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DROPLET DISPERSION IN A ROUND TURBULENT JET

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ABSTRACT

A novel experimental method has been developed for the investigation of particle dispersion in turbulent shear flows. Droplets of water are injected individually onto the centerline of a round, turbulent jet. The position of each droplet at various axial stations is measured with a laser light scattering technique. In addition, the times-of-flight of each particle from the nozzle to the measurement plane can be measured. The results show that the dispersion follows a quadratic behavior for short times and a linear behavior in the long time limit. In this sense, the particles exhibit the same behavior as is expected in a stationary, isotropic turbulence.

INTRODUCTION

The rapid mixing of liquid and solid particles in a turbulent gas flow is relevant to many practical processes. Examples include spray and pulverized coal combustion and particulate emmission. Both gas turbulence and particle characteristics determine the mixing rate.

Considerable effort has been made to predict particle dispersion in spray combustion environments (Durst et al (1984), Shuen et al (1985), Faeth (1983), Gosman and Ionnides (1981), Sirignano (1988)). A common modelling approach is to determine particle trajectories by integration of the equations of motion in a Lagrangian reference frame. Only a limited number of studies consider the important issue of particle-turbulence interaction. The cause is in part due to a lack of theory which can be readily applied to practical problems, and a lack of experimental study involving Lagrangian measurements. Particle dispersion, gasification, and drag can be affected by gas velocity, temperature, concentration, and density fluctuations. Ultimately, this information will be needed for model development.

This paper presents experimental measurements of particle dispersion within an isothermal shear flow. The measurements are of a Lagrangian type; single particles are tracked from a known initial point. This experiment is in contrast to Eulerian dispersion measurements obtained by seeding an entire flow and measuring concentrations at fixed downstream points.

The basic theory for the dispersion of a particle, developed by Taylor (1921), considers a particle in a stationary, isotropic flow. Use of the theory requires knowledge of the Lagrangian particle velocity autocorrelation function R_L, which is generally not known. The fundamental result of the development is the following expression for the particle dispersion as a function of the velocity correlation:

$$
\begin{aligned}
\langle X_p^2(t)\rangle &= \int_0^t \int_0^{t'} \langle V_p(t')\, V_p(t'')\rangle dt'dt'' \\
&= \langle V_p^2\rangle \int_0^t \int_0^{t'} R_L(t',t'')dt'dt'' \qquad (1)
\end{aligned}
$$

where V_p is the particle velocity relative to the mean flow, and $R_L(t',t'')$ is defined by $\langle V_p(t')V_p(t'')\rangle/\langle V_p^2\rangle$. The dispersion $\langle X_p^2\rangle$, is the mean square particle displacement. This result can be generalized to three dimensions and under some conditions the theory can be extended to non-homogeneous self-preserving flows. Two important special cases are observed. For short separation times $t''-t'\rightarrow 0$, such that $R_L(t',t'')\rightarrow 1$. Eq. 1 can be integrated, and the dispersion is quadratic in time. For long separation times, $R_L(t't'')\rightarrow 0$, and the dispersion is linear in time. The slope of this line is defined to be the particle diffusivity.

Most measurements of dispersion presented in the literature are of the Eulerian Type. There are two notable studies in which Lagrangian measurements are presented. Snyder and Lumley (1971) photographed particles transported in a grid generated flow. Direct measurements of the velocity correlation and the dispersion rate were presented. Vames and Hanratty (1988) have made dispersion measurements for droplets in pipe turbulence.

EXPERIMENTAL METHODOLOGY

The experimental difficulty in tracking particles from a fixed initial point has been overcome using a sheet of laser light and position-sensitive photodiode. Essentially, the experiment consists of injecting a monodisperse droplet stream onto the centerline of a round turbulent jet. A plane of laser light and a silicon photodiode are used to locate the particle position. Droplet dispersion statistics are computed from the position measurements.

A schematic of the experiment is shown in Figure 1. A steady stream of monodisperse droplets are generated using a piezoelectric transducer. The laser sheet defines the viewing plane. Scattered light is focused to a spot on the silicon photodiode, which has an active area of 1 cm^2. The diode has four photo current outputs - one on each side. By comparing the signal from opposing sides, the position of the droplet can be measured. The diode signals are amplified, bandpass filtered and fed to a peak detection integrated circuit. The peak values are then stored by the data acquisition system, and an x, y coordinate for each droplet is computed. Experimental uncertainty of the position measurement is approximately ± 1 mm. A total of 8000 droplets is used for dispersion statistics at each axial location downstream from the air jet nozzle. A typical distribution of droplet displacement is shown in Fig. 2. The scatter data are for an axial location of $x/D = 50$, where x is the distance downstream from the nozzle, normalized by the nozzle diameter D.

RESULTS and DISCUSSION

It is desired to measure the dispersion dependence with axial downstream distance, and relate this to the droplet time of flight. From these measurements, a particle diffusivity can be estimated by considering the limiting case of Taylor's theory. The diffusivity is dependent on the flow characteristics and time scales, as well as particle parameters. For the present study, results are for jet Reynolds numbers of 10,000 to 20,000 based on a nozzle diameter of 7 mm. The droplet diameter was measured by video micro-photography to be 185 ± 2 μm. The droplet size is governed by an orifice attached to the transducer. The present data includes results obtained for two slightly different droplet sizes. The droplet spacing is roughly 1000 drop diameters ;thus, the droplets are non-interacting.

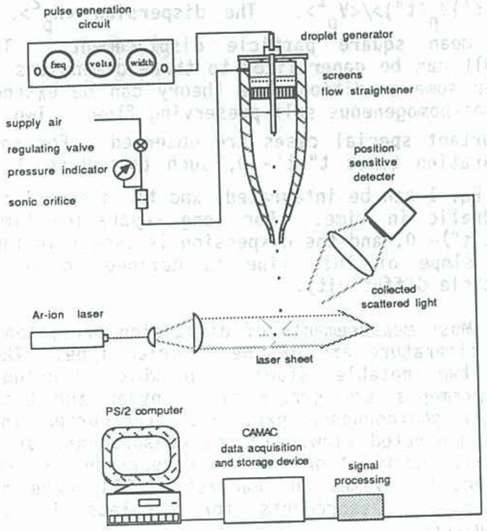

Fig.1. Schematic of droplet dispersion apparatus.

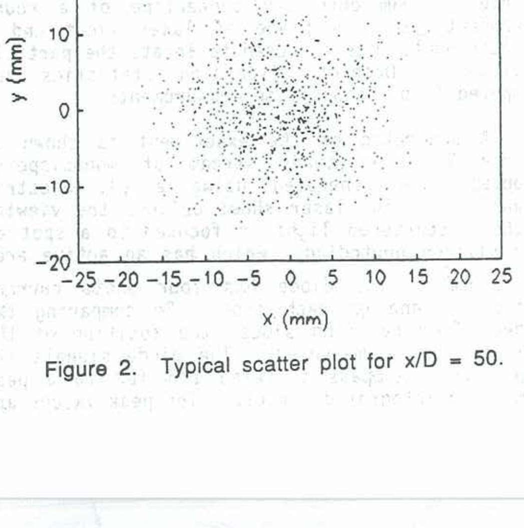

Figure 2. Typical scatter plot for x/D = 50.

From the scatter data such as that shown in Fig. 2 the probability density function (pdf) and the droplet mean square displacement $\langle X_p^2 \rangle$ (i.e. dispersion, or variance) can be calculated. Fig. 3 shows the pdf for several x/D locations. The solid line is a Gaussian distribution with the same variance as the experimental data. There is no a priori reason to expect a Gaussian distribution since the droplet are projected through a non-isotropic flow field which is non-stationary in the Lagrangian reference frame.

The dispersion as a function of axial distance is directly measured, but must be related to the droplet time of flight. The average time of flight is estimated by

$$t = \int_0^x dx/\langle U_p \rangle \qquad (2)$$

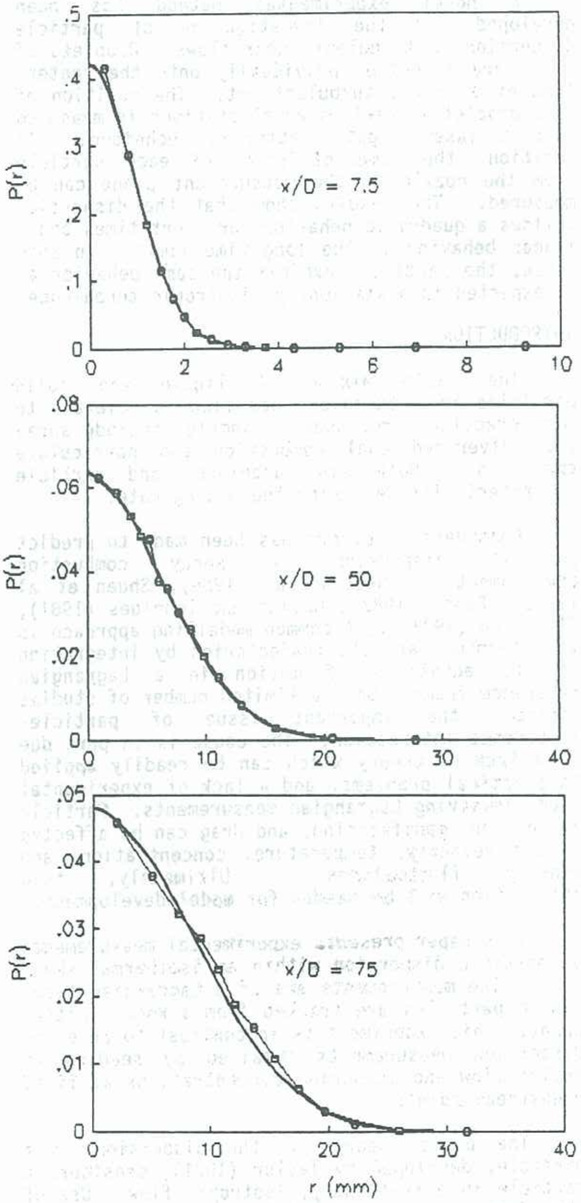

Fig. 3. Measured probabality density functions at three axial locations. Solid lines are Gaussian distributions.

where $<U_p>$ is the mean axial particle velocity. Fig. 4 shows the esemble averaged time of flight determined from measurements.

The data of Fig. 4 combined with the pdf at each axial location determines the time dependence of the droplet dispersion. These data are plotted in Fig. 5. The result is similar to those of Snyder and Lumley (1971) and Vames and Hanratty (1988). The particle diffusivity is measured from the linear segment of Fig. 5. Both limiting cases of Taylor's theory are observed in spite of the fact the flow is neither isotropic, homogeneous, nor stationary. The limiting quadratic dependence on time is clearly demonstrated in Fig. 6 for small times of flight. The slope of this line gives the mean square velocity $<V_p^2>$ in the radial direction. Figure 6 shows results for two particle sizes. The experiment is being modified so that a wider range of particle sizes may be investigated. A summary of the present results is provided in Table 1.

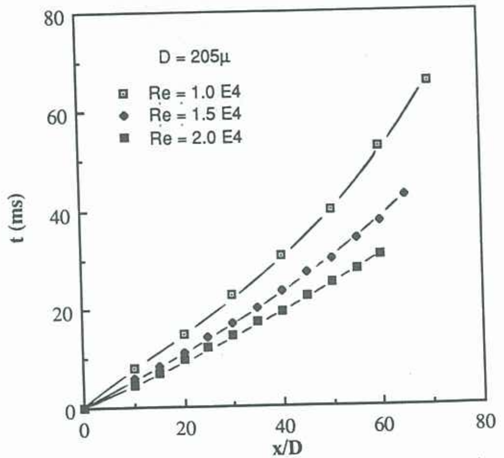

Fig. 4. Droplet time of flight measurements.

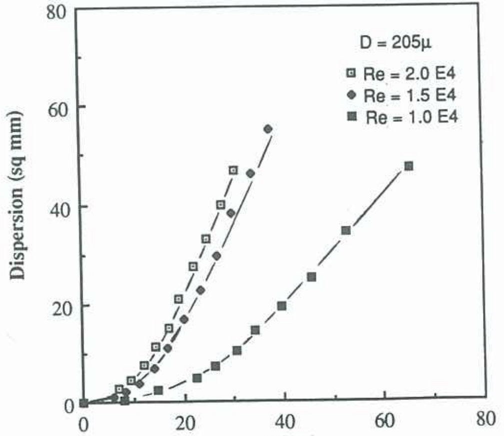

Fig. 5. Droplet dispersion as a function of time of flight.

CONCLUSION

A technique has been developed which facilitates collection of statistically large sample sizes of particle displacement. The displacement distributions are Gaussian and the measurements of dispersion show the same limiting cases as do measurement from other types of flows.

The authors are currently extending this work to include a wider range of droplet diameters and jet Reynolds numbers. The effects of density and temperature fluctuations will then be investigated.

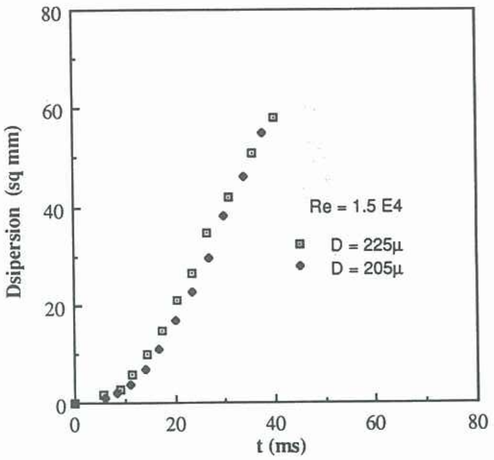

Fig. 6. Dispersion for two droplet sizes.

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Table 1. Sumary of dispersion measurements.

10^{-4} Re	Diameter (µm)	$d<X_p^2>/dt$ (cm^2/s)	$<v_p^2>$ $(cm/s)^2$
1.0	205	11	120
1.5	205	22	410
2.0	205	23	560
1.5	225	18	480
grid*	46.5	~3	
pipe**	150		256

* Data of Snyder and Lumley for grid generated turbulence using copper beads.

** Data of Vames and Hanratty for pipe generated turbulence using water droplets.

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