PI Data Update Form
Final Report (3/00–11/04)
Microgravity Research Division

PIs Last Name	Yoda
First Name	Minami
Middle Initial	
Prefix	Dr.
Suffix	
Affiliation	Georgia Institute of Technology

Phone: (404) 894-6838 **Fax:** (404) 894-8496

Email: minami.yoda@me.gatech.edu

Address:

School of Mechanical Engineering
Georgia Institute of Technology
771 Ferst Dr., NW
Atlanta, GA 30332-0405

Task Research Title

Novel Optical Diagnostic Techniques for Studying Particle Contact and Deposition Upon a Large Cylinder in a Sheared Suspension

Monitoring Center	GRC		NAG3-2373
Research Type	Ground	*Discipline*	Fluid Physics
Initiation Date		*Expiration Date*	

Degree	Students	Degrees
BS		
MS	2	2
PhD	1	1
Totals	**3**	**3**

Co-Investigator Name	Co-Investigator Affiliation
1.	
2.	
3.	
4.	
5.	
6.	

Task Monitor: Nasser Rashidnia Phone: 216-433-3622
Task Monitor email: nasser.rashidnia@grc.nasa.gov

Impact on America

Industrial Affiliates
Please list any industry research contacts you may have

Who is using the results of your research?

Have you developed any innovative technologies, and if so, what are they?

Where have your recent graduate students found employment?
Of the three graduate students who were funded by this grant, Dr. Claudia Zettner iscurrently employed by ExxonMobil Upstream Research Corporation (Houston, TX), and Mr. Brent Bailey is employed by McKenneys Inc. (Atlanta, GA). Mr. Ulf Andresen has completed his Master's degree, and is pursuing a doctorate with another research advisor in Mechanical Engineering at Georgia Tech.

Acronyms(Please list and define any acronyms associated with your project)

Project Objective

The objectives of this research project were:

1) To study the fluid dynamics of sheared particle-liquid suspensions and the impact of differential particle-fluid inertia
2) To develop new techniques for observing suspension particle contact and deposition upon solid surfaces.

Project Description

Dr. Yoda was supported by the NASA Office of Biological and Physical Research on a four-year grant from March 2000 through November 2004 for a ground-based study on the fluid dynamics of sheared particle-liquid suspensions and the impact of differential particle-fluid inertia on such flows. Such inertial effects can only be observed in reduced-gravity environments since they are overwhelmed by buoyancy effects on Earth. Moreover, these inertial effects will have a significant impact upon suspension flows in microgravity. Suspension dynamics are of importance in a wide variety of advanced life systems applications, including water reclamation and dust mitigation in confined habitats.

Project Significance

This study establishes the experimental methodology and techniques required to carry out micro- or reduced-gravity experiments on the impact of differential particle-fluid inertia on particle-fluid interactions and suspension flows. These effects can only be observed in reduced-gravity environments since they are overwhelmed by buoyancy effects on Earth. Moreover, these inertial effects will have a significant impact upon suspension flows in microgravity. Suspension dynamics are of importance in a wide variety of advanced life systems applications, including water reclamation and dust mitigation in confined habitats.

Project Accomplishments

A new aqueous low-viscosity (viscosity $\mu = 5$ cP) refractive index- and density-matched suspension has been developed consisting of non-colloidal polymethyl methacrylate (PMMA) particles suspended in a ternary mixture of water, glycerin and ammonium thiocyanate.[1] The maximum transmission through this suspension T (defined as the ratio of the illumination power transmitted through 1 cm of suspension to that transmitted through 1 cm of the suspending liquid) for a volume fraction $\phi = 10\%$ of particles with radii $a \approx 50$ μm is about 60% at 22.5°C for illumination at 488 nm. Comparisons with an organic solvent-based suspension system consisting of PMMA particles suspended in a ternary mixture of UCON oil, Triton-X and dibromohexane used for laser-Doppler velocimetry studies[2] show that this suspension system has comparable or slightly better transmission characteristics. Given its relatively nontoxic nature and low viscosity, this suspension system will be useful for a variety of suspension mechanics experiments.

The dynamics of neutrally buoyant prolate and oblate spheroids immersed in a simply sheared liquid were studied using a plane Couette channel as a simple three-dimensional model of suspended particle dynamics in a dilute suspension (*i.e.*, in the absence of particle-particle interactions). Recent two-dimensional numerical studies using the lattice-Boltzmann technique have suggested that these bodies, when constrained to rotate about one of their principal axes, undergo a rotation transition from a time-periodic to a stationary state above a critical shear-based Reynolds number and that this transition is independent of particle shape except for a sphere in simple shear flow.[3] More recent three-dimensional lattice-Boltzmann simulations suggest, however, that the dynamics of neutrally buoyant spheroidal particles in (plane) Couette flow—when free to rotate about any axis—are more complex, with prolate spheroids undergoing two rotation transitions and nutation between these transitions, while oblate spheroids undergo only one rotation transition.[4] These new results demonstrate that the classical problem of a sphere in simple shear flow is actually a special case that cannot be generalized to other particle shapes, and that even slight deviations from sphericity due to surface roughness (for example) may have a significant impact on suspension particle dynamics.

A plane Couette flow facility based upon a previous design[5], was designed and built to study cylinders and spheroids in simply sheared single-phase liquids and suspension flows. The facility, which is compatible with the new aqueous, density- and refractive index-matched suspension system, consists of an endless belt stretched over two large rollers immersed in the working fluid; the belt is then driven by a 90V ¼ hp DC motor. The flow coordinate system is defined with x along the flow direction, y along the velocity gradient direction, and z along the vorticity direction. The test section half-width (*i.e.*, y-dimension) h = 1.27 cm; the test section length) and depth (*i.e.*, x- and z-dimensions, respectively) were 20 cm and 16 cm, respectively. The linearity and steadiness of the simple shear flow the test section were characterized using both single-component laser-Doppler velocimetry (LDV) and particle-image velocimetry (PIV). For conditions corresponding to a particle- and shear-based Reynolds number $Re_G = a^2G / \nu <$ 20 (a = particle or spheroid semimajor dimension; G = shear rate; ν = fluid kinematic viscosity), the linearity of the flow, quantified by the deviation between the average measured and the expected x-velocity components normalized by the belt speed U_b, was less than 6%.

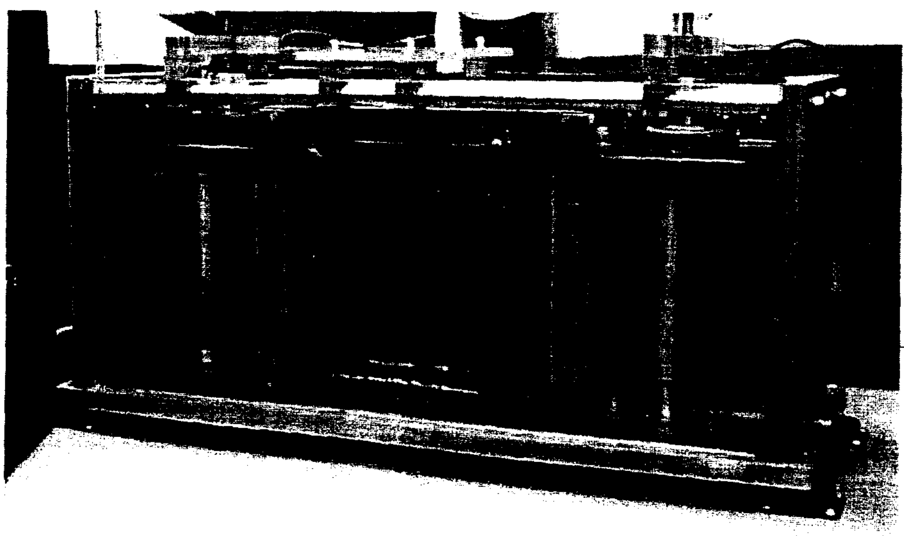

Figure 1 Side view of plane Couette facility for generating simple shear flows for both liquids and suspensions. Note the two large rollers flanking a white circular cylinder in the center of the test section.

Rotation periods T were first measured for neutrally-buoyant circular and elliptical cylinders with aspect ratio $AR = b/a = 0.75$ (a and b = cylinder semimajor and semiminor dimensions, respectively) immersed in a simply sheared suspension using our aqueous suspension system at various shear-based Reynolds numbers. Figure 2 plots the average rotation period normalized by the shear rate, as a function of Re_G (for the suspensions, ν was calculated using the Krieger model[6]) at a confinement ratio $\kappa = a/h = 0.25$. These measurements are compared with previous results for single-phase flow.[7] The symbols represent different particle volume fractions ϕ: $\phi = 0$ (○), 0.01 (◇), 0.03 (△) and 0.06 (□), with open and filled symbols denoting circular and elliptical cylinder results, respectively. The data for cylinders in simply sheared liquids and suspensions are in reasonable agreement.

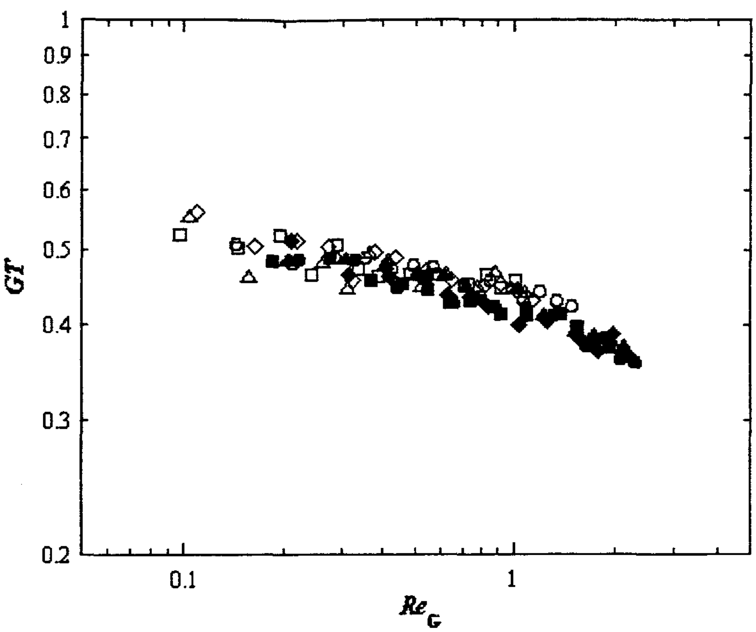

Figure 2 Log-log plot of normalized rotation rate Ω / G *vs.* shear-based Reynolds number Re_G for circular and an $AR = 0.75$ elliptical cylinders in simple shear flow of suspensions at volume fractions up to 6% and single-phase liquids.

For the three-dimensional studies, spheroids were manufactured from three different materials for these studies:

1) DMS Somos 7545 resin (specific gravity SG = 1.20) was fabricated into spheroids using stereolithography rapid prototyping;
2) Polydimethylsiloxane (PDMS) (SG = 1.07) was molded into spheroids using molds manufactured with stereolithography rapid prototyping;
3) Acrylic (polymethylmethacrylate, or PMMA) (SG = 1.17) was milled into spheroids using a micro-CNC (computerized numerical control) mill.

In all cases, the spheroids had an aspect ratio $AR = b/a = 0.33$ and 0.5, and $a = 0.45$ cm, giving a confinement ratio in the test section $\kappa = a/h = 0.35$. A variety of spheroids with different SG were developed so measurements could be carried out for both single-phase and suspension flows.

Rotation periods were measured for spheroids constrained to rotate about both their major and minor axes. Figure 3 presents rotation period data for the two prolate spheroids with AR = 0.33 [top] and 0.5 [bottom] rotating about their minor [left] and major [right] axes. The symbols denote different spheroid materials, namely DSM Somos (triangles) and PDMS (circles); the open and filled triangles denote different types of belt drive to attain different ranges of Re_G. No rotation transition was observed for both types of prolate spheroids rotating about their major axes, presumably because the transition (if it occurs) occurs at a critical Reynolds number Re_{cr} beyond the range attainable with the plane Couette channel (*i.e.*, $Re_{cr} \gtrsim 35$). A transition to a stationary state was observed, however, for both prolate spheroids rotating about their minor axes, with Re_{cr} = 19.2 and 33.5 for AR = 0.33 and 0.5, respectively.

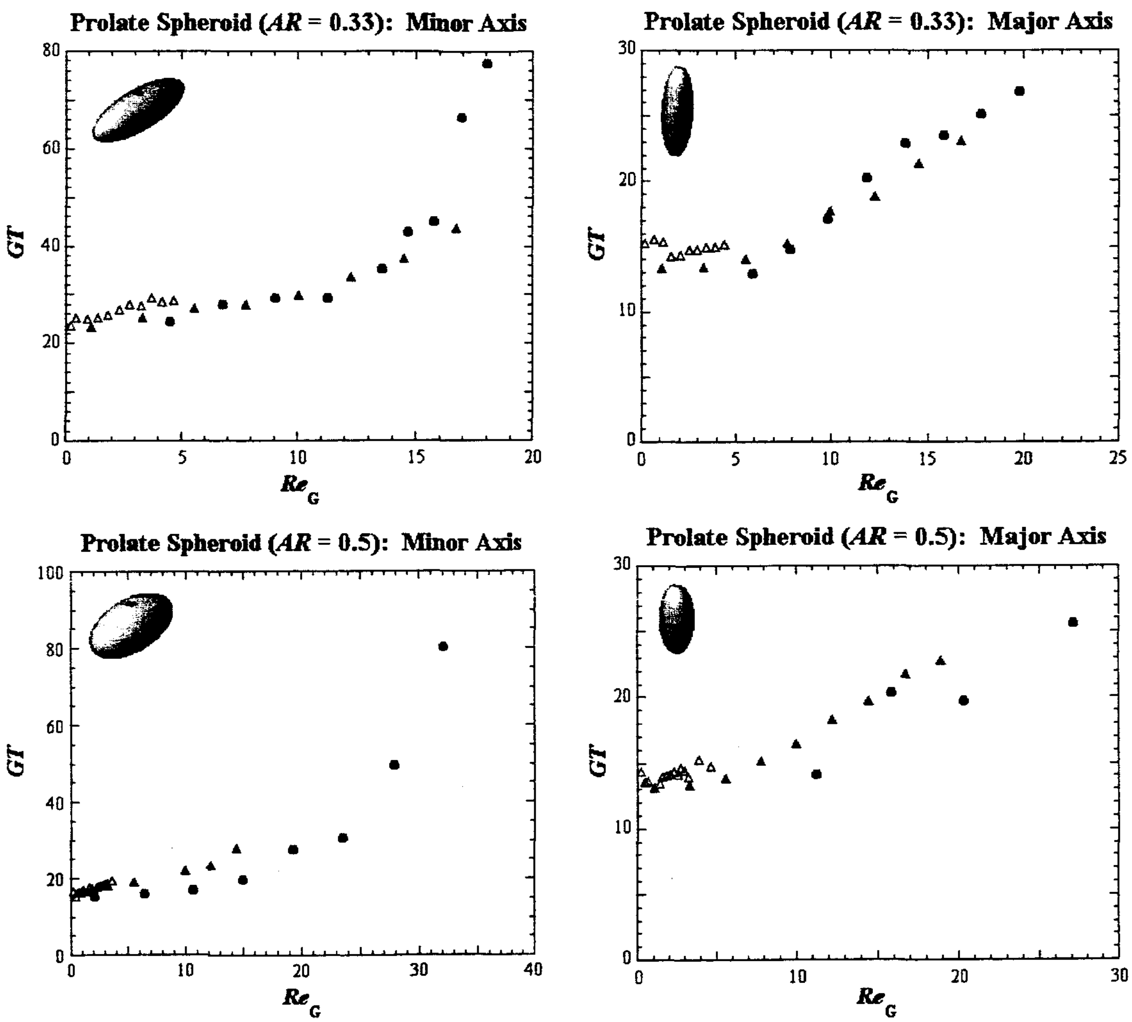

Figure 3 Normalized rotation rate as a function of shear-based Reynolds number for various prolate spheroids.

Figure 4 presents similar data for the two oblate spheroids with AR = 0.33 [top] and 0.5 [bottom] rotating about their minor [left] and major [right] axes. No rotation transition was observed for the oblate spheroids rotating about their *minor* axes, again most likely because the transition (if it occurs) occurs at a critical Reynolds number Re_{cr} beyond the range attainable in these experiments. A transition to a stationary state was observed, however, for both oblate spheroids rotating about their major axes, with $Re_{cr} = 10.3$ and 30.5 for $AR = 0.33$ and 0.5, respectively.

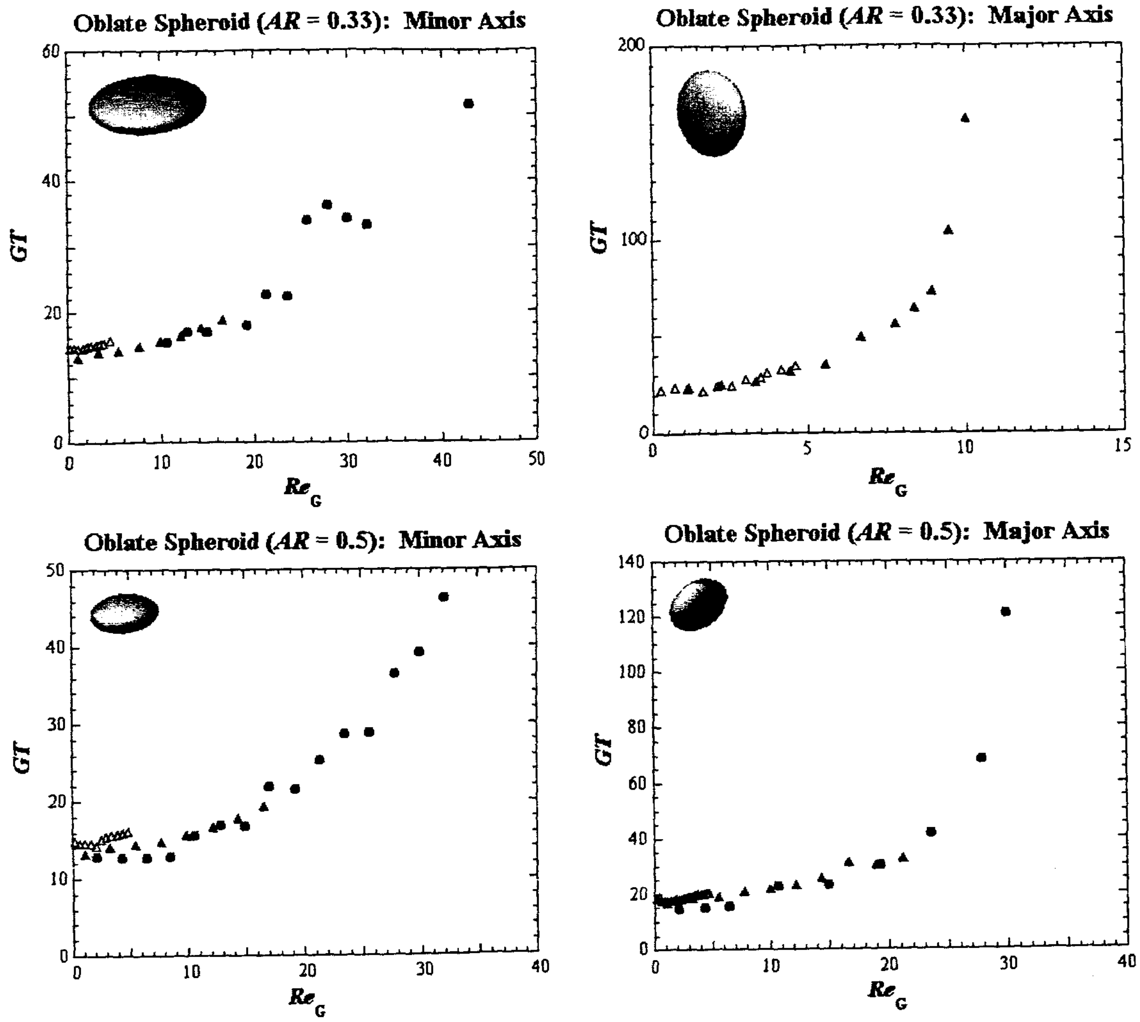

Figure 4 Normalized rotation rate as a function of shear-based Reynolds number for various oblate spheroids.

The prolate and oblate spheroid cases that do show a transition closely follow the scaling law proposed by Ding and Aidun,[3] with $GT \propto [Re_{cr} - Re_G]^{-1/2}$ as $Re_G \rightarrow Re_{cr}$. Most interesting, although these bodies were constrained to rotate about one of their principal axes, we observed this transition at $Re_{cr} = 33.5$ for an $AR = 0.5$ prolate spheroid rotating about its minor axis, in direct contradiction of the lattice-Boltzmann results reported by Qi and Luo[4], who reported that this body would *remain rotating* about its minor axis for $Re_G \lesssim 50$. We are currently checking our results, since this discrepancy may be due to friction in the spheroid mounting in the experiments. We then plan to write up the spheroid rotation period results for publication in *Experiments in Fluids*.

Publications and Presentations Supported by this Grant:

B. C. Bailey and M. Yoda (2001) Particle proximity sensors for suspension flows. 54th Annual Meeting of the American Physical Society Division of Fluid Dynamics, San Diego, CA

B. C. Bailey and M. Yoda (2003) An aqueous low-viscosity density- and refractive-index matched suspension system. *Experiments in Fluids* **35**, 1

M. Yoda and U. C. Andresen (2005) "Experimental observations of dynamic transitions for prolate and oblate spheroids in simple shear," in preparation

B. C. Bailey and M. Yoda (2000) Novel optical diagnostic techniques for studying particle deposition upon large cylinders in a sheared suspension. 5th Microgravity Fluid Physics and Transport Phenomena Conference, Cleveland, OH

M. Yoda, B. C. Bailey and U. C. Andresen (2002) Particle deposition in suspensions: cylinders in a simply sheared suspension. 6th Microgravity Fluid Physics and Transport Phenomena Conference, Cleveland, OH

C. M. Zettner and M. Yoda (2001) Moderate aspect ratio elliptical cylinders in simple shear with inertia. *Journal of Fluid Mechanics* **442**, 241

References:

[1] B. C. Bailey and M. Yoda (2003) An aqueous low-viscosity density- and refractive-index matched suspension system. *Exp. Fluids* **35**, 1

[2] M. K. Lyon and L. G. Leal (1998) An experimental study of the motion of concentrated suspensions in two-dimensional channel flow. Part I. Monodisperse systems. *J. Fluid Mech.* **363**, 25

[3] E.-J. Ding and C. K. Aidun (2000) The dynamics and scaling law for particles suspended in shear flow with inertia. *J. Fluid Mech.* **423**, 317

[4] D. Qi and L.-S. Luo (2003) Rotational and orientational behaviour of three-dimensional spheroidal particles in Couette flow. *J. Fluid Mech.* **477**, 201

[5] C. M. Zettner and M. Yoda (2001) The circular cylinder in simple shear at moderate Reynolds numbers: An experimental study. *Experiments in Fluids* **30**, 346

[6] I. M. Krieger (1972) Rheology of monodisperse lattices. *Advances in Colloid and Interface Science* **3**, 111

[7] C. M. Zettner and M. Yoda (2001) Moderate aspect ratio elliptical cylinders in simple shear with inertia. *Journal of Fluid Mechanics* **442**, 241