Fiber Alignment in Confined Shearing Flows

Simulation and Validation of Slurry Dynamics and Rheology

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Motivation

GOAL: An inexpensive and rapid simulation method validated by experiments for predicting the rheology and microstructural dynamics of concentrated suspensions.

- Microstructure at high concentrations?
  - significantly different from spheres – orientation dependence!
- Irreversible dynamics and microstructure in general flows.
  - shear-induced migration in oscillatory flows!
- Effect of microstructure on rheological measurements?
  - benefit from accurate models and simulations!

Rod Rheology (Tapia et al., 2017)

Andreas Acrivos (spheres) Journal of Rheology 1995 39:5, 813-826

Increasing power requirement

Region of interest

Increasing water content

Intrinsic Viscosity

Particle Volume Fraction

Shear viscosity ($\eta_s$, Pa·s)

$A=L/d$

$\phi_m$
Examine the irreversible dynamics in slurries and apply findings to generate accurate predictive capabilities for real suspensions.

* Previous work: including contact forces and lubrication can accurately predict the microstructure in sheared suspensions of spheres and rigid fibers.

* Using suspensions of particles that are
  - non-colloidal
  - neutrally buoyant
  - in Newtonian fluids

* Challenges:
  - understanding how shape, concentration, orientation, etc. affects rheology and flow
  - can apply to fundamentals of coating and pumping
* Expanding studies beyond mono-modal spheres to poly-disperse and rod systems.
Pipe Flow Experiments (Previous IAB Meeting)

Objective:
Measure the spatial and orientation distribution in pipe flow using refractive indexed matched particles, fluorescence and direct imaging.

Particles: PMMA, \( (\rho \sim 1.19 \text{ g/cm}^3) \), \( \text{A=L/d=11.3 \& 22.6} \)
Fibers are rigid, non-colloidal, non-inertial, and neutrally buoyant.

Fluid: Newtonian mixture of Triton X-100, ZnCl\(_2\), and water, adjusted to make the particles neutrally buoyant.

- Oscillatory displacement of the suspension in tube flow
- Experiments performed under various number densities \( (n_0L^2d = 0.42 \text{ to } 3) \)

\( n \): number of fibers per unit volume
\( L \): fiber length
\( d \): fiber diameter
\( n_0L^2d > 1 \) in concentrated regime
We observe nematic structures in some of our experiments.
Previous Findings:
• Experimental evidence of shear-induced migration of concentrated fiber suspensions.
• Migration of fibers scales with $\varphi A (\propto nL^2d)$, instead of $\varphi$.
• Fibers tend to align in the flow direction, while fibers near the wall show vorticity alignment.

Simulations:
• Altered boundaries from parallel plates to circular tube.
• Updated the short-range repulsive interaction to a Hertzian contact force.
• Added oscillating flow to match experiments.
• Update the flow field as fibers migrate toward center of channel/tube.
Oscillatory displacement of the suspension in simple shear flow.

Experiments performed under various gap sizes, volume fractions, and strain amplitudes.

**Shear Cell Experiments - Setup**

Objective:
Measure the orientation distribution in shear flow using *refractive indexed matched* particles, fluorescence and direct imaging.

Particles: PMMA, \( \rho \sim 1.19 \text{ g/cm}^3 \), \( A=L/d=11.3 \ & 22.6, \ d=0.23 \ & 0.46 \text{ mm} \)
Fibers are rigid, non-colloidal, non-inertial, and neutrally buoyant.

Fluid: *Newtonian* mixture of Triton X-100, ZnCl\(_2\), and water, adjusted to make the particles neutrally buoyant.

- Oscillatory displacement of the suspension in simple shear flow.
- Experiments performed under various gap sizes, volume fractions, and strain amplitudes.
Shear Cell Experiments - Videos

H=1.5L, A=11, d=0.46mm, gamma=2.5

H=1.5L, A=11, d=0.23mm, gamma=2.5

Or maybe I'll just show one video. I have not decided.
• Free surface diffracts laser, making image quality difficult to process systematically.
• Exclude particles in analysis that are within one particle length of the boundaries.
Order parameter: $S_\alpha = 1 - 2\langle \cos^2 \alpha \rangle$

- $\alpha$ is the angle between the fiber’s projection in the flow-vorticity plane and the flow direction
- $S_\alpha = 1$: alignment in the vorticity direction
- $S_\alpha = -1$: alignment in the flow direction
Shear Flow Simulations

Simulate concentrated suspensions of rods in a parabolic flow between two plates:

\[ u(x) = \dot{\gamma}(t) y e_x \]

- Periodic in the flow and vorticity directions. Bounded by walls in gradient direction.

- Flow impacts movement and rotation of particles.

- Short range repulsive force between rods (collision).

\[ \dot{x}_\alpha = u(x_\alpha) + \xi^{-1} (I + p_\alpha p_\alpha) \cdot F_\alpha \]

\[ \dot{p}_\alpha = \Omega \cdot p_\alpha + B (I - p_\alpha p_\alpha) \cdot E \cdot p_\alpha + \frac{12 \xi^{-1}}{L^3} (I - p_\alpha p_\alpha) \cdot \tilde{F}_\alpha \]

\[ B = \frac{A_e^2 - 1}{A_e^2 + 1} \quad \xi^{-1} = \ln(2A) / 4\pi \mu L \]
Simulation - Results/Comparisons

• Volume fraction of 20%
• Vorticity alignment in simulations at strain amplitude of 3

• Steady state orientation distribution
• Vorticity alignment observed for system in confinement (bounded)
Objective:
Measure resuspension of settled fibers in suspension.
Using refractive index matched particles, fluorescence and direct imaging.

- Resuspension has been evaluated theoretically and experimentally for spheres.
- Preview of settled fibers being resuspended.
- Industrial Relevance: Mixing applications and relating heavy particles with rheological properties!
## Project Summary

### Experiments

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<td><strong>Rheology of concentrated suspensions of rigid fibers</strong></td>
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### Simulations

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- Have demonstrated the ability to predict microstructure in uniform shearing flows.
- Data for validating the prediction of microstructure in non-uniform shearing flows has been generated for both spherical and non-spherical particle suspensions.

**CONTINUING WORK:** Improve simulations predicting the microstructure in non-uniform flows.
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Deliverables:
- Paper published on quantitative measurements of shear-induced migration of concentrated fiber suspensions in tube flow.
- Simulations validated by experimental data for the prediction of the spatial and orientation distribution using a contact-force model.
- Measurements of fiber alignment in confined shear flow system.
Accomplishments and Acknowledgment

Accomplishments *since last CPaSS Meeting*:


**Acknowledgment**

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**Disclaimer**

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation/Sponsors.