Investigation of the Influence of Microgravity on Transport Mechanisms in a Virtual Spaceflight Chamber-A Flight Definition Program

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BACKGROUND AND INTRODUCTION

A need exists for understanding precisely how particles move and interact in a fluid in the absence of gravity. Such understanding is required, for example, for modeling and predicting crystal growth in space where crystals grow from solution around nucleation sites as well as for any study of particles or bubbles in liquids or in experiments where particles are used as tracers for mapping microconvection. We have produced an exact solution to the general equation of motion of particles at extremely low Reynolds number in microgravity that covers a wide range of interesting conditions[1,2]. We have also developed diagnostic tools and experimental techniques to test the validity of the general equation[3]. This program, which started in May, 1998, will produce the flight definition for an experiment in a microgravity environment of space to validate the theoretical model. We will design an experiment with the help of the theoretical model that is optimized for testing the model, measuring g, g-jitter, and other microgravity phenomena. This paper describes the goals, rational, and approach for the flight definition program.

Objective

The first objective of this research is to understand the physics of particle interactions with fluids and other particles in low Reynolds number flows in microgravity. Secondary objectives are to (1) observe and quantify g-jitter effects and microconvection on particles in fluids, (2) validate an exact solution to the general equation of motion of a particle in a fluid, and (3) to characterize the ability of isolation tables to isolate experiments containing particle in liquids. The objectives will be achieved by recording a large number of holograms of particle fields in microgravity under controlled conditions, extracting the precise three-dimensional position of all of the particles as a function of time and examining the effects of all parameters on the motion of the particles. The feasibility for achieving these results has already been established in the ongoing ground-based NRA, which led to the "virtual spaceflight chamber" concept[4].

Tasks

The program objective will be met through the following tasks:

1. Apply and Refine the theoretical analysis to help specify the flight experiment matrix.
2. Conduct computer experiments to assist with the hardware design.
3. Collect and analyze additional data from the IML-1 holograms.
4. Produce a preliminary experiment design
5. Specify the required measurement capability.
6. Breadboard and test the experiment.
7. Perform ground feasibility demonstration.
8. Specify requirements of a flight package:
9. Conduct reviews
   a) Science Requirements Document (SRD).
   b) Science Concept Review (SCR).
   c) Requirements Definition Review (RDR).

Particle Mechanics in Microgravity

Traditionally, the study of particle motion in a fluid has considered the effect of drag and gravity.[5] The effect of drag has usually been accounted for with correlations for the drag coefficient based on the Stokes drag, corrected for higher Reynolds number effects. This approach can be shown to be approximately valid when the particles are much heavier than the displaced fluid and when the unsteadiness of the flow field is much slower than the characteristic time for steady development of the fluid layer adjacent to the particle.

More advanced investigations of the particle behavior have included additional terms in the particle equation of motion, resulting in the BBO (Basset-Bousinesq-Oseen) equation. Except for the case of particles settling in an undisturbed flow, all solutions of the more complete particle momentum equation in the Stokes regime have resorted to numerical integration of the equation. Because the numerical solution is involved, many investigations have preferred to neglect some of the more troublesome terms in the equation, even in situations where this is not justifiable.

Theoretical analysis

Recently Coimbra and Rangel have shown that an analytical solution of the complete particle momentum equation is possible. Because it is an analytical solution, it is many times more powerful than a typical numerical solution, it is easier to implement in a general fluid flow, and furthermore, the effect of the various terms in the original equation can be readily identified in the solution. A very well controlled experiment is essential to test the validity of any solution. Because the equation is valid in the Stokes regime (small Reynolds number), a microgravity environment is crucial to investigate wide ranges of particle/fluid density ratios. In a 1-g environment, heavy particles would tend to rapidly accelerate to higher Reynolds numbers, unless the particles are too small. The same thing would occur for very light particles (bubbles). Microgravity allows for a more controlled experiment. Desirable experiments would consider particles of at least two different sizes and fluids of two different viscosities. It would be important to consider isolated particles as well as interacting particles. The fluid motion must be very carefully controlled. Examples of controlled motions would be impulsive acceleration, constant acceleration, and oscillatory motion. It would be important to measure any residual gravity.

In normal gravity, viscous and gravitational forces almost always dominate the motion of a sphere. In microgravity, many common cases exist in which normally negligible terms in the equation of motion become important.[6] A complete understanding of the equations allows us to understand the motion of particles in a fluid as well as to choose experimental parameters in a new experiment to advantage, leading to special cases of the equations that will govern the design of the experiment.

COIMBRA-RANGEL SOLUTION TO THE MAXEY RILEY EQUATION OF MOTION OF A PARTICLE IN A FLUID[7]

Equation of motion for particles subjected to unsteady creeping flows

The creeping flow motion of small particles in a viscous fluid is described by the following well-known dimensionless equation (Maxey and Riley, 1983):[8]

$$\frac{dV_i}{dt} = \alpha\frac{DU_i}{Dt} - \alpha\frac{d(V_i - U_i)}{2dt} - (V_i - U_i)$$
$$+ (1-\alpha)\frac{\tau g_i}{U_o} - \sqrt{\frac{9\alpha}{2\pi}}\left\{\int_0^t \frac{d(V_i - U_i)}{d\sigma}\frac{d\sigma}{\sqrt{t-\sigma}} - \frac{V_i(0) - U_i(0)}{\sqrt{t}}\right\}. \tag{1}$$

In Equation (1), α is the fluid-to-particle density ratio, g_i is the acceleration of gravity, and V_i and U_i are the particle and fluid velocity, respectively. The dimensionless times t and σ were nondimensionalized by the particle's relaxation time $2a^2\rho_p/(9\mu)$, the velocities by the characteristic flow velocity U_o, and the coordinates and particle radius by the characteristic length of the flow L. Equation (1) is valid for low particle Reynolds numbers $(a|V_i - U_i|/\nu)$ and for low dimensionless number $a^2\,U_o/L\,\nu$. The particles are assumed to be small in comparison to the integral length scale of the flow, which means that the Faxen correction is negligible, thus not being included in Equation (1).[9]

Defining ϕ_i as the differential velocity $V_i - U_i$, and approximating the substantial derivative following a fluid particle (D/Dt) in the right-hand-side of Equation (1) as a time derivative along the particle's trajectory (d/dt), Eqn. (1) can be rewritten as

$$\frac{d\phi_i}{dt} = (\alpha - 1)\frac{dU_i}{dt} - \alpha\frac{d\phi_i}{2dt} - \phi_i - \sqrt{\frac{9\alpha}{2\pi}}\left\{\int_0^t \frac{d\phi_i}{d\sigma}\frac{d\sigma}{\sqrt{t-\sigma}} - \frac{\phi_i(0)}{\sqrt{t}}\right\} + (1-\alpha)\frac{\tau g_i}{U_o}. \tag{2}$$

Using fractional derivatives Coimbra and Rangel have produced an exact analytical solution to the Maxey-Riley form of the equation of motion.

Important solutions for different prescribed flow fields $U(t)$ presented in reference 23 include:

1. Gravitationally induced motion in a quiescent fluid.
2. Impulsive start at zero gravity.
3. Impulsive start in a gravity field.
4. Unperturbed fluid velocity increasing linearly in time.
5. Unperturbed fluid velocity varying as polynomial in time.
6. Unperturbed fluid velocity varying harmonically in time.

All of these cases are of great importance in spaceflight experiments.

Gravitationally induced motion in a quiescent fluid

The Coimbra-Rangel solution of the Maxey-Riley equation was used to predict the velocity and displacement for this specific case; producing solutions that can be compared with less general solutions that predict this particular case. The following figures show the preliminary results.

Figure 1 shows the behavior of the dimensionless velocities for five different values of the fluid-to-particle density ratio α. The solutions are shown for values of α equal to 100, 5, 8/5 (critical value for the general solution), 1/5, and 1/100. The particle's velocity is normalized by its own terminal velocity.

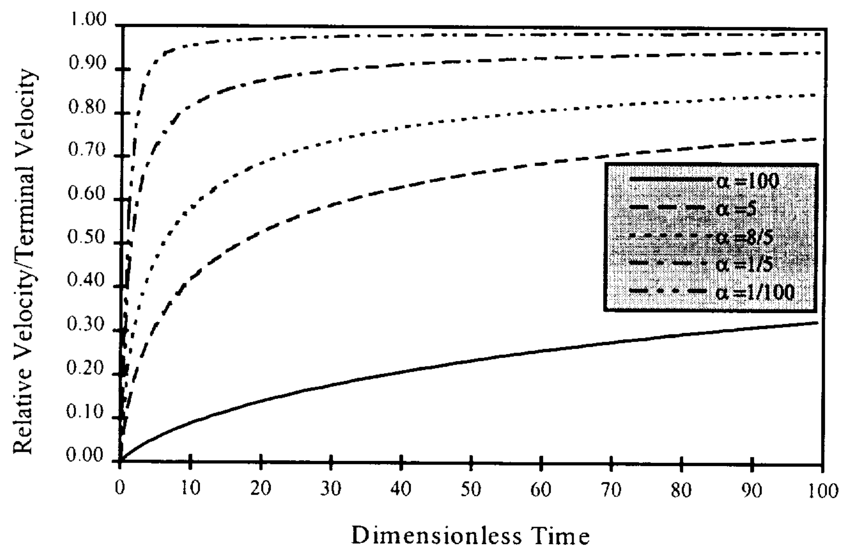

Figure 1. Exact solution for the normalized particle velocity in gravitationally induced motion through a quiescent viscous fluid.

Figure 2 shows a comparison of the Coimbra-Rangel solutions of Eqn. (1) with the solutions found when the last term (the *history term*) in the right-hand-side of Eqn. (1) is neglected. This approximation is made often because of the difficulties that arise from the inclusion of this term. As can be inferred from **Figure 2**, the approximation turns out to be a crude one unless the fluid-to-particle density ratio approaches zero.

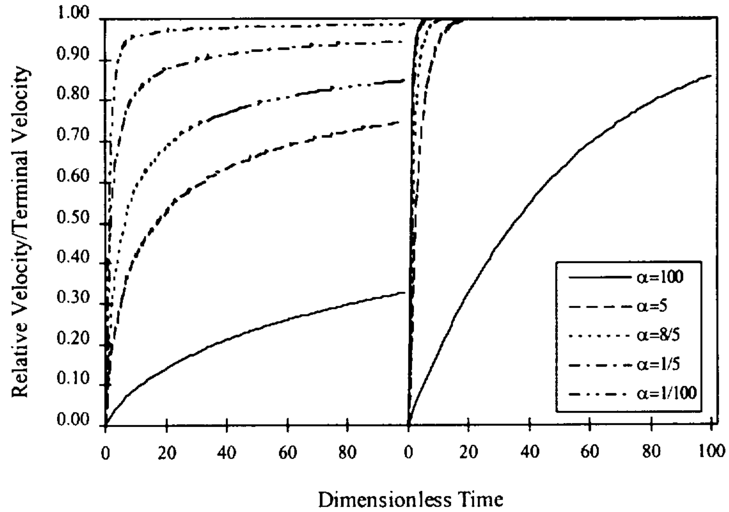

Figure 2. Comparison of exact solutions given by Equations 14, 15, and 16 (left) with solutions for the momentum equation neglecting the history term contribution (right).

Particle displacement with time for all density ratios except for the one corresponding to a very light particle, approach the near-linear behavior that is expected by particles that attain terminal velocity very soon after being released when the history term is neglected. On the other hand, when history effects are considered, the displacements diverge from the linear behavior except for the much heavier particle. This striking difference in behavior indicates that the history term should be considered in any situation departing from a value of α which is much smaller than one. The error in not considering the history effects is even more drastic when the unperturbed flow field varies with time since, in the general case, the memory effects do not decay in time as in the present case.

FLIGHT EXPERIMENT DESIGN

Since the feasibility of this experiment has already been established, one of the first milestones will be the design of a cost efficient flight experiment that will: 1) monitor and quantify the microgravity environment, 2) monitor the precise position of the particles in a distribution in a fluid, and 3) integrate the experiment with an isolation table so that a controlled force field can be applied to the particle distribution. The force field will include at least the following:

- No isolation in the Spacelab vibration environment.
- Isolation from Spacelab.
- Oscillatory motion from 1 to 10 Hz with amplitudes of a few millimeters.
- Programmed forcing functions such as steps and ramps to be determined.
- Convective fields to be introduced mechanically.

A small, windowed chamber will house the fluid and particles. The particles will include several sizes and weights, chosen in such a manner that different weights will be identifiable in the data. A holographic time history will be produced of the particle distribution, allowing particles to be precisely tracked in three dimensions in time.

Figure 3 illustrates the instrument concept, which is based upon simplicity and reliability. A laser diode will produce diverging light that illuminates one or more chambers after collimation. As the light passes through the chamber, it will pick up particle and crystal profile information and in-line holograms will be recorded on 35 mm film. Since the system is compact, two or more cells can be operated in a shoebox-sized container. By employing more than one cell, crystals can be released into the solutions at different times or, alternatively, different types of materials can be grown at the same time, comparing the influences of microgravity on two types of material.

In our previous work, we have shown that the edge of a particle or object can be located with an accuracy of better than 2 micrometers. This will be over an order-of-magnitude improvement above our work in the IML-1 spaceflight. This ability will allow the particle position to be precisely tracked, thus permitting the detection of very small motions.

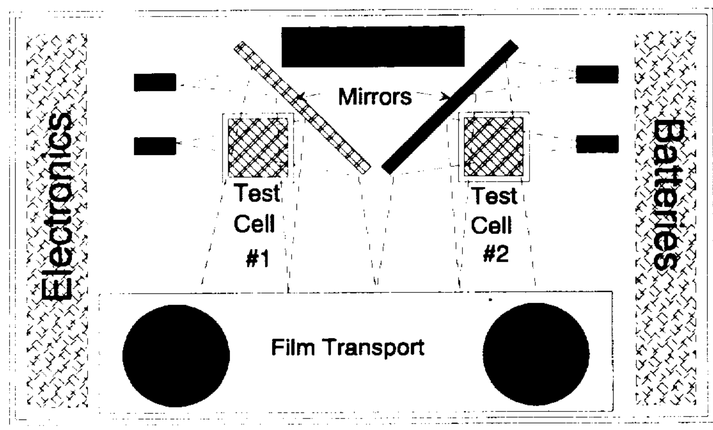

Figure 3. Flight system.

Preliminary In-line holography experiments

We have conducted preliminary experiments to select optimal components and configurations for an inline holocamera for the space flight particle tracking system. The approach was to set up a generic in-line holocamera using dimensions similar to what is anticipated in the space flight system and perform comparison experiments using the candidate components and configurations. We selected several slide mounted particle sizes for hologram evaluation (e.g. 10-100 micron diameter). Preliminary experiments suggest that diode lasers will be adequate for recording (**Figure 4**).

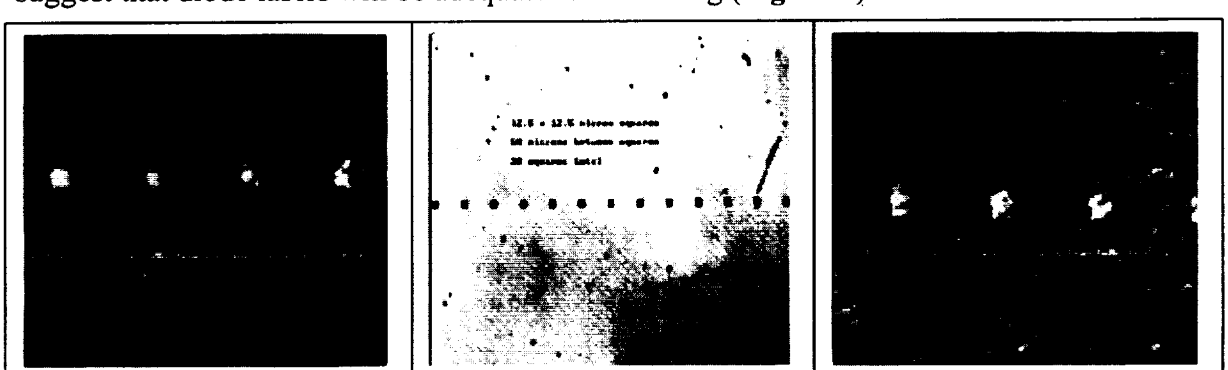

Figure 4: Comparison of Original image (center) with laser diode holographically recorded and reconstructed image (left) and HeNe laser recorded and reconstructed image (right). Particle size is 12.5 microns. Diverging wave used to record and reconstruct.

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