DECOUPLING THE ROLES OF INERTIA AND GRAVITY ON PARTICLE DISPERSION

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ABSTRACT

Inertial and gravitational forces determine a particle's motion in a turbulent flow field. Gravity plays the dominant role in this motion by pulling the particles through adjacent regions of fluid turbulence. To better understand and model how a particle's inertia effects its displacement, one must examine the dispersion in a turbulent flow in the absence of gravity. In this paper we present the particle experiments planned for NASA's KC-135 Reduced-Gravity Aircraft, which generates microgravity conditions for about 20 seconds. We also predict the particle behavior using simulation and ground-based experiments. We will release particles with Stokes numbers of 0.1, 1, and 10 into an enclosed tank of near-isotropic, stationary, and homogenous turbulence. These particle Stoke numbers cover a broad range of flow regimes of interest. Two opposed grids oscillating back and forth generate the turbulent field in the tank with a range of turbulence scales that covers about three orders of magnitude and with turbulence intensities of about ten times the mean velocity. The motion of the particles will be tracked using a stereo image velocimetry technique.

Using a model for particle dispersion, which is supported by data from direct numerical simulations and quasi-numerical simulations, we estimate the average particle dispersion for our three Stokes numbers to be less than 20 cm after 10 seconds.

INTRODUCTION

Particle laden flows are common to both nature and man-made applications. There are many natural phenomena such as volcanic activity, sedimentation, and blood flow that involve the flow of a fluid interspersed with solid or semi-solid particles. Likewise, examples of man-made particle flows abound such as solid rocket combustion, dispersion of chemical and biological agents, paint sprays, and filtration systems. A majority of these applications occur in turbulent fluid environments that complicate the modeling process because the particles respond to the local fluid turbulence they see while moving through the fluid. Modeling these particle-laden flows is a necessary step in improving our understanding of the physics involved and consequently for designing new technologies in this area.

In addition to the inertial component, the movement of a particle in turbulent flow is greatly affected by gravity. Gravity pulls the particles through different "neighborhoods" of fluid turbulence, which complicates any experimental attempt to study its response to the surrounding fluid. That is, particles that respond to most of the fluid turbulence in the absence of gravity respond to a great deal less turbulence in the presence of gravity.

We have taken three different approaches to measure the response of the particles in order to model the effect of particle inertia on particle dispersion. First, Direct Numerical Simulation (DNS) allows us to vary the inertial effects in a simple turbulent field. Second, Quasi-Numerical Simulation (QNS), which is a hybrid numerical/experimental technique[1], allows for more complex turbulence fields but is limited to particles constrained to move in a two dimensional plane. Third, one can measure the dispersion of real particles in a turbulent airflow. This last method has the largest range of turbulence scales but provides little information on the fluid turbulence as seen by the moving particle. Traditional ground-based experiments of this type are limited because gravitational drift masks most of the inertial effects. Therefore, we have designed an experiment for tracking the motion of a single particle in a known turbulent field in the absence of gravity. The tests will be conducted onboard NASA's KC-135 Reduced-Gravity Aircraft (about 20 seconds of microgravity).

Few have been able to study these kinds of flows experimentally. Yudine[2] predicted that the particle would respond less to the turbulence than one might expect simply because gravity is pulling it through adjacent fluid neighborhoods. Csanady[3] expanded this work to show how increased drift would change the shape of the fluid velocity autocorrelation (continuity effect). Wells and Stock[4] used electrostatic charge to remove the influence of gravity. They found, for their single Stokes number case, that if the drift velocity is less than the turbulence intensity, the particle dispersion is independent of drift, implying that particle inertia does not play a dominant role. They were only able to run a single particle size, however, due to difficulties with their experimental setup. In our current set of experiments, we plan on investigating the behavior of at least 3 different particle sizes for Stokes numbers of 0.1, 1 and 10.

APPROACH

The experimental component to our research program involves studying particle dispersion through a turbulent fluid in the absence of gravity. The tests will be conducted onboard NASA's KC-135 Reduced-Gravity Aircraft that provides about 20 seconds of microgravity. This is sufficient to achieve dispersion times of desirable length. We will release particles of various sizes in an enclosed tank of grid-generated, isotropic, and stationary turbulent airflow and track their dispersion using a stereo image velocimetry technique. Although the data collected will provide less information than our other methods regarding the turbulence seen by the particles, it will extend the range of turbulent scales experienced by the particle and include particle motion in all three dimensions.

Our experimental apparatus (see Figure 1) consists of a closed rectangular Plexiglas tank measuring 30.5 x 30.5 x 61 cm with two grids on opposite sides of the tank. The grids are moved back and forth, sinusoidally 180 degrees out of phase with each other using a pair of stepper motors and a crank-slider mechanism that are located outside of the tank. The grid's mesh size (2.54 cm), stroke length (4.5 cm), and oscillation frequency (6 Hz) have been optimized to produce a turbulent flow field with about three orders of magnitude in scales. Characterized by a near-zero mean velocity, the isotropic turbulence in this type of flow is desirable for its simplicity, with the generated turbulence in the plane parallel to the grid being homogenous and decaying in a self-similar manner relatively far downstream from the grid. The stationary and isotropic turbulent conditions are ideal for studying particle dispersion because the particles will remain in a relatively small volume, facilitating the techniques for tracking their dispersion.

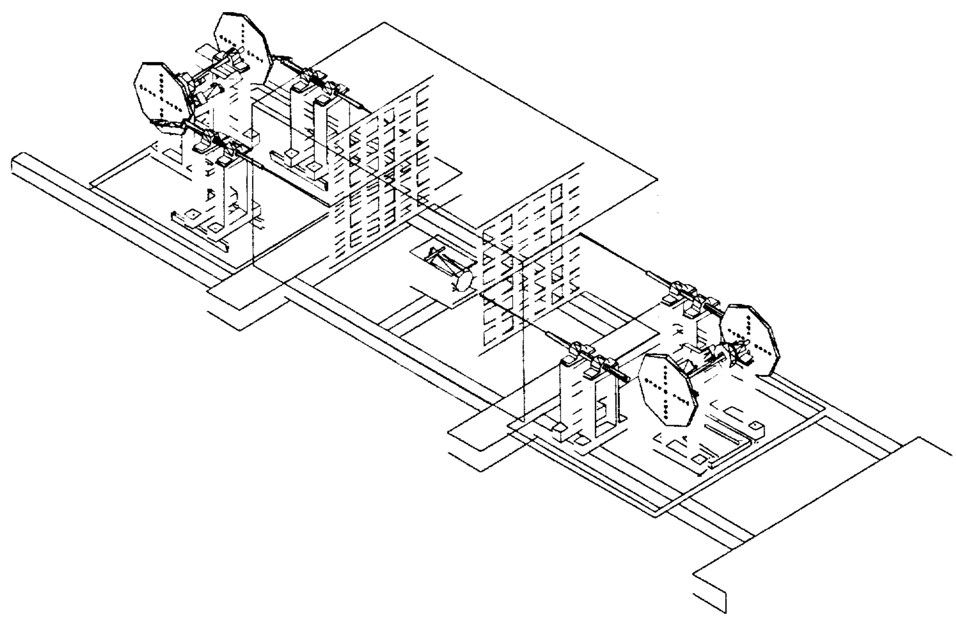

Figure 1. Experimental Apparatus

At the start of every run, we insert the particles into a desired interrogation volume in the tank using an injection system that propels one or more particles upward from the initial resting position. The injection system consists of a semi-rigid plastic dish that is hit from below by a lever operated by a DC servomotor (see Figure 2). The motor speed is regulated to place the particle at the desired tank location with a minimum in mean velocity. Any velocity imparted to the particle by the injection system will damp out in about three to four particle time constants due to the exponentially decaying nature of particle velocity.

The solid particles consist of hollow ceramic spheres (PQ Corporation) with diameters of 100 μm and 300 μm and glass beads (GlenMills, Inc.) of 500 μm to provide particle Stokes numbers of 0.1, 1, and 10, respectively. Because of the Stokes number dependence on particle mass, we are using hollow ceramic spheres to allow for larger particle diameters with the smaller Stokes numbers. The density ratio of the particle to the air is on the order of 10^3, which allows us to simplify the particle transport equation. The dominance of electrostatic forces typical for these small particles makes it necessary to place only one or few particles in the interrogation volume of the stereo image velocimetry (SIV) system at the onset of every parabolic trajectory.

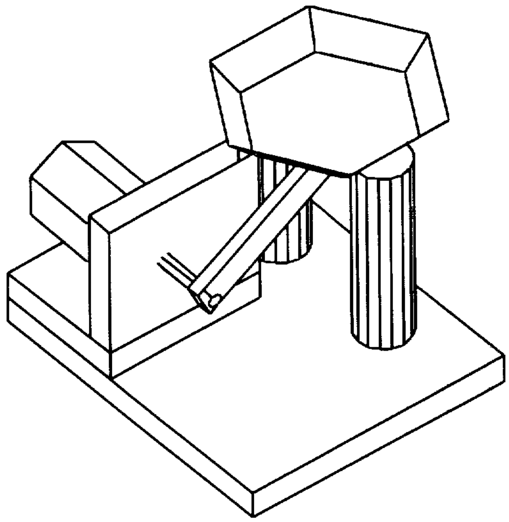

Figure 2. Particle Injector

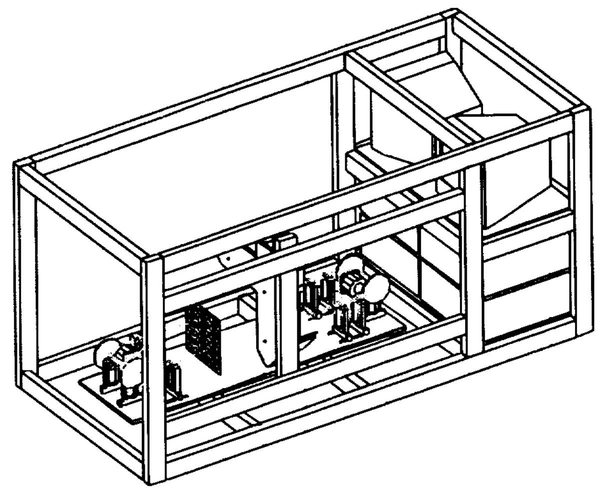

Figure 4. Equipment Rack

The SIV apparatus (see Figure 3) incorporates a single color video camera and several filters and mirrors to capture orthogonal views of the particles in the tank. Light from the particles will bounce off each first-surface mirror and continue through the filters that color the image either blue or red. The two orthogonal images (red and blue) are then combined with a beamsplitter and stored via a Sony DXC-950 color video camera onto a Hi-8 cassette. The entire experimental system is housed in an equipment rack that is bolted to the floor of the KC-135 as shown in Figure 4.

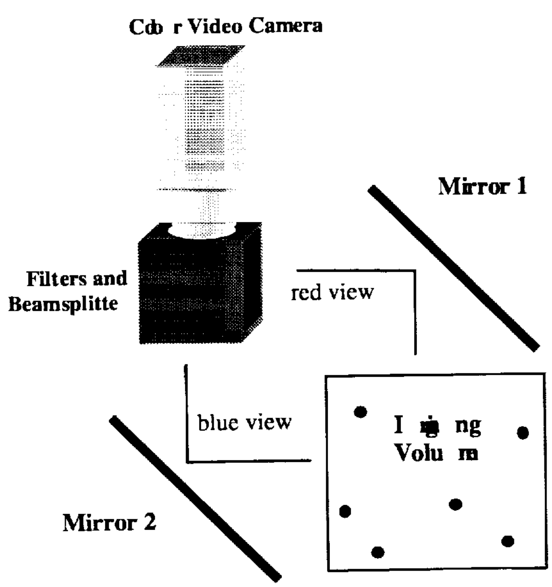

Figure 3. SIV Apparatus

RESULTS

Laser Doppler Velocimetry (LDV) measurements inside the tank of grid-generated turbulence at varying distances from the grids were used to characterize the flow parameters before conducting the microgravity experiments[5]. Initially, only one oscillating grid was used to generate the turbulence in the tank. Results from these measurements, as seen in Figure 5, show that the turbulence is near-isotropic since the ratio of turbulence intensities in the forced (u') and unforced (v') directions are close to one. The data was taken while moving away from the grid (x direction) and is normalized by the grid mesh length.

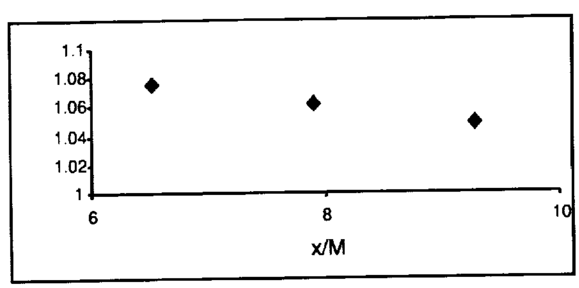

Figure 5. Ratio of u'/v' Moving Away from the Grid

A problem we encountered with the one grid approach was the presence of a mean velocity in the flow of air in the tank. Figure 6 shows the velocity profiles in the forced and unforced directions and the non-zero mean, especially in the forced direction. Preliminary results using the two-grid approach has reduced the mean velocity and increased the turbulence intensity to ten times this mean velocity, while maintaining the near-isotropy. We are currently experimenting with this grid system to improve on these results.

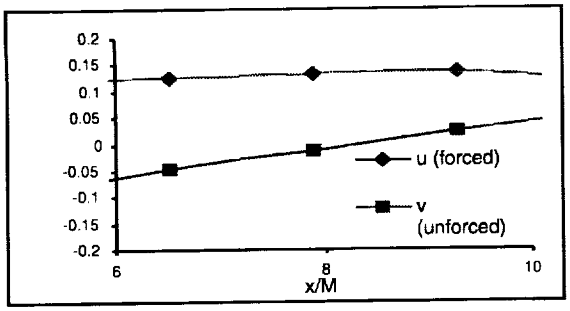

Figure 6. Mean Velocity Profiles

The goal of our upcoming microgravity experiments is to examine the dispersion of three different size particles, which characterize three regimes in particle flow. A Stokes number of 0.1 is representative of a flow where the particle closely follows the fluctuations in the velocity of the surrounding fluid. In the other extreme, a Stokes number of 10 will respond very little to the carrier fluid much like a boulder falling through air. In between, we will examine the case with a Stokes number of 1.

To estimate what we will see in the microgravity experiments, we can use results from our DNS[6] and QNS[5] techniques. Particle dispersion measurements were obtained from the DNS simulation for Stokes numbers that ranged from 1.21 to 3.44 in the absence of gravity for a Reynolds number, based on the Taylor microscale, of 42. The Stokes numbers were calculated by dividing the particle integral scale by the fluid integral scale. Particle dispersion measurements were estimated for the QNS method at a channel Reynolds number of 6600 in the absence of gravity. As expected, these data confirm that smaller particles disperse more than larger particles. The smaller the particle, the more it is affected by the variations in the fluid velocity. Larger particles have too much inertia to respond to all of the fluctuations of the flow and therefore disperse less. We can model this behavior[7] and estimate the average dispersion of our three particle sizes using the following:

$$\overline{y_2^2}(t) = 2\overline{u_f^2}T_f^2(1+St)\left\{\frac{t}{T_f(1+St)} - \left[1-e^{\frac{-t}{T_f(1+St)}}\right]\right\}$$

where the T_f is the integral scale of the fluid velocity, $\overline{u_f^2}$ is the mean squared fluid velocity, and St is the Stokes number.

By normalizing the DNS and QNS dispersion measurements by a characteristic length of particle fluctuations, $y^* = \overline{y_2^2}(t) / 2\overline{u_p^2}T_p^2$, and normalizing the time with T_p, we can collapse all runs onto a single curve as shown in Figure 7.[5] This is true regardless of Stokes number, flow conditions and measurement method. For our microgravity experiments then, after 10 seconds, particles with Stokes numbers of 0.1, 1, and 10 will have average displacements of 19.8, 19.6, and 17.8 cm respectively.

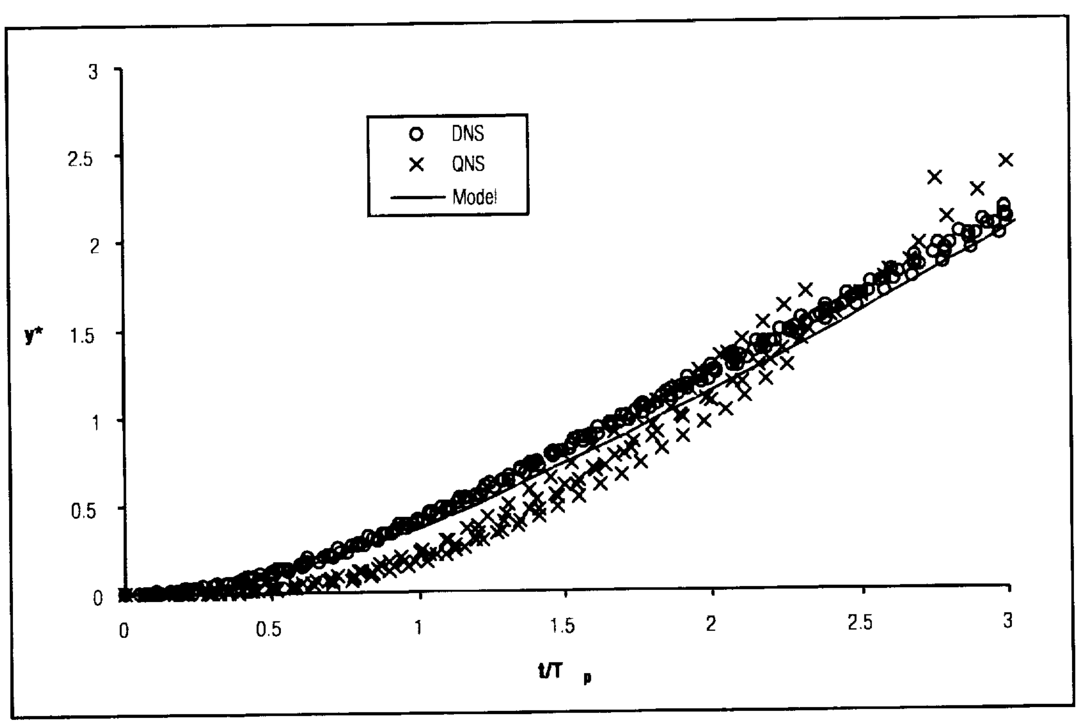

Figure 7. Particle Dispersion Comparison of DNS and QNS with the Model

CONCLUSION

Results from DNS and QNS show that particle dispersion decreases with increasing Stokes number as one might expect. In addition, for particles of constant Stokes number, greater turbulence results in more dispersion. These methods also verified the dispersion model.

Our next step is to examine the inertial effects on particle dispersion in the absence of gravity for a larger range of turbulence scales. Particles will be released inside an enclosed tank of grid-generated, isotropic turbulence while in NASA's KC-135 Reduced-Gravity Aircraft. In the 20 seconds of microgravity, we will track the dispersion of these particles, which range from 0.1 to 10 in Stokes number, using a three-dimensional stereo image velocimetry technique. Using a dispersion model verified by DNS and QNS results, we estimate that these particles will have an average dispersion of less than 20 cm. Removing the masking effects caused by gravity will allow us more insight into the role of inertia on particle dispersion.

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