray drops and the interaction of these drops with the turbulent flow field and is further complicated by evaporation, ignition and burning of the fuel. An added complication in understanding the behavior of the spray arises from the fact that the drops are injected with relatively high momentum so there is a significant transfer of kinetic energy from the drops to the continuous phase. As the process develops, the transfer of kinetic energy proceeds from the drops to the gas and then from the gas to the drops. Especially in diesels, the particle concentration will be very high near the injection point so particle-particle interaction will be significant. In other regions of the chamber, the particle field is dilute or void of particles. The turbulent flow in the cylinder is generally not homogeneous and nonisotropic. Modeling the mass, momentum, and energy exchange in such environments becomes extremely difficult. The situation may be somewhat less complicated for gas turbine and liquid fueled rocket engines because the flows are nominally steady. However, significant gas phase compressibility exists and instabilities may be generated not only by the spray interacting with the large scale eddies but also due to the formation of strong acoustic waves. In all of the cases wherein liquid fuel injection is used, the environment is characterized by large gradients in the drop concentration, initially high momentum of the drops such that the drop momentum affects the dispersion and interaction with the turbulent gaseous phase flow, rapid evaporation, and high levels of turbulent swirl and recirculation in the ambient gas phase flow. The liquid drops may collide in the dense spray region, and they may deform and breakup under the flow-induced aerodynamic pressure forces. Other applications such as scrubbers, chemical reactors, spray dryers, cyclone separators, and sediment transport may be less formidable but also require a solid understanding of the basic interaction mechanisms of particles in a turbulent flow and how these phenomena affect the dispersion of the inertial particles.

Theoretical descriptions of the particle behavior have evolved over the years (Tchen, 1947, Lumley, 1957, Hinze, 1959). Hjelmfelt and Mockros (1966) considered the extension to Basset's equation of motion for describing the behavior of particles under the influence of a highly fluctuating flow with the assumptions that the particles are small relative to the smallest eddies in the flow (Kolmogorov length scale), the suspension is dilute so that there is no significant particle-particle interaction, and that the flow turbulence is homogeneous and stationary. They evaluated the effect of the simplifications to the approaches for a range of particle-to-fluid densities. It is generally accepted that the refined derivations of Maxey and Riley, (1983) describe the motion of small spherical particles in the presence of unsteady, nonuniform flow. These equations are useful in assessing the relative importance of the of the various forces affecting the motion of the particles. To the experimentalist, the theory is useful in determining what quantities need to be characterized with the greatest accuracy. Unfortunately, the constraints to Stokes flow wherein a linear drag coefficient can be employed limits the applicability of the analysis to small particles having low particle Reynolds number. The requirement that the particle Reynolds number be small ($<<1$) is most often violated in the treatment of particle dispersion predictions. Furthermore, the requirement of a dilute particle field is also violated for fuel spray injection and when particles fields with concentration gradients interact with large scale turbulent structures to form clusters. The particle concentrations in these clusters can be as much as an order of magnitude greater than the mean concentration averaged over a region much larger than the large scale eddy. Consequently, the assumptions limit the analyses to specific multiphase flow situations.

The work of Winant and Browand (1973) and of Brown and Roshko (1974) demonstrated that turbulent shear layers have large-scale, vortical structures with three-dimensional small scale structures superimposed on them. Interaction of these structures known as vortex pairing plays a significant role in the growth of the mixing zone. Experimental work by Lazaro and Lasheras (1989), and Bachalo, et al. (1990) and the numerical investigations by Crowe, et al. (1988) indicated that the dominant particle dispersion mechanism is the large-scale eddies generated by the shear layer. As indicated by Kiger and Lasheras (1994), this result should be expected in the early part of the developing shear layer because the large-scale motion contains the greatest portion of the turbulent kinetic energy. The experiments and analysis of Lazaro and Lasheras (1989) represent a well-designed effort to probe the dispersion mechanisms presented by a shear layer forced at a frequency of 140 Hz to form highly coherent eddies in the shear layer for inhomogeneous, anisotropic turbulence at relatively high Reynolds number. Using line-of-site attenuation and Fraunhofer diffraction, they were able to acquire data on the form of droplet dispersion which showed that the spray is lifted periodically by the vortices. While the large dispersion "streaks" were present in the upstream front of the vortices, the core region of the large vortices were found to be relatively depleted of large particles. Drop size selectivity also occurred with the larger particles accumulating in the outer periphery of the streaks. A similar behavior has been observed by Ye and Richards (1996) and Longmire and Eaton (1994). Longmire and Eaton observed the clustering of drops recognized earlier by Bachalo, et al. (1988) as the result of the particle laden jet interacting with the large scale structures.

A fundamental study of the interaction of relatively large drops and the simulated vapor interacting with a large vortex in a two-dimensional flow field has been reported by Hancock et al. (1992) and Hancock and Chin (1993). Using $TiCl_4$ reacting with water to form small particles of TiO_2, they were able to clearly illustrate the motion of the monosized droplets interacting with the large scale vortical structures. The vapor line generated by the water drops moving in the $TiCl_4$ laden stream allowed the visualization of the local gas phase motion since the ~1 μm particles may be regarded as sub-inertial and thus, will track the gas phase flow. An important observation is that the local gas slip flow past the drops may be visualized and the magnitude estimated. Similar investigations into the dispersive mechanisms of turbulent flows have been conducted by Ye and Richards (1996). Albeit an idealized case, these fundamental studies provide insight to the more complex phenomena using straightforward diagnostics.

Observations of these particle dispersion phenomena using light sheet visualization and time dependent beam extinction provide valuable information on the qualitative behavior. Developments in the optical diagnostics for two phase flow measurements have resulted in a much better quantitative data that may be used to validate the theories and modeling efforts. The Fraunhofer diffraction approach and laser beam extinction measurements used, for example, by Lazaro and Lasheras, are suitable for two-dimension flows. Simple laser light sheet illumination that is phase-locked with the jet forcing frequency can yield valuable qualitative information on the flow structure, particle dispersion and quantitative information on the local particle concentration. However, the gas phase mean and rms velocities and the dispersed phase particle size, velocity and concentration need to be measured to more fully characterize the vortical interaction and particle dispersion. The Phase Doppler Particle Analyzer (PDPA) (Bachalo and Houser, 1984) was developed for this purpose. This method simultaneously measures the gas phase turbulence parameters, based on the small sub-inertial particles in the flow and the particle size and velocity as well as the time averaged concentration points within the flow field. Generally, the method provides a time averaged (strictly, flux averaged quantities assumed to be the time average) measurements of these quantities. Fortunately, the instantaneous flow measurements at points within the flow field would provide much more information than is needed for most practical applications. The temporal, ensemble, and spatial averages are useful for both the validation of theory and modeling and simplifies the flow description. The PDPA instrument does provide a time history of the particles passing the sample volume so information is available on the time-varying characteristics . However, quantities such as the particle slip velocity requiring the measurement of the gas phase velocity very close in space to the measurement of the particle velocity measurement and the local particle number density can only be estimated. The ensemble averaged results are generally used to estimate the slip.

In the following sections, an outline of the information sought will be provided and the potential for the measurement of these parameters will be discussed. A review of the measurement techniques to address these requirements will be given along with their capabilities and limitations. Following the credo of a good experimentalist which states that one should use the simplest method that will provide the information needed, the discussion to follow will cover some of the optical methods available and that have been used in multiphase flow studies. The PDPA will be discussed in terms of its measurement capabilities and the requirements in the data interpretation. Development of the method through applications to basic particle interactions with the turbulence are discussed.

MULTIPHASE FLOW THEORY AND EXPERIMENTATION REQUIREMENTS

Gas Phase Turbulence Characterization:

The laser Doppler velocimeter (LDV) (Yeh and Cummins, 1962), has been used in the characterization of complex turbulent flows for the past two decades. The method has continuously evolved into a robust, reliable, and accurate tool for this purpose. Extensive evaluations and comparisons to other means such as pitot-static probes and hot-wire anemometers has served to raise the confidence in the data that this instrument can produce. Time-averaged measurements of the three velocity components are obtained and the mean, rms, and the higher order velocity correlations are obtained from the accumulated statistical distributions. Since the flow velocity measurements are inferred from the measurements of small particles in the flow, there is the concern that these seed particles are indeed small enough to approximate the flow mean velocity and turbulence fluctuations. Numerous analyses have been conducted to define the tolerable inertial characteristics of the particles in various flow fields. Despite the fact that particles generally must have a slip velocity to produce the restoring force required to bring the particle to the local flow velocity, equation. 1, the seed particles are generally of small enough mass to report a reasonable facsimile of the flow characteristics. The particle response equation is:

$$\frac{\rho_p \pi d_p^3}{6}\frac{du_p}{dt} \cong C_D \frac{\rho_g \pi d_p^2}{8}(u_g - u_p)\left|u_g - u_p\right|$$

and for a Stokes flow, $C_D = 24/Re_p$ and $Re_p = \rho_g \frac{\left|u_g - u_p\right|}{\mu_g} d_p$ where u_p and u_g are the particle and gas phase velocities, ρ_p and ρ_g are the particle and gas densities, d_p is the particle diameter, and μ and ν are the dynamic and kinematic viscosity. Hence, the temporal rate of change of the particle velocity is given as

$$\frac{du_p}{dt} = \frac{18\nu\rho_g}{d_p^2\rho_p}(u_g - u_p)$$

Although it is assumed that the LDV produces a time-averaged result, in fact, it produces a flux-average of the measured quantities. Assuming that the seed particles are uniformly dispersed in the flow, the particle arrival rate will depend on the instantaneous magnitude of the flow velocity at the sample volume. More particles will pass the sampling volume during high velocity excursion relative to low velocity events so the velocity distribution will be biased toward the higher values. Much controversy has evolved around this problem and the means for its correction (Edwards, 1987). An additional source of error will occur if the seed particles are not uniformly distributed (concentration is independent of the location) throughout the flow field. If regions of high velocity have a greater concentration of seed particles than regions of low velocity, for example, then the sample will be biased toward the higher velocity. Fortunately, for the purposes of evaluating the state-of-the-art theories and modeling efforts, the magnitude of these errors are probably insignificant.

A brief discussion on the measurement of the turbulence frequency spectra using stationary probes may be useful, especially when assessing the response requirements of the particles. Turbulence frequencies fall in the range of 1 to 10,000 Hz (Hjelmfelt and Mockros, 1966). The convection of the turbulent eddies past the sampling probe (hot-wire anemometer or LDV) so the frequency reported is due, in part, to the convection velocity of the turbulent structures. Particles moving with the mean flow velocity are carried by the eddies and experience a radial acceleration due to the curvilinear motion, to convection out of one eddy and into another, and during interaction and breakup of the eddies. Particles will not experience the apparent accelerations that are inferred from the stationary probe data. Thus, the particle response requirements are not as severe, for example, as in a flow undergoing a simple sinusoidal fluctuation at a similar frequency.

Particle Dynamics in Turbulent Flows:

In turbulent flows, the particles are subjected to turbulent eddies that have a range of length scales from the small scales that may be as small as the largest particles to the large scales that are on the order of a characteristic length scale in the flow (e.g. jet diameter for jet flows). In the case of shear layers or jets emitting into a relatively quiescent flow, large coherent structures form over the near field region (few jet diameters for axisymmetric jets). As the flow propagates downstream, vortex pairing occurs and the coherent structures breakup into smaller eddies of random size. If the jet is laden with particles (e.g. Longmire and Eaton, 1994) or the flow is a shear layer with the high velocity stream carrying a dilute concentration of particles (e.g. Lazaro and Lasheras, 1994), the particles will interact with the large scale eddies and disperse normal to the flow direction. The particle response to the accelerations in the local flow field motion is characterized by the Stoke's Law particle characteristic relaxation time

$$\tau = \frac{d_p^2 \rho_p}{18 \mu_g}$$

which shows the strong dependence on the particle size on the relaxation time. It must be emphasized that this response is true for Re_p <<1. For high density particles (e.g. water droplets in air) greater than 10 μm, the slip velocity can have such magnitude as to violate this condition. In that case, a nonlinear drag correlation is required (Torobin and Gauvin, 1960). Because of the problem dealing with the nonlinear drag coefficient, Stokes drag is generally assumed, even when Re_p >> 1. As an example, using the Stokes drag coefficient will result in an error as large as a factor of 3 too low for $Re_p \sim 50$. In spray injection into combustors with pressure atomizers, it is not uncommon to have drop slip velocities for the largest drops as high as 1 to 10 m/s for a Sauter mean drop size of 20 μm which results in $Re_p = 13$ to 130.

The analyses of the particle response to turbulent flows have been developed by Hinze (1972), Maxey and Riley (1983), Lazaro and Lasheras (1989), Kiger and Lasheras (1992a, 1992b), and Simo and Lienhard (1991). Simo and Lienhard developed relationships based on the Stokes drag assumption for maximum particle size (mass) that will respond to the Kolmogorov time scales and the large scales in the turbulence. The Kolmogorov time scale is given as

$$\tau_k = (\nu_g / \varepsilon)^{1/2}$$

where ε is the local turbulence dissipation rate. For an axisymmetric jet, Friehe, van Atta, and Gibson (1971) give the following expression

$$\varepsilon \frac{D}{U^3} = 48 (x/D)^{-4}$$

Making the substitutions leads to

$$\frac{\tau}{\tau_k} = 0.38 \, \mathrm{Re}_D^{\frac{3}{2}} \frac{x}{D} \left(\frac{d_p}{D} \right)^2 \left(\frac{\rho_p}{\rho_g} \right).$$

where x is the distance from the jet exit and D is the exit diameter of the jet. For insignificant slip between the particle and the surrounding fluid,

$$\frac{\tau}{\tau_k} << 1$$

which may be set as less than 0.1. For a first approximation, $\tau/\tau_k = 1$ is a reasonable choice to provide a lower bound on the drop size that will respond to the range of turbulence length scales in the flow. With the appropriate substitutions, they arrived at

$$d_{pk\max} = 1.6 D_o \left(\frac{x}{D_o} \right) \left(\frac{\rho_g}{\rho_p} \right)^{1/2} \mathrm{Re}^{-3/4}$$

where Re is the jet Reynolds number and D_o is the jet diameter. For the largest particles that should respond to the large scales, the analysis of Hinze yields an expression that approximates the response as

$$\frac{d_{p\Lambda\max}}{\Lambda} \le \left[\frac{u'\Lambda}{\nu} \left(\frac{\rho_p}{\rho} + \beta \right) \right]^{-1/2}$$

where Λ is the macroscale of the turbulence, u' is the rms velocity of the gas phase, and β is given by

$$\beta = 1 + \frac{\rho}{2\rho_p}$$

which is approximately equal to 1 for the present case of water drops in air. The macroscale of turbulence may be taken as equal to the cylinder diameter, D. The above expression can then be simplified to

$$\frac{d_{p\Lambda\,\max}}{D} \le \left[\frac{u'D}{\nu}\left(\frac{\rho_p}{\rho}\right)\right]^{-1/2}$$

Thus, only particles of density ρ_p that are smaller than d_p given in the above expression will respond to the large scale turbulence with rms fluctuations of u'.

EXPERIMENTAL METHODS IN TURBULENT TWO-PHASE FLOW RESEARCH

Visualization

Much can be learned about the global nature of the particle interaction with the large-scale turbulent structures using pulsed laser light sheet illumination. For example, Longmire and Eaton (1994) used a pulsed laser to generate a light sheet oriented along the jet axis to visualize the development of a particle laden axisymmetric jet. The images were recorded, digitized, and analyzed to estimate the local particle number density. The jet airflow was visualized using glycerin smoke. Hancock, et al. (1992) used an interesting approach consisting of adding titanium-tetrachloride ($TiCl_4$) vapor into the flow stream. Water drops injected into the flow stream, fig. 1 evaporate and the water vapor reacts with the $TiCl_4$ to form micron-sized TiO_2 particles and HCl. The particles readily respond to the flow but are large enough not to diffuse too rapidly. A laser light sheet was used to illuminate the particles and visualize both the drop and TiO_2 particles using the Lorenz-Mie light scattering. The vapor trail begins at the point where the drop encounters the $TiCl_4$ vapor laden stream. As the TiO_2 particles form, they are convected downstream. Near each drop, the direction of the TiO2 streak and its length give an indication of the air slip velocity.

Figure 2a and b from Hancock et al. shows the interaction of the drop stream with the eddy. Although the drops are not significantly affected by the eddy as seen in the first figure, the vapor lines are swept into the core of the vortex to form a local concentration of small particles or, in the case of an evaporating drop, a concentration of vapor. This behavior of the small drops was predicted by Simo and Lienhard (1991). Figure 2b clearly illustrates the strong interaction of the drops with the laminar vortex. The drops follow the outer periphery of the eddy as described by Lazaro and Lasheras, 1989. Although the reproduction of the figure does not show it, the small TiO2 particles are convected inward from the drops at a sharp angle to the line of the drops. This indicates that the air flow is slipping inward to the vortex core producing the drag that turns the drops into the arc trajectory. The radial motion is due to the centrifugal

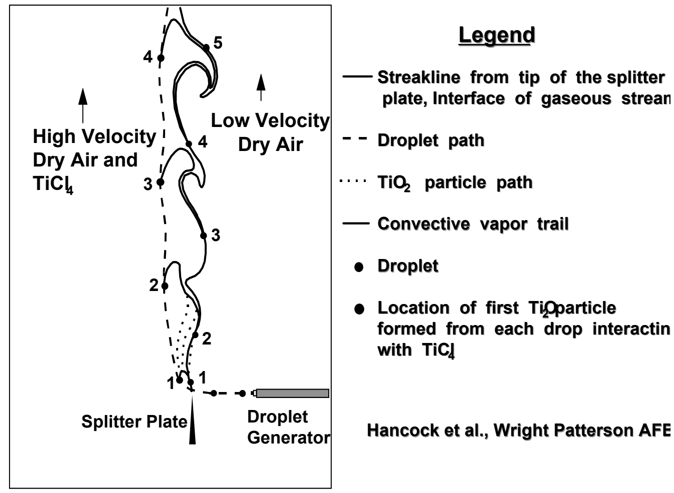

Figure 1. Schematic drawing of the apparatus of Hancock, et al.(1992) for visualizing the interaction of drops with vortices in a shear layer.

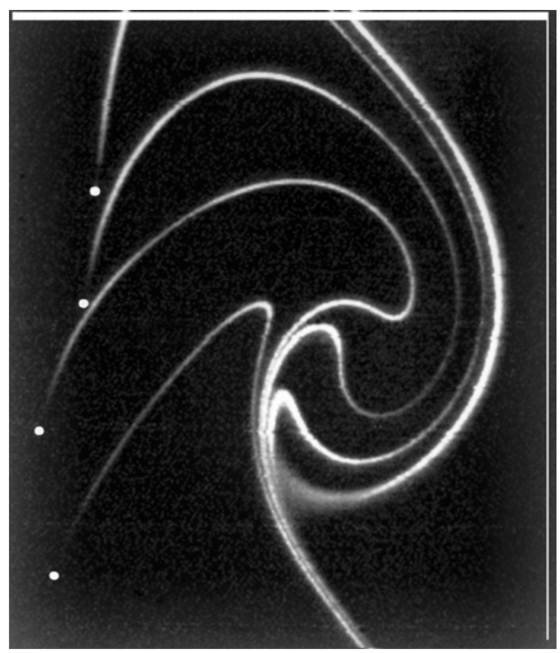

Figure 2a. Weak interaction shows a small deflection of the drops and an accumulation of the small sub-inertial particles in the core of the eddy.

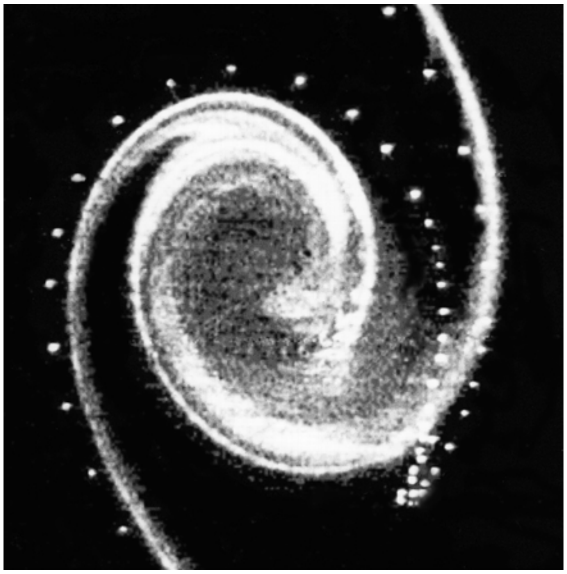

Figure 2b. Strong interaction showing the wrapping up of the drop stream into the vortex to form the streak formation resulting in a high local drop concentration or clustering.

Figure 2. Streaklines formed by water drops injected into a forced shear layer laden with $TiCl_4$ vapor showing the interaction with large scale laminar eddies (from Hancock et al, (1992).

Figure 3. Instantaneous flow visualization showing the dispersion structure for a polydispersion of particles in a forced shear layer (from Lazaro and Lasheras, 1989).

forces of the drop moving in a curvilinear path balanced by the drag forces due to the air wrapping up into the vortex. As the particles increase their tangential velocity, they also produce a greater radial acceleration as a result of the centrifugal forces so the separation between the small particle paths and the drops increases.

Ye and Richards (1997) used the method of Hancock et al. (1992) to investigate the effects of the point of injection of drops into an acoustically-forced jet on the dispersion of the drops and small particles (that could simulate the vapor), figure 4. They showed that the drops injected near to the centerline remained in the inner core region. Injections at larger radial distances from the center resulted in progressively larger dispersions of the vapor and droplets. This method is also useful in mapping the local direction of the slip velocity so that the drag force magnitude and direction can at least be estimated for each drop location.

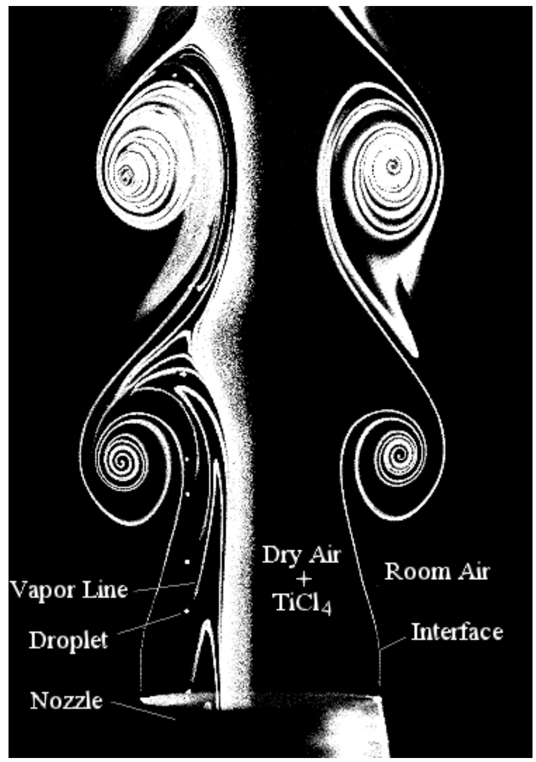

Figure 4. Phase-Locked images of the droplets and vapor lines along with the jet/air interface.

Phase Doppler Particle Analyzer (PDPA)

Before describing some of the experiments investigating the detailed behavior of the dispersed phase in a turbulent flow, a brief description of the PDPA will be given. The method was first described by Bachalo and Houser (1984) and in greater detail by Sankar and Bachalo (1991) and Sankar, et al. (1992). The PDPA is an extension of the well-known laser Doppler velocimeter (LDV) instrument. The PDPA makes use of two intersecting beams to measure the particle or drop velocity from the Doppler difference frequency of the scattered light and the drop size interferometrically from the phase shift of the signals produced by pairs of detectors spatially separated by a known distance, figure

5. The instrument is a single particle counter which means that the sample volume must be small enough and/or the particle field dilute enough so that there is a reasonable probability that only one particle is resident in the sample volume, figure 6, at one time. The sample volume is formed by the focused laser beams and the intersection of the image of a slit aperture in the receiver. A further limitation is that the particles must be spherical or quasi-spherical. The deformation of the drops due to aerodynamic forces induced by flow accelerations and turbulence may be estimated from the Weber number given as

$$We = \rho_g \left| u_g - u_p \right|^2 d_p / \sigma$$

where σ is the surface tension. The deviation from spherical for liquid particles under steady state aerodynamic deformation can be estimated as (Hinze 1947)

$$\left(\frac{2\delta}{d}\right)_{\max} = -0.095\rho_g \frac{d_p}{2}\frac{(u_g - u_p)^2}{\sigma} = -0.095 We/2$$

where δ is the radial displacement of the droplet surface from its position in the undeformed state, ρ_g is the density of the air or surrounding fluid, (u_g-u_p) is the relative velocity between the fluid and the drop, and σ is the drop surface tension. In the case of impulsive deformations due to turbulence etc., the deformation is estimated as

$$\left(\frac{2\delta}{d}\right)_{\max} = -0.17\rho_g \frac{d_p}{2}\frac{(u_g - u_p)^2}{\sigma} = -0.17 We/2$$

which is approximately twice that of the steady state case. The drop size measurements in such cases will have an error that depends upon the degree of the distortion. As an upper bound, drops will deform to the point of break-up for Weber numbers of 6 to 8.

The PDPA measures each particle passing through the sample volume to produce a flux-dependent size and velocity distribution. As with the LDV, the distributions are assumed to be the time average. Since the sample volume is formed with a Gaussian laser beam intensity, the sampling of the particles must be corrected for the changed of sample volume size with particle size (Bachalo, et al. 1988). The time between samples is also recorded so a time history of the particle arrivals is also available. This allows the detection of phenomena such as the periodic passage of particle accumulations or clusters. This capability offers the opportunity to investigate the details of the particle interaction with turbulent eddies and the mechanisms associated with the formation of particle clusters.

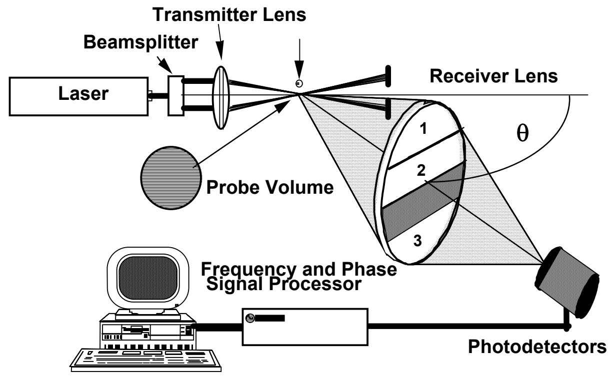

Figure 5. Schematic diagram of the PDPA showing the segmented receiver that collects light from three different apertures at known separation.

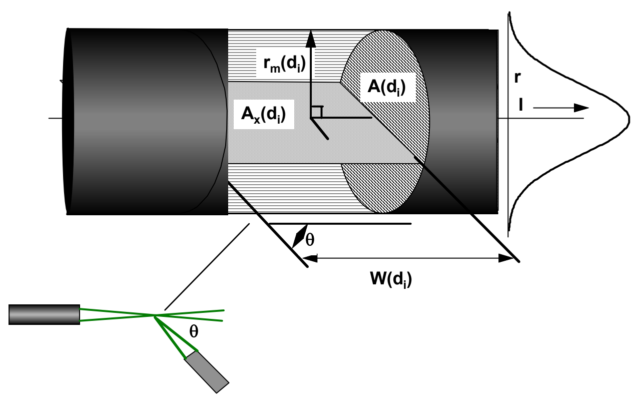

Figure 6. Schematic diagram of the sample volume showing the focused beam diameter, the apparent fringes formed by the intersection of the two laser beams, and the limitation of the length of the beam by the image of the slit aperture located in the receiver optics package.

There is a potential for measurement error due to the particle concentration gradients in the flow. Since the instrument obtains particle size and velocity distributions based on the particle flux, there will be proportionately more readings during periods of time when there is a volume of the fluid containing a higher concentration of particles passing the probe volume. To understand this problem, consider the case of a jet or spray of particles injected into an environment with a lower concentration of particles, figure 7a. As the volume of fluid containing a higher particle concentration of particles is convected past the sample volume, the number of readings per unit time increases. As a region of lower particle concentration passes, proportionately fewer readings per unit time are recorded. This will bias the mean and rms to the velocity excursions of carrying the higher concentration of particles. Figure 7b illustrates the problem wherein a shear layer is seeded with a higher concentration of particles in the low speed side. Fluid flow excursions from the side with the higher particle concentration passing through the sample volume will generate proportionately more readings biasing the flow velocity to the low speed side.

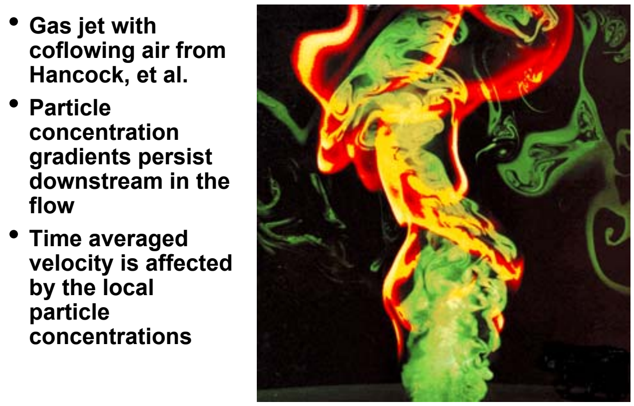

Figure 7a. Examples of particle concentration gradients in seeded jet flows.

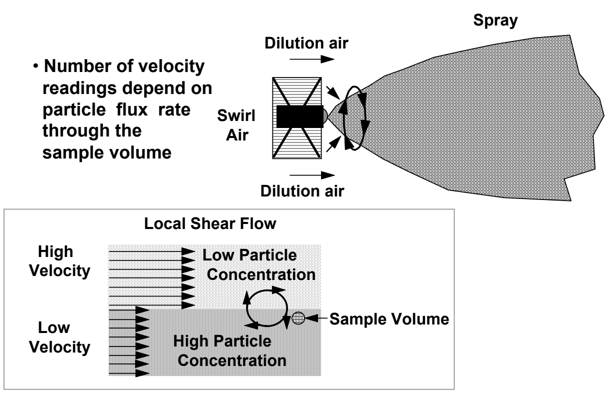

Figure 7b. Schematic showing the possible measurement errors due to particle concentration gradients

Figure 7. Measurements errors that can occur as a result of particle concentration gradients in the flow field.

Particle concentration bias may be compensated by a similar approach used for the velocity bias correction. The possible correction scheme may be posed by estimating the separation between particles, x(t) which is proportional to the local concentration.

$$\vec{x}(t) \cong \frac{\Delta t_i}{2}\left[\vec{v}_{i+1}(t)\right]$$

This correction is then applied to the velocity readings to weight them with respect to the particle separations of local number density as

$$\vec{v} = \left[\sum_{i=1}^{N} \vec{v}_i(t)\vec{x}_i(t)\right] / \frac{1}{N}\sum_{i=1}^{N} \vec{x}_i(t) .$$

It must be emphasized that this expression has not been evaluated for its reliability in mitigating the concentration bias problem.

The PDPA has been applied very extensively to the characterization of sprays and sprays interacting with turbulent flows. In a basic study the verify the drag coefficient, C_D for drops in dilute environment but under various turbulence levels, Rudoff and Bachalo (1991) measured the relaxation velocities of spray drops incident upon a cylinder used to for a stagnating flow, fig. 8. The right circular cylinder was mounted in a wind tunnel and the spray injected into the test section well upstream of the cylinder. As the drops approached the cylinder, they decelerated in accordance with their relative inertia. This information was then used to calculate the drag coefficient as a function of the Reynolds number, fig. 9. These data are very useful in establishing whether there are significant effects on the drag due to drop-drop interaction and due to free-stream turbulence. The results of Torbin and Gauvin (1960) were produced by observing isolated drops falling in a quiescent environment.

Simo and Lienhard (1991) used the PDPA to study the details of the particle response in a turbulent jet and to determine whether the turbulence spectra could be reliably measured. Their data showed that at relatively large distances downstream (x/D_o = 35) that the particle rms velocity fluctuations plotted as a function of τ/τ_k for a microscale Reynolds number, $\mathrm{Re}_\lambda = u_g' \lambda_g / \nu$ of 150

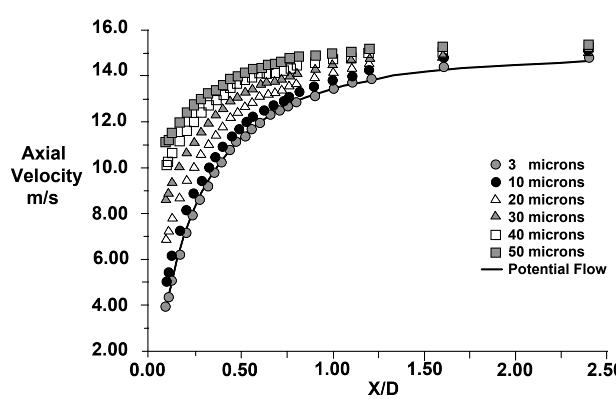

Figure 8. Particle response to the stagnating flow impinging on a right curricular cylinder. The free-stream turbulence intensity was approximately 30%.

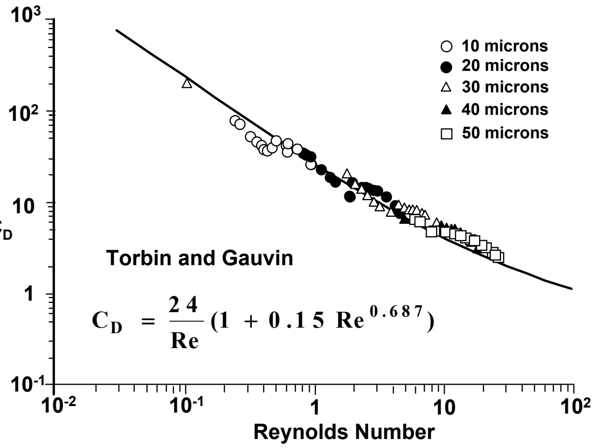

Figure 9. Reduced data of the Drag Coefficient as a function of Reynolds number showing the agreement with the correlation of Torbin and Gauvin.

adequately tracked the turbulence fluctuations up to $\tau/\tau_k = 1$. Although not conclusive because of the scatter in the data, their data showed that the particle is slightly energized ($u_p'^2/u_g'^2 > 1$) for rms velocity near $\tau/\tau_k = 1$. Clearly, in regions of small-scale motion, the strong accelerations of the turbulent straining motion can only be followed by the very small particles. They observed that the small inertial particles had the tendency to collect in regions of high strain rate or low vorticity. This is in agreement with the observations of Hancock, et al. using the flow visualization.

Bachalo, et al. (1993) conducted basic experiments in a high speed jet to establish the particle response to the gas phase turbulent fluctuations and to evaluate the simplified particle response correlation presented above. Table 1 shows the jet exit velocities and the corresponding estimated diameters of the max. size particles that will respond to the smallest and largest scales in the flow. Using the PDPA, the size and velocity of particles entrained in a high speed axisymmetric jet were measured. An example of the drop size and velocity plot for one location is shown in figure 1. Each dot on the plot is a particle measurement in the size-velocity plane for a jet Reynolds number of 30,000 at an axial location two jet diameters downstream. The correlation for the largest particle that should follow the large scale motion (derived in an earlier section) which is responsible for the largest turbulent velocity fluctuations was computed to be approximately 3 μm. It is apparent that for particles larger than 3 μm, the maximum velocity reached and thus, the rms velocity fluctuations begin to decrease monotonically with drop size.

Table 1

U (m/s)	d_p (mm) Kolmogorov	d_p (mm) Large Scales
40	0.42	5.4
55	0.34	4.7
60	0.30	4.4
80	0.25	3.8
100	0.21	3.4
125	0.17	3.0
150	0.16	2.9
175	0.14	2.6
200	0.13	2.5
225	0.12	2.4
250	0.11	2.2
275	0.1	2.1
300	0.1	1.9

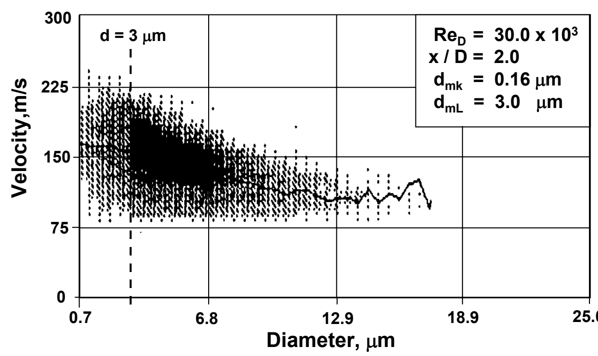

Figure 10. Plot of the drop size versus the drop velocity with each point on the plot representing a single drop measurement. The particles larger than 3 mm begin to lag the high velocity turbulent flow excursions.

Measurements were also made of the rms velocity at 7 jet diameters downstream with a jet Reynolds number of 50,000, figure 11. Both the streamwise and transverse rms velocities were measured for a range of particle sizes. These data also show the decrease in the measured rms velocity with increasing drop size. This provides an indication of the particle response to the turbulence at high relatively high Reynolds number. It is also interesting to note that the transverse rms is not tracked as well as the axial indicating that the turbulence-induced velocity accelerations are more energetic in the transverse direction so that the larger particles cannot respond adequately.

Because of the importance of the particle dispersion mechanisms in turbulent flows, fundamental experiments have been conducted to study the behavior of the particles as they interact with the turbulence. In addition, the

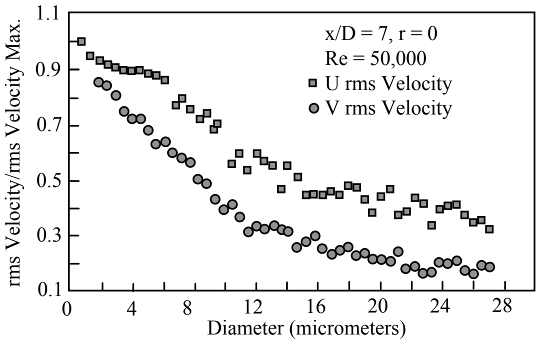

Figure 11. Streamwise and cross-stream turbulence intensity for a turbulent high speed jet measured as a function of particle size.

PDPA method needed to be developed to enable the acquisition of these additional data as well as the data interpretation methodologies. Even a basic spray combustion system utilizing a pressure atomizer with swirl air flow presents a degree of complexity in understanding the flow behavior and the response of the drops, figure 12. The spray drops are injected at a relatively high velocity into a swirling flow with recirculation. The larger drops (drawn in for this illustration) fly ballistically through the flow field with only a small deviation in their trajectory. The smaller drops, showing a progressively greater response to the flow with decreasing drop size, will have a greater deflection by the drag forces. The swirling dilution air flow and the induced flow produced by the spray forms a shear layer with larger scale eddies, similar in character to the large scale eddy (inset) interaction studied by Hancock, et al.

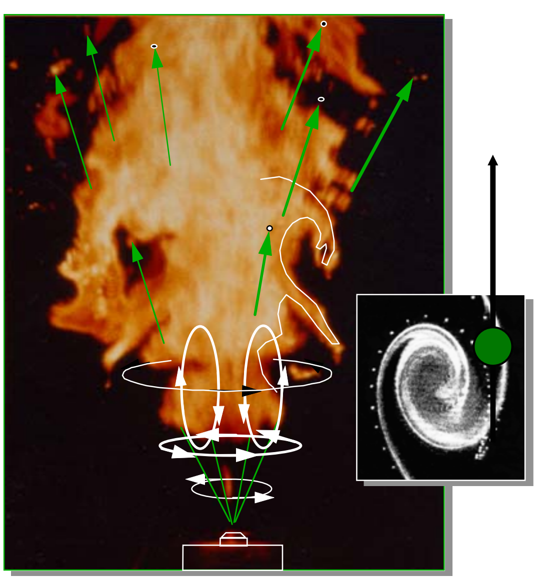

Figure 12. Photo of a spray flame using a pressure atomizer and swirl dilution air to stabilize the flame. Large spray drops injected at high velocity pass through the swirl and recirculation whereas small drops respond to the air flow field.

Particles passing through the probe volume, for example as shown in the figure, will come in clusters as the large scale eddies pass. Parts of the data record will show clustering followed by voids. This can be seen in figure 13 wherein the particle arrivals show groupings with a high to low change in the velocity magnitude. The spacing of the drops cannot be taken as the drop spacing since the arrival rate is also dependent upon the velocity. It is the spacing of the particles arriving at the probe volume that is needed in estimating the clustering or the local number density. The spacing is given as

$$\bar{x}_i(t) \cong \frac{\Delta t_i}{2}\left[\bar{v}_{i+1}(t)\right]$$

where Δt is the time between drop arrivals and v_{i+1} is the velocity of the particle arriving at the end of the time interval. The particle velocity versus time record was obtained from a spray combustor flow that was shedding large scale eddies, as shown in figure 12. This information is important in assessing the particle dispersion since it affects the combustion stability, efficiency, and pollutant formation.

The study of basic particle interactions with large scale eddies have been investigated by Lazaro and Lasheras (1989), Bachalo, et al, Kiger and Lasheras (1994), Longmire and Eaton (1992), and Ye and Richards (1996). In the study of Bachalo et al., a right circular cylinder was mounted in a wind tunnel with a spray and seed particle source upstream, figure 14. The particles passed over the cylinder and interacted with the vortices forming on the leeward side. Particles of different sizes can be expected to follow different curvilinear trajectories when the interact with the eddies. The degree of the interaction depends upon the time of the interaction and

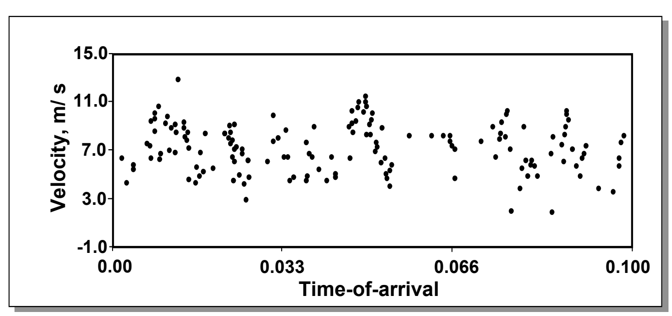

Figure 13. Measured velocity for the particle arrivals with each dot indicating a single particle. The groups of drops indicate clusters.

the response time of the particle. This may be stated in terms of Stokes number, Humphries and Vincent (1978), as

$$St_r = \frac{T_t}{\tau}$$

where T_t is the characteristic time scale of the large scale eddies given as

$$T_t = \frac{D}{u_e - u_p}$$

where $|u_e - u_p|$ is the relative velocity between the particle and the eddy convection velocity. A simple substitution results in the expression for the particle transit Stokes number as

$$St_r = \frac{1}{\tau} \frac{D}{u_e - u_p}$$

which must be much greater than 1 for the particle to respond to the turbulent eddy. That is, the interaction time with the eddy must be longer than the characteristic response time of the particle.

Centrifugal forces will also influence the dispersion of the spray drops. Small particles will follow the rotation of the eddy or vortex, whereas progressively larger drops will cross streamlines and be centrifuged out of the eddy, Hardalupas, et al. (1992). The magnitude of the centripetal forces relative to the Stokes drag forces are estimated using the centrifuge Stokes number, Dring and Soo (1978) as

$$St_\psi = \frac{18}{\psi} \frac{\nu}{d_p^2} \frac{\rho}{\rho_p}$$

where ψ is the angular velocity.

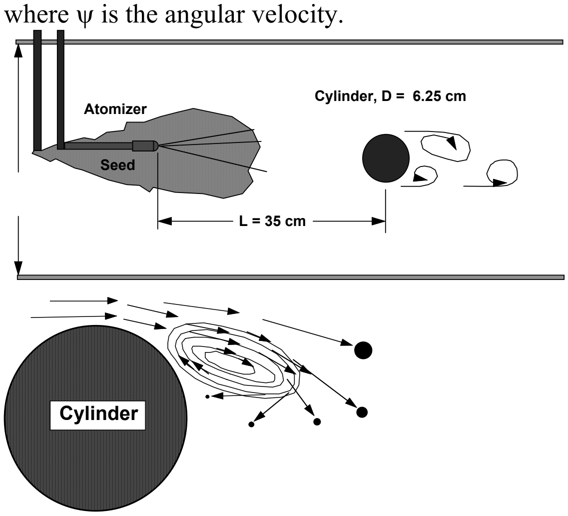

Figure 14. Particle interaction with a vortex street shed by a right circular cylinder. Lower figure shows the expected particle response.

Detailed measurements of the drop size, velocity and local number density were obtained in the wake (Bachalo, et al., 1994). Figure 15 is the velocity versus time plot at one of the locations in the wake obtained from the PDPA showing the periodic u and v velocity as a result of the shedding of the eddies. The coherent frequency is due to the shedding whereas the superimposed higher frequencies are due to the turbulence, figure 15a. In an effort to correlate the local time-dependent number density with the velocity or phase of the shedding, the autocorrelation of the velocity record was computed to eliminate much of the higher frequency, incoherent frequency components. The cross-correlation between the number density and the velocity was then computed. There is a strong correlation between the velocity and number density but with an approximately 90 degree phase shift. This is due to the fact that a downward excursion in velocity carries droplets moving over the upper side of the cylinder into the wake. Since there are few samples in each time increment for the number density estimates, the statistical certainty is not high but appears to be adequate for this evaluation. The approach was used to aid in the development of the PDPA hardware and data reduction systems to allow investigations of particle interactions in regions where the turbulence is fully developed consisting of a range of eddy sizes, vortex pairing, and turbulent kinetic energy dissipation.

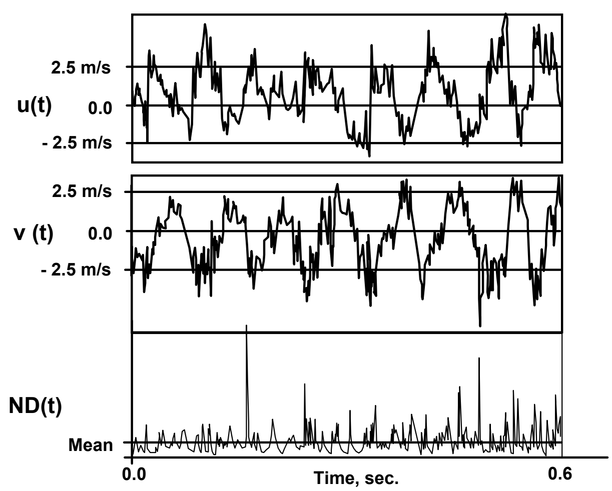

Figure 15a. Raw data for the stream-wise and cross-stream velocity versus time showing the shedding frequency with the superimposed turbulence fluctuations. The lower frame shows the time dependent number density computed for short uniform time intervals.

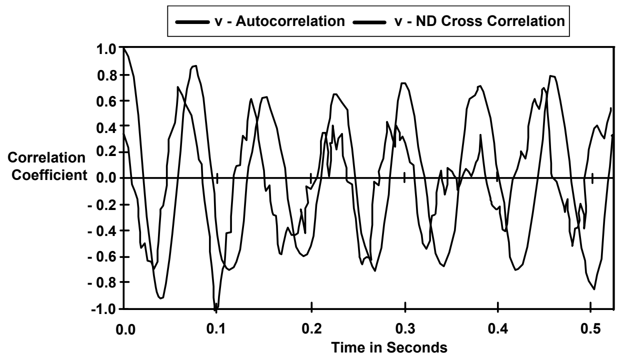

Figure 15b. Velocity versus time plot after the autocorrelation was used to filter the data. The cross-correlation of the time dependent number density with the velocity was computed and displayed.

Figure 15. Time dependent velocity and number density data obtained in the wake of the circular cylinder showing the shedding frequency.

Summary and Conclusions:

A brief review of the work completed on the interaction of particles or droplets with turbulent flows has been presented. The basic theory has been developed for describing the dispersion of particles under the conditions of Stokes flow (Re_p<<1) and dilute suspensions. Unfortunately, most flows of practical interest have Rep>1so the theory becomes a less reliable estimate of the behavior. A number of experiments have been developed that provided a greater insight to the phenomena. These experiments have focused on the fundamentals of the particle interaction with coherent large scale eddies produced by forcing the instabilities in a shear layer. The investigations showed the segregation of particles by size as a result of the interaction. The large particles migrate to the outer layer of the eddy whereas the smallest particles migrate to the low shear center of the eddy.

Experimental methods including flow visualization using laser light sheet illumination with Lorenz-Mie light scattering and line-of-site time-dependent beam extinction along with Fraunhofer diffraction have been used to acquire information on the global features of the interaction. The PDPA was developed to probe the local details of the phenomena. The PDPA provides instantaneous and time-averaged data at points within the flow field to produce information on the particle dynamics, spatial size distribution, and information on the local number density. Time-dependent measurements showed the formation of drop clusters. The instrument was also used to verify the drop drag correlations for environments with relatively high flow turbulence intensity and varying drop number density. The results were consistent with the correlations developed for isolated drops falling in a quiescent environment. Data reduction and interpretation methods have been developed by studying basic particle interactions with large scale eddies. Further development of the method is required to study the interaction with turbulent flows that have a full range of eddy sizes and where the number density can no longer be consider to be dilute.

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