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NOVEL OPTICAL DIAGNOSTIC TECHNIQUES FOR STUDYING PARTICLE DEPOSITION UPON LARGE CYLINDERS IN A SHEARED SUSPENSION

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ABSTRACT

On a twelve-month voyage to Mars, one astronaut will require at least two tons of potable water and two tons of pure oxygen. Efficient, reliable fluid reclamation is therefore necessary for manned space exploration. Space habitats require a compact, flexible and robust apparatus capable of solid-fluid mechanical separation over a wide range of fluid and particle densities and particle sizes. In space, centrifugal filtration, where particles suspended in fluid are captured by rotating fixed-fiber mat filters, is a logical candidate for mechanical separation. Non-colloidal particles are deposited on the fibers due to inertial impaction or direct interception. Since rotation rates are easily adjustable, inertial effects are the most practical way to control separation rates for a wide variety of multiphase mixtures in variable gravity environments. Understanding how fluid inertia and differential fluid-particle inertia, characterized by the Reynolds and Stokes numbers, respectively, affect deposition is critical in optimizing filtration in a microgravity environment.

This work will develop non-intrusive optical diagnostic techniques for directly visualizing where and when non-colloidal particles deposit upon, or contact, solid surfaces: "particle proximity sensors." To model particle deposition upon a single filter fiber, these sensors will be used in ground-based experiments to study particle dynamics as in the vicinity of a large (compared with the particles) cylinder in a simply sheared (*i.e.*, linearly-varying, zero-mean velocity profile) neutrally-buoyant, refractive-index matched solid-liquid suspension.

The objectives of this new research project are:

1. To develop new optical diagnostic techniques for directly visualizing where and when particles deposit on a solid surface using fluorescent activation or quenching of an indicator species bound to the particle when it approaches (comes within $O(100 \text{ nm})$ of) the ligand-bound surface;
2. To design and test a compact, self-contained experimental apparatus to study sheared refractive index-matched suspensions; and
3. To use this apparatus in ground-based experiments to study particle deposition on one large cylinder immersed in simple shear flow of a neutrally buoyant suspension.

Particle proximity sensors are based upon the ligand-specific nature of many common fluorescent species. Fluorescent emission from these so-called "fluorescent indicators" will

either be quenched or activated in the presence of some minimum concentration of a specific ion. For example, the fluorescent intensity of disodium fluorescein decreases by nearly an order of magnitude as pH decreases from 7 to 5. We have already identified several candidate fluorescent indicators that are quenched by pH and calcium ion concentration gradients.

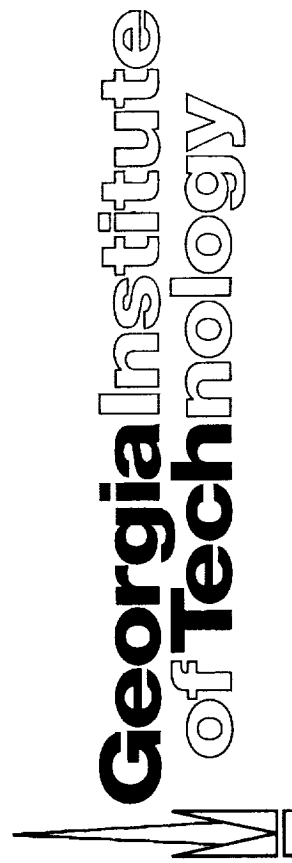
Given that most of these indicators are used in biochemical applications, these fluorescent indicators have been mainly characterized for aqueous chemistries. The suspension liquids currently used by most investigators are, however, organic solvents. We are therefore developing new alternative suspension systems based upon aqueous salt solutions that will match both the refractive index and density of commercially available polymethylmethacrylate (PMMA) particles. An aqueous neutrally-buoyant, refractive index-matched suspension system will allow us to use pH- and Ca^{++} -specific fluorescent indicators with their well-characterized behavior, and take advantage of standard techniques for binding these indicators to the surface of and/or incorporating these indicators within the bulk of PMMA particles. Using these fluorescent indicators would also greatly simplify preparation of the solid surface; binding H^+ , OH^- or Ca^{++} ions to solid glass surfaces using silanes is standard chemical procedure. Development of a novel water-based suspension system would also greatly simplify suspension mechanics experiments in terms of cost and chemical hazards.

We plan to use particle proximity sensors to study particle dynamics near a large cylinder immersed in a simply sheared suspension. As the dyed particles approach the cylinder, whose surface is bound with the appropriate ion, the fluorescent indicator bound to the particle surface will be quenched when the particle is within $O(100 \text{ nm})$ of the cylinder. The kinetics of this quenching should be virtually instantaneous, occurring within $O(10 \text{ nsec})$. If the flow is illuminated by light at the appropriate exciting wavelength, the quenched particles can be imaged at the illumination wavelength to determine particle deposition upon the cylinder, while the unquenched particle dynamics away from the cylinder can be imaged at the fluorescence wavelength. The effects of fluid inertia, flow confinement (due to finite test section width), and ratio of particle to cylinder diameter will be explored. The results will be compared with our previous studies of a cylinder immersed in a simply sheared Newtonian liquid.

This ground-based project is the first step towards "heavy" and "light" suspension flow experiments in microgravity. Considering the current limitations of computational techniques in many-particle suspension simulations and the impossibility of decoupling inertial and buoyancy effects upon Earth, microgravity environments are ideal for studying the effects of differential particle-fluid inertia. In addition, particle proximity sensors could be a valuable diagnostic technique in studying several multiphase flow problems of importance in manned space exploration, such as dust deposition on solar arrays and seal degradation in dusty environments.

Novel Optical Diagnostic Techniques for Studying Particle Deposition

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Motivation

- Study interaction of noncolloidal particles with solid surfaces in sheared particle-liquid suspensions
- Fluid and particle inertia (Re and St) effects on
 - Particle contact and deposition upon solid surfaces
- Nonintrusive “particle proximity sensor”
 - Indicator on particle reversibly and rapidly triggered when particle within small distance ($< 1 \mu\text{m}$) of surface
 - Optical changes (e.g. color, intensity) easily detectable without disturbing flow
- Reduced-gravity application: centrifugal filtration
 - Separate particles from fluid to reclaim water and air

Objectives

- Develop “particle proximity sensors”: techniques for visualizing noncolloidal particle contact with (deposition on) solid surfaces
 - Fluorescent particles “turn off” as they approach solid surface due to ligand concentration gradient
 - Reversible, nonintrusive technique
- Use technique to study particle deposition upon cylinders in simple shear flow of neutrally buoyant suspension
 - Model filter fiber in centrifugal filtration
 - Basic bluff body flow

Model Suspension Systems

- Optical techniques used in suspension systems with refractive index- and density-matched phases
- Current suspension systems use organic liquids
 - Three liquids to match n , ρ of PMMA or PS particles
 - Viscosity of liquid phase $O(100 \text{ cP})$
- New aqueous suspension system
 - Two liquids (water, glycerin) + one salt (ammonium thiocyanate) to match n , ρ of PMMA particles
 - Fluorescent indicators require aqueous chemistry:
 - Lower viscosity liquid phase
 - Less chemical hazard

Suspension Characteristics

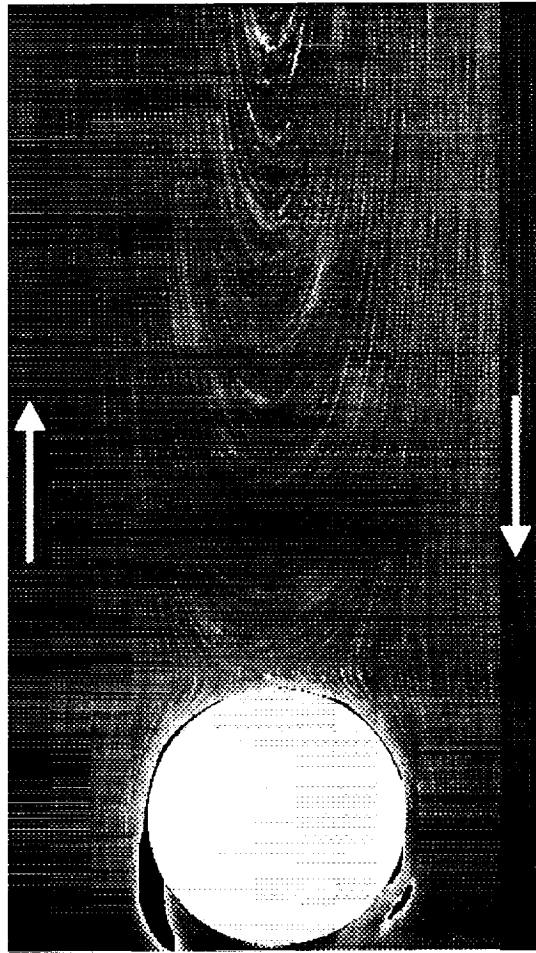
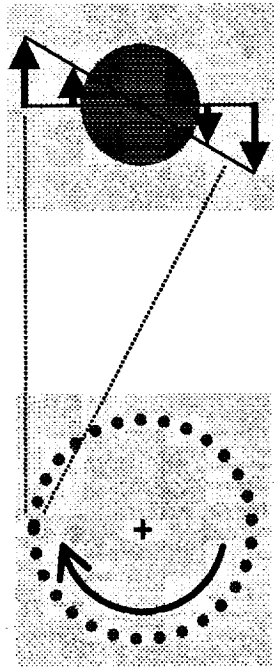
- 59.8% (w/w) water and 11.2% (w/w) glycerin solutions of NH_4SCN match n of 100–200 μm dia. PMMA particles ($n = 1.487$)
- Mix in different proportions to vary liquid density
 - At 1g, match PMMA density ($\rho = 1.19 \text{ g/cm}^3$) with 54.0% (w/w) aqueous solution
 - At low g, heavy and light index-matched suspensions
- Transmission for 1 cm thick suspension >95% at 5% particle volume fraction, 23°C, 514.5 nm
- Viscosity of liquid phase $O(10 \text{ cP})$

Particle Proximity Sensor

- Use one of the common fluorescent Ca^{++} indicators
 - Can be irreversibly bound to PMMA surfaces
 - Add Ca^{++} in low (ppm) concentrations to suspension
 - Coat solid surface with porous polymer layer that binds $\text{Ca}^{++} \Rightarrow \text{Ca}^{++}$ concentration gradient next to surface
- Ca^{++} indicator on particle quenches within $O(100 \text{ nm})$ of Ca^{++} -depleted solid surface
 - Reversible: particle leaving surface fluoresces again
 - Instantaneous: indicator responds within $O(10 \text{ ns})$
- Use as tracer particles in new aqueous suspension to study suspension mechanics and particle contact

Cylinder in Simple Shear

- Centrifugal filtration
 - Particles deposited upon rotating filter basket
 - Cylinder in simply sheared suspension models particle deposition upon single filter fiber in body-fixed frame

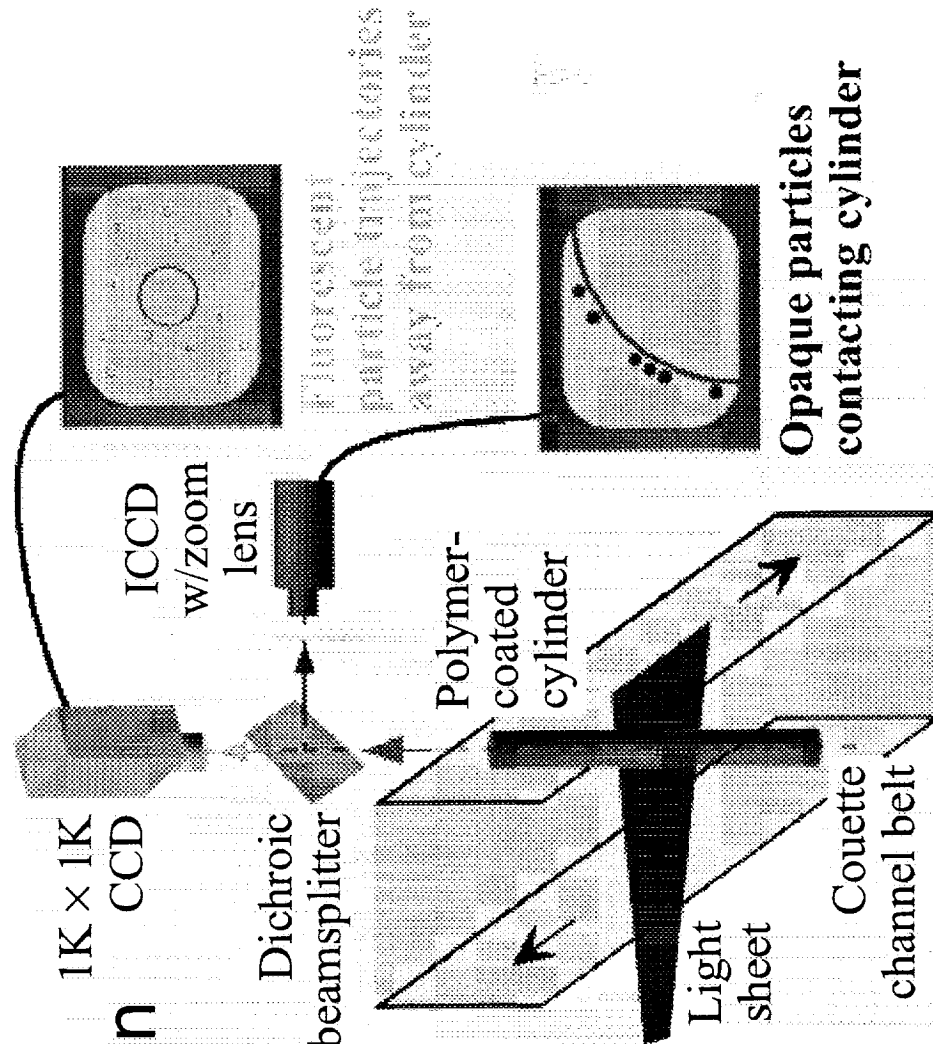


Streamlines for torque-free circular cylinder in single-phase simple shear at $Re_G = 8$
 (Zettner and Yoda 2000)

Experimental Setup

Cylinder in simply sheared suspension

- Two cameras imaging different wavelengths
 - Illuminating $\lambda \Rightarrow$ Particle trajectories
 - Fluorescent $\lambda \Rightarrow$ Particle contact, deposition.



Future Work

- Year 1: Technique Development
 - Test various Ca^{++} indicators for PMMA particles; develop porous polymer layer for glass surfaces
- Year 2: Technique Calibration
 - Calibrate particle contact sensor in basic sedimentation flow (heavy particles)
- Years 3 and 4: Cylinders in Simply Sheared Inertial Suspension
 - Fixed and torque-free circular and elliptical cylinders: cylinder diameter \gg particle diameter
 - Suspension mechanics and particle deposition