SCALE-UP STUDY OF VISCOUS PARTICLE MOTION UNDER MICROGRAVITY CONDITIONS

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ABSTRACT

The viscous motion of spherical particles is studied using ground experiments. Experiments are designed to generate controlled motion of a light particle through a non-uniform flow field. The flow field is generated by a liquid filled, rotating horizontal cylinder. The cylinder is used to create an artificial microgravity environment which circumvents the effect of gravity. Flow characteristics are altered by means of the cylinder’s angular velocity and specific fluid/particle combinations. The configuration of this experiment enables particle motion to be studied for extended time periods, much like a microgravity environment. Experimental results are used in conjunction with analytical work to study lift forces induced by the non-uniformity of the flow.

INTRODUCTION

The study of spherical particle motion has implications in numerous fields of research. Droplet emission from sprays, particularly those involving fuel combustion or chemical application, is a field of ongoing research. Particle motion is relevant in studying the motion of aerosols, fluid markers, and laboratory grown crystals. Resulting from boiling or cavitation, bubble motion in liquids can be modelled as spherical particles depending on bubble composition. Particle motion research also has relevance in numerous other automotive, aerospace, power generation, and heating/cooling applications.

Unsteady particle motion was first studied separately by Boussinesq [2] and Basset [1], based upon the initial work of Stokes [7]. From these papers, Oseen [5] derived the equation for the gravitationally induced motion of a solid spherical particle in a quiescent fluid, known today as the BBO equation. In 1947, Tchen [8] extended the BBO equation to uniform, unsteady flow fields and in 1983, Maxey and Riley [4] further extended the equation to non-uniform and unsteady flows. Although all of these works were derived assuming negligible convective effects or more specifically, infinitesimal particle Reynolds numbers, many practical applications meet these requirements.

The majority of the research for low Reynolds number particle motion is currently done either analytically or numerically. As the Reynolds number approaches unity and beyond, research is usually carried out numerically due to the non-linearity of the governing equations. Due to the lack of effective experimental methods, experimental data in this field of research is minimal. Particle motion experiments are hindered primarily by the effect of gravity. As a result, a relatively heavy or light particle sustained in a fluid will migrate relative to the fluid, eventually reaching the boundaries of the fluid container. Therefore, experimental data is typically measurable only for short periods of time. A true microgravity environment would
eliminate the issue of gravity and produce accurate experimental data for any fluid/particle density ratio. This project deals with the design, construction, and execution of ground experiments to simulate a microgravity environment. Results will be compared to existing analytical and numerical solutions. Experimental data will aid in the design of actual microgravity experiments for future spaceflight missions, particularly fluid physics, biotechnical, and x-ray crystallography experiments subjected to the oscillatory environment of the International Space Station.

METHODOLOGY

Dimensional analysis or “scaling” is used to enable the translation of experimental results to different applications. Relative to most practical applications, the test particles used for the experiments will be large, hence the title “scale-up.” This method is analogous to the model/prototype relationship commonly used in aircraft design. Dimensional analysis shows the specific parameters that are relevant in order to correctly interpret the experimental data. Correct replication of the relevant parameters would give results for a scale model that are indicative of the prototype. These dimensionless parameters were found to be the Reynolds number, Strouhal number, and fluid/particle density ratio.

To study the transient motion of particles, an experimental setup was designed to subject a body of fluid to an unsteady environment. Test particles were placed in the unsteady fluid and their resulting motion was monitored. Two experiments were considered. The first involved the rectilinear acceleration of a fluid filled, transparent cell. The second experiment utilized a fluid filled, transparent cylinder which rotated horizontally along its axis. In both experiments, the particles are placed in the respective fluids and monitored visually with digital photography. The latter experimental setup was chosen for several reasons. The rotating cylinder was chosen primarily for its ability to closely simulate microgravity conditions. A radial pressure gradient exists as a result of cylinder rotation, effectively preventing a light/heavy particle from rising/sinking due to gravity. As a consequence, a particle less dense than the surrounding fluid would be driven toward the center of rotation due to the radial pressure gradient, which increases with cylinder rotation speed. The particle will hover near the axis of cylinder rotation due to the contribution of buoyancy, pressure, lift, and viscous drag forces. In the case of the linearly accelerated fluid cell, test particles would be tethered to counteract the effects of buoyancy.

Aside from the benefits regarding buoyancy forces, the rotating cylinder possesses other desirable attributes. The non-uniform flow field generated within the cylinder enables the study of particle lift forces resulting from particle rotation. In addition, low particle Reynolds numbers can be achieved with relatively low oscillation frequencies, eliminating the need for high speed digital photography. This experimental setup is similar to the rotating bioreactors used for tissue growth.

Equipment selection for the experiment started with mechanical components. Two cylinders (6 and 3.5 inch outside diameter) were constructed with transparent acrylic plastic to accommodate the fluids and particles. An aluminum flange and shaft was machined to provide a means of gripping and rotating the cylinder. The flange was held and rotated by a drill chuck mounted to a horizontally rotating axle, supported by a pair of ball bearing pillow blocks. Threaded rods formed the junction between the pillow blocks and the fixed, stainless steel mounting platform. The cylinder is kept horizontal by means of the threaded rod adjustments. Rotation is provided by a one-half horsepower, 90 volt DC motor and a 10 amp DC motor controller. Power from the motor is transferred by means of a belt and pulley system. The teeth on the belt and the pulleys insured no slippage occurred during cylinder rotation.
Particle motion was recorded using a digital video camera directed along the axis of cylinder rotation. Since particle motion was confined to the radial direction, measurements for particle motion in the axial direction were not necessary. A microscope was attached to the camera providing increased optical amplification for better resolution of small particle displacements. Digital pictures and video were sent to a computer for storage and analysis. The frame, motor, controller and camera are attached to the laboratory workbench and shown in Figure 1. The camera and microscope assembly along with the 3.5 inch cylinder is shown in Figure 2.

Test particles and fluids were selected to create the desired environments for studying particle motion. In order to take advantage of the radial pressure gradient generated by the rotating cylinder, it was imperative that the solid test particles be less dense than the test liquid. The selected particles were made of polystyrene with a weight density of 1.05 grams per milliliter, slightly denser than water. A suitable test fluid for the experiment required the fluid to be denser than the polystyrene particles. With the fluid/particle density ratio being one of the relevant parameters in the experiment, three fluids were chosen to create several variations of this ratio. Although the fluid/particle density ratio could also be varied using particles of different densities, very few non-porous solids have a density significantly less than polystyrene and the use of a denser particle would eliminate many suitable liquids from consideration. Therefore, the fluids chosen were LST Heavy Liquid, Dupont Krytox, and a glycerin and water solution. These liquids have weight densities of 2.85, 1.90, and 1.10 grams per milliliter respectively.

RESULTS AND DISCUSSION

Analytical work was performed in conjunction with experimental work to determine the feasibility of the experiments, and also to enable an accurate interpretation of the experimental data (see, e.g. Coimbra and Kobayashi). Utilizing a force balance on the particle, a particle equation of motion was derived including the effects of particle inertia, virtual mass, steady and history drag, as well as steady and history lift. The steady drag and lift forces refer to work
Figure 2: The camera and microscope arrangement for measurements from the 3.5 inch cylinder.

done by Stokes [7] and Saffman [6]. The two history forces take into consideration the effect of prior particle movement with a decreasing emphasis attributed to the more distant past. The resulting integro-differential equation indicated that a light particle subjected to a horizontally rotating flow would eventually settle to a specific equilibrium position.

The equilibrium particle position was determined by studying the dimensionless form of the particle motion equation. Particle radius is represented by \( a \), fluid/particle density ratio by \( \alpha \), and fluid kinematic viscosity by \( \nu \). To simplify the notation, the quantity \( k \) is defined as \( 2/(2+\alpha) \) and a particle characteristic time scale \( \tau_p \) is defined as \( 2a^2/9\alpha\nu \). Using these definitions, length is scaled with \( a \), time is scaled with \( \tau_p \), and velocity is scaled with \( a/\tau_p \). As time increases, all differential terms of the particle momentum equation become negligible, resulting in the consideration of only steady drag, steady lift, and gravity forces. These terms dictate the particle’s equilibrium position. With the origin taken at the axis of rotation, the particle’s equilibrium position in Cartesian coordinates is given by [3] to be equal to the following.

\[
\begin{align*}
x_{\text{equil}} &= \frac{(1 - \alpha) \tau_p^2 \rho g}{\omega a \left[ 1 + \omega^2 (2C_L - 3h)^2 \right]} \\
y_{\text{equil}} &= \frac{(2C_L - 3h) (1 - \alpha) \tau_p^2 \rho g}{a \left[ 1 + \omega^2 (2C_L - 3h)^2 \right]}
\end{align*}
\]

In equations (1) and (2), \( h = \alpha/(2 + \alpha) \), \( g \) is the magnitude of the gravitational acceleration, and \( \omega \) is a dimensionless angular velocity equal to \( \Omega \tau_p \), where \( \Omega \) is the magnitude of the cylinder angular velocity. \( C_L \) is defined as \( C_S \sqrt{h}/2\pi \sqrt{2\omega} \), where \( C_S \) is the Saffman [6] lift coefficient equivalent to \( 6.46 \).

Several observations can be made from studying equations (1) and (2) qualitatively. The \( x \)-equilibrium position will be always positive or always negative depending on the direction of cylinder rotation. Unlike equation (1), equation (2) indicates that cylinder rotation plays no role in determining whether equilibrium point lies above or below the \( x \)-axis. Instead, the quantity \( 2C_L - 3h \) determines the location of the \( y \)-equilibrium position. More specifically,
Figure 3: Experiments showed particle behavior in response to increases in $\alpha$ and $\Omega$. The observed particle displacements are exaggerated for clarity.

the particle will settle to a location above or below the horizontal center plane depending on whether $2C_L$ is larger or smaller than $3h$. If lift were neglected altogether, or if $C_L < 1.5h$, the particle will settle above the horizontal plane and approach $y = 0$ as rotation speed increases.

Experiments were performed using various sizes of polystyrene particles together with each of the test fluids. With particle motion concentrated near the cylinder axis, the 3.5 inch cylinder provided an adequate environment and required a smaller volume of test fluid. For use in numerical calculations, the fluid and particle density along with the fluid viscosity was measured. Digital images were taken for each fluid and particle combination at various angular velocities. The images were used to study the particle response to changing input parameters. A summary of the results is shown in Figure 3.

The results indicated that for a given angular velocity, increasing fluid/particle density ratios resulted in the particle settling to a position nearer to the axis of rotation. This phenomenon was attributed to the radial pressure gradient. For all tests, the particle assumed an x-equilibrium position according to the direction of cylinder rotation, and approached the axis of rotation with increasing rotation speeds. In the y-direction, experimental results indicated the particle settled to an equilibrium position always below the axis of rotation. A comparison with the analytical work concluded that the quantity $(2C_L - 3h)$ was always positive, or that $C_L > 1.5h$. This result shows the presence of lift and indicates that for non-uniform flows, lift forces are important in deriving the particle motion equation.

CONCLUSION

Laboratory experiments were used to study viscous particle motion at low and moderate Reynolds numbers. Particle motion was generated and studied in a fluid filled, horizontal rotating cylinder. Flow characteristics are varied by using different combinations of fluids, particles, and rotation speeds. Digital photography was used to determine the particle positions under various flow conditions. Due to the non-uniformity of the flow field, lift effects were included in the analysis. This work indicated the existence of an equilibrium particle position for a light particle, and the parameters which affect this position.
REFERENCES


