

CHARACTERIZATION OF PARTICLE MOTION IN A MICROGRAVITY SIMULATOR FOR BIOMEDICAL APPLICATIONS

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ABSTRACT

This project is dedicated to the experimental verification of the theoretical model of motion of non-neutrally buoyant particles in a rotating cylinder filled with a Newtonian fluid. This model can be used to describe the mechanics of three-dimensional bodies, moving through a viscous fluid in rotary wall vessel (RWV) bioreactor, which simulates microgravity conditions. Under microgravity conditions cells and biological tissue develop three-dimensionally due to the reduced effect of gravity. This 3-dimensional growth has important implications in many areas of biomedical research. The experimental setup used in the project consisted of a buoyant particle in a mixture of glycerin and water in an aluminum cylinder with a plexiglass face for optical access. The cylinder rotated on its horizontal axis, similar to a bioreactor, and the motion of the particle was photographed at three rotational frequencies with a high-speed digital camera. The photographs were then analyzed, and the data treated with T-statistics. The data then was compared with the predicted motion of suspended particles by the theoretical model, which predicts that the equilibrium orbit of the particle is to the left of the center of rotation. It was found to follow the same trend as the model, but with an average 14% difference due to misalignment of the camera.

INTRODUCTION

Characterization of the motion of particles within a microgravity simulator has applications not only for space science, but biomedical science as well. Previous experiments have shown that tissue cultured under simulated microgravity conditions develops and resembles more closely tissue that is grown in the body (Freed et al, 1997; Freed et al 1999). This is a result of the tissue's ability to grow and differentiate in three dimensions due to the reduced effect of gravity. This three-dimensional growth has important implications for research in areas such as tissue replacement, cancer treatment, and bio-product production as researchers are now able to observe how cells interact and differentiate, and how tissue develops under microgravity conditions. Research is also being done on various tissues and cells to determine the effects of microgravity on cellular function (Cooper et al, 2001; Savery et al, 2001; Sytkowski & Davis, 2001) in order to better understand the long-term effects of space travel on the human and animal body.

Microgravity can be simulated on the ground with the use of a rotating wall vessel (RWV) bioreactor originally developed by NASA scientists. The RWV bioreactor consists of a cylinder that rotates on its horizontal axis with a coaxial membrane centered at the axis to allow for

exchange of oxygen and nutrients, and removal of waste. Cells and tissue maintain an orbit within the fluid away from the external walls of the cylinder due to the balance between centripetal and gravitational forces. A model of the motion of non-neutrally buoyant particles within a rotating vessel filled with a Newtonian fluid, which is similar to the flow conditions experienced by cells in a RWV bioreactor, has been developed (Coimbra & Kobayashi, 2002). This model is useful as it will allow for more accurate timing of the rotation of the cylinder and better positioning of the tissue within the cylinder.

The position of the orbit of the particle varies depending on flow direction and particle density, and is not in the center of the cylinder. For small particle Reynolds numbers given by $Re_p = \alpha W_o / \nu$, and small shear Reynolds numbers given by $Re_s = a^2 \Omega / \nu$, and $Re_p \leq Re_s$, the Cartesian coordinates for the equilibrium position of a particle is given by:

$$x_{eq} = \frac{-Re_p}{Re_s \left[1 + \left(\varepsilon_L^{NL} |Re_s|^{1/2} - \frac{Re_s}{3} \right)^2 \right]} \quad (1)$$

$$y_{eq} = \frac{-Re_p \left(\varepsilon_L^{NL} |Re_s|^{1/2} - \frac{Re_s}{3} \right)}{Re_s \left[1 + \left(\varepsilon_L^{NL} |Re_s|^{1/2} - \frac{Re_s}{3} \right)^2 \right]} \quad (2)$$

where $\varepsilon_L^{NL} = 3J(\varepsilon)Re_s / \pi^2 \sqrt{2} |Re_s|$ (Coimbra & Kobayshi, 2002), and $J(\varepsilon)$ is defined as $J(\varepsilon) = 2.255 - 0.6463/\varepsilon^2$, with $\varepsilon \equiv Re_s^{1/2} / Re_p$ (McLaughlin, 1991). These equations predict that the location of the particle will be to the left and below the center of rotation of the cylinder for $Re_p \leq Re_s$. The aim of this project was to experimentally verify the x-equilibrium position of the particle as predicted by the model, using a setup similar to that of the RWV bioreactor, and a high-speed digital photography system.

MATERIALS AND METHODOLOGY

The experimental setup, depicted in Figure 1, consisted of an aluminum cylinder with a plexiglass cover that was connected to a motor-pulley system which rotated the cylinder on its horizontal axis. Aluminum was chosen so that the cylinder would be more rigid during rotation. The cylinder then was filled with a mixture of glycerin and water, and a polystyrene particle of 1.6 mm radius was added. Before connecting the cylinder to the motor setup, all air bubbles were removed to minimize the disturbance of the particle equilibrium position and to obtain better imaging of the particle. The glycerin-water mixture and particle were both chosen to result in $Re_p < 1$. A 12-megapixel digital camera with a microscopic lens was placed in front of the plexiglass face, aligned as close as possible to the center of rotation of the cylinder. The alignment of the camera was aided by a light source made up of two small beams that crossed at the center of the cylinder. The rotation of the cylinder was then varied three times in order to

achieve three different values of Re_s that would be within the range of $0.1 \leq Re_s \leq 1.0$. Photographs were taken at each rotational frequency once the particle settled to a stable position.

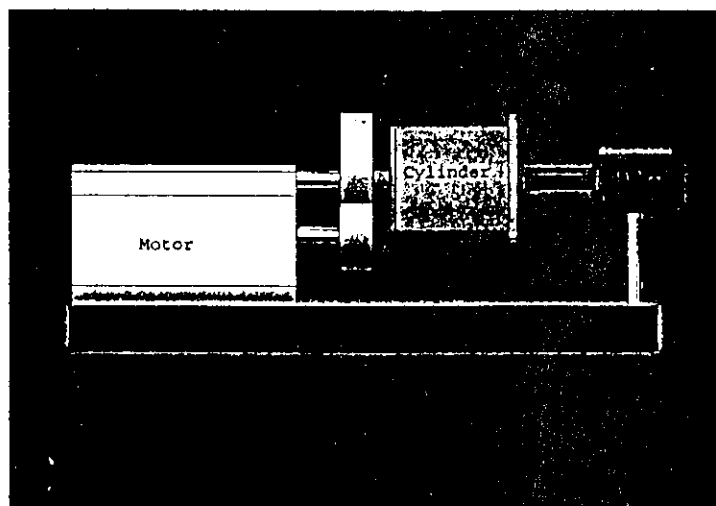


Figure 1: A basic drawing of the experimental setup.

The photographs were analyzed using Adobe Photoshop, which displays the number of pixels and allows for distances to be determined by pixel location. The number of pixels can be correlated to actual distance since the number of pixels that makes up the particle, and the particle radius are known. The center of the cylinder was assumed to be the center of the photograph and was identified first. The radius of the particle was determined and from that the location of the center of the particle was found. The distance of the center of the particle from the y-axis then was determined by counting the number of pixels. The particle x distance was non-dimensionalized with the particle radius and plotted versus the corresponding Re_s . The theoretical model was also plotted for comparison. All data was analyzed using T-statistics.

RESULTS

The results of the data analysis are plotted in Figure 2. For a Re_s of approximately 0.7, $x_{eq}/radius$ was about 0.03, which is to the right of the center, and is a difference 16% of the particle radius, as compared to the theoretical. For Re_s of approximately 0.4, $x_{eq}/radius$ was about -0.06, which is also a difference 16%, and for Re_s of approximately 0.1, $x_{eq}/radius$ was about -0.6, which is a difference of 10%. Both are located to the left of the center. The average of the differences was 14%.

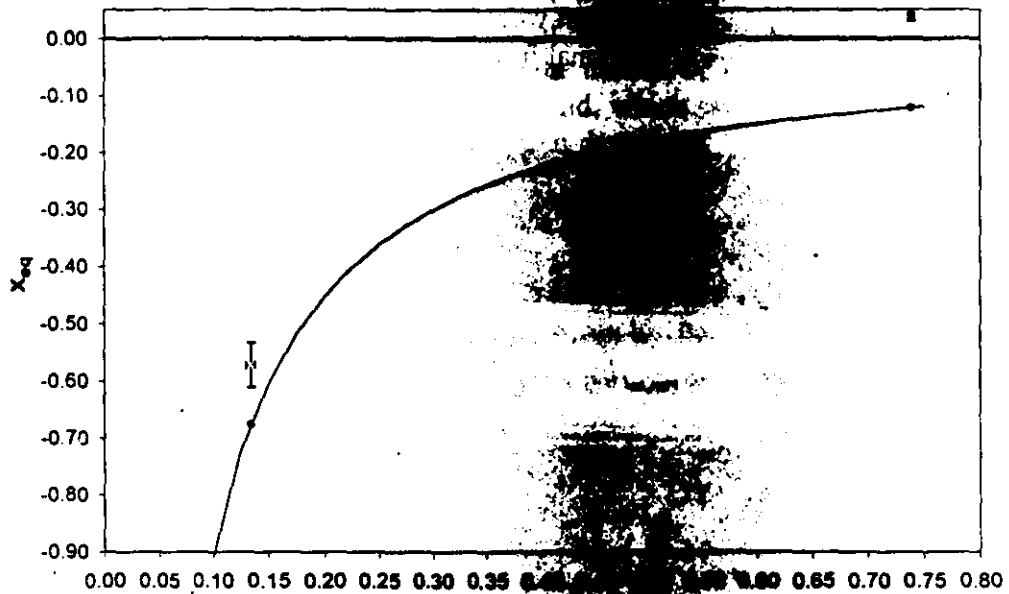


Figure 2: Plot of $x_{eq}/radius$ versus Re_s for the experimental data and the theoretical model.

DISCUSSION

The data for Re_s of 0.4 and 0.1 both showed that the particle was located to the left of the center of the cylinder, which is predicted by the model. For Re_s of 0.7 the particle was found to be located very slightly to the right of the center. However, this can be explained by the fact that the camera was probably not thoroughly aligned with the center of the cylinder. This would also account for the bias error that can be seen in Figure 2. The experimental data points are all shifted approximately the same amount above the theoretical graph. However, the trend of the experimental data matches that of the theoretical model, so if the data points were to be shifted down by the same amount, they would match the line of the theoretical graph.

Although there is a definite bias error due to the misalignment of the camera, the experiment is very repeatable as demonstrated by the small error bars of the data points shown in Figure 2. These errors are attributed to the estimation of the radius of the particle from the photographs. The particles were not fully steady and this causes the circumference of the particle to be slightly blurry. However, the estimation of the particle size would differ only in the range of a few pixels, which is of the order of a few micrometers. The error can also be attributed to the fact that the particle moves in the lateral (z) direction as the rotation of the cylinder is changed. This would cause a small change in the apparent size of the particle as the particle would appear slightly bigger as it moved a little closer to the plexiglass face of the cylinder.

A qualitative comparison of the photographs also shows that the particle's equilibrium position is to the left of the center of rotation. The model also predicts that at lower Re_s , the distance of the particle equilibrium position from the center of rotation increases and should more clearly be seen. This is shown in Figure 3.

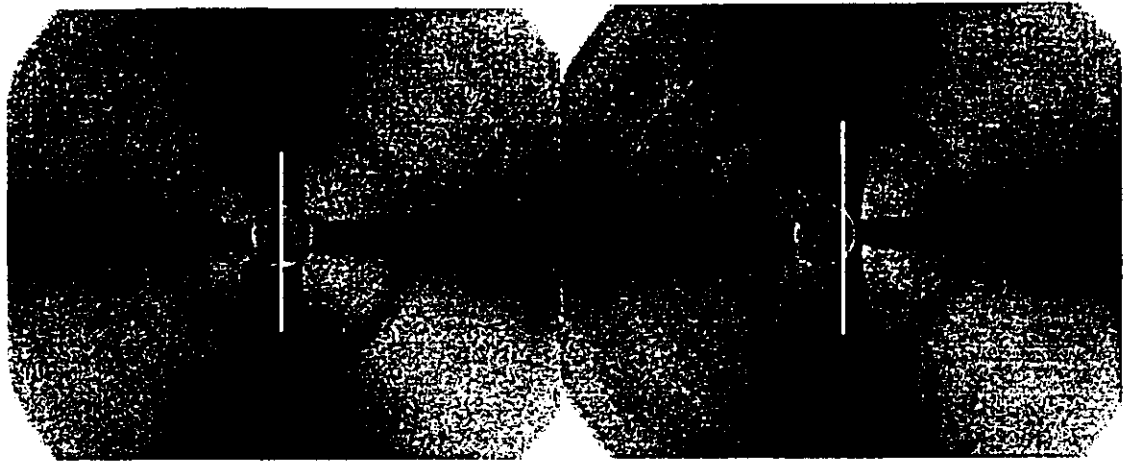


Figure 3: Two photographs of the particle with the center of the cylinder marked. The photograph on the left is for Re_s of 0.7, and the photograph on the right is for Re_s of 0.1.

CONCLUSION

Despite the bias error, the experimental data shows that the equilibrium position of the particle is located to the left of the center of rotation of the cylinder, which is in concurrence with the theoretical model. The bias error of the experiment can be reduced by proper alignment of the camera with the center of the cylinder. Future improvements for this project include the changing of the setup so that the cylinder would be able to be rotated at lower speeds. Also, in order to fully verify the theoretical model, the y equilibrium position predicted by the model must also experimentally determined. However, this distance is much smaller compared to the x -equilibrium position, which makes it harder to verify. This can be accomplished by changing the flow parameters so that the equilibrium position is maximized. This will be the next goal of the project.

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REFERENCES

- Coimbra CFM, and Kobayashi M.H. (2002). On the sedimentation of a Small Particle in a Rotating Cylinder *J. Fluid Mech.* (in press).
- Cooper D.; Pride M.W.; Brown E.L.; Risin D.; Pellis N.R. (2001) Suppression of antigen-specific lymphocyte activation in modeled microgravity. *In Vitro Cell Dev Biol. Anim.* 37 (2), 63-65.
- Freed L.E., Langer R., Martin I., Pellis N. R., Vunjak-Novakovic G. (1997) Tissue engineering of cartilage in space. *Proc. Natl. Acad. Sci. USA* 94, 13889-13890
- Freed L.E., Pellis N., Searby N., de Luis J., Preda C., Vunjak-Novakovic G. (1999) Microgravity cultivation of cells and tissue. *Genet. Eng. Biotechnol. Bio. Bull.* 12(2), 57-66.
- McLaughlin J.B. (1991) Inertial migration of a small sphere in linear shear flows. *J. Fluid Mech.* 224, 261-274.
- Savary C.A.; Graziuti M.L.; Przepiorka D.; Tomasovic M.; McIntyre B.W.; Woodside D.G.; Pellis N.R.; Pierson D.L.; Rex J.H. (2001) Characterization of human dendritic cells generated in a microgravity analog culture system. *In Vitro Cell Dev. Biol. Anim.* 37 (4), 216-22.
- Sytkowski A.J. and Davis K.L. (2001) Erythroid cell differentiation in vitro in the simulated microgravity environment of the NASA 1.5g wall vessel bioreactor. *In Vitro Cell Dev. Biol. Anim.* 37 (2), 79-83.