Fiber Alignment in Confined Shearing Flows

Simulation and Validation of Slurry Dynamics and Rheology

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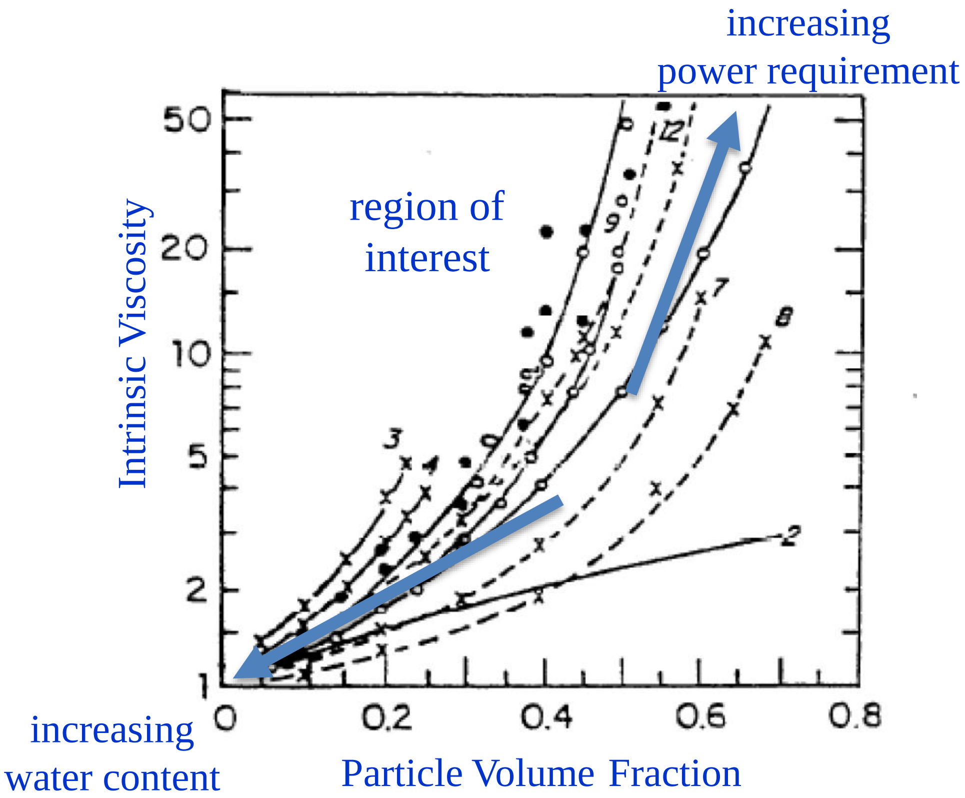
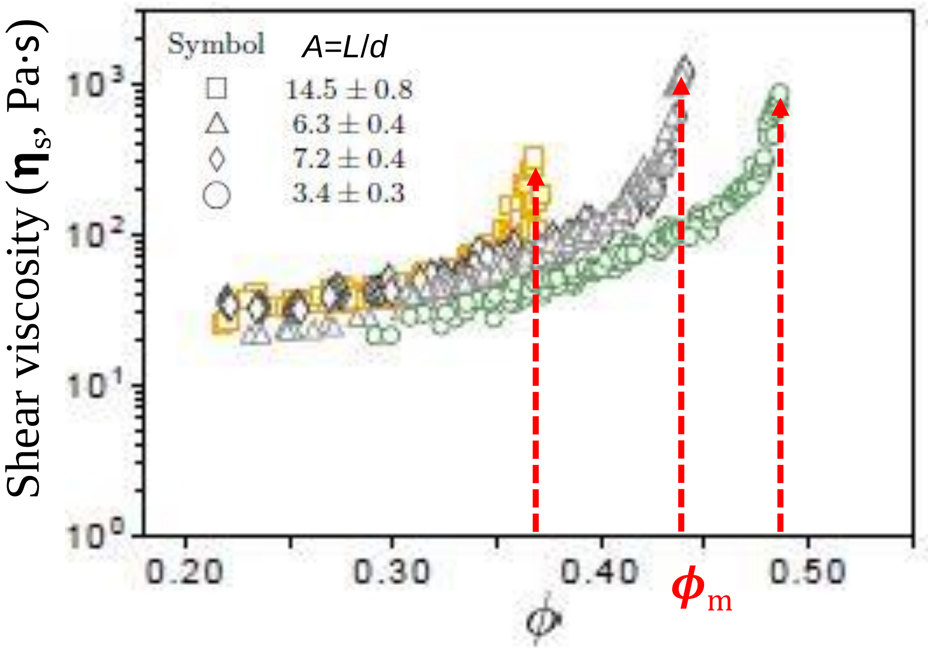
Motivation

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



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



Rod Rheology (Tapia et al., 2017)

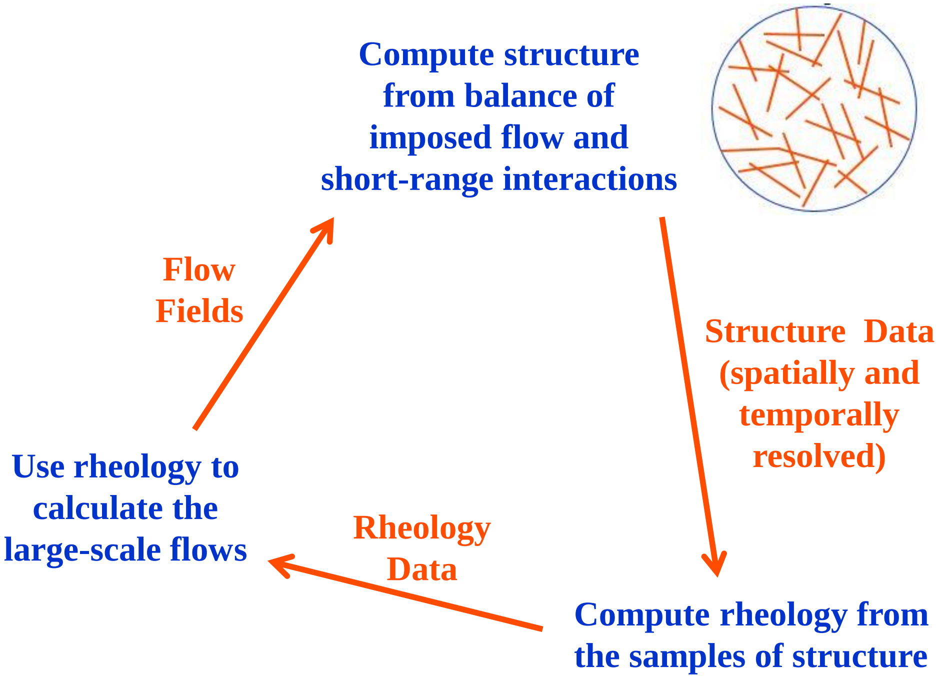
- Microstructure at high concentrations?
    - significantly different from spheres – orientation dependence!
- Irreversible dynamics and microstructure in general flows.
    - shear-induced migration in oscillatory flows!
- Effect of microstructure on rheological measurements?
    - benefit from accurate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

Challenges and Scope

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**



Compute structure from balance of imposed flow and short-range interactions

Structure Data (spatially and temporally resolved)

Compute rheology from the samples of structure

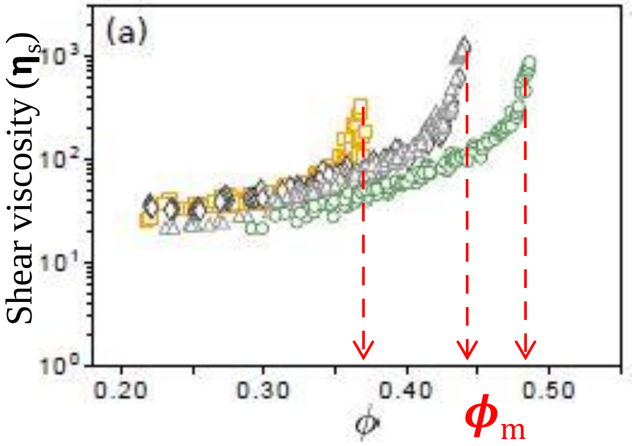
Rheology Data

Use rheology to calculate the large-scale flows

Flow Fields

*** 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)

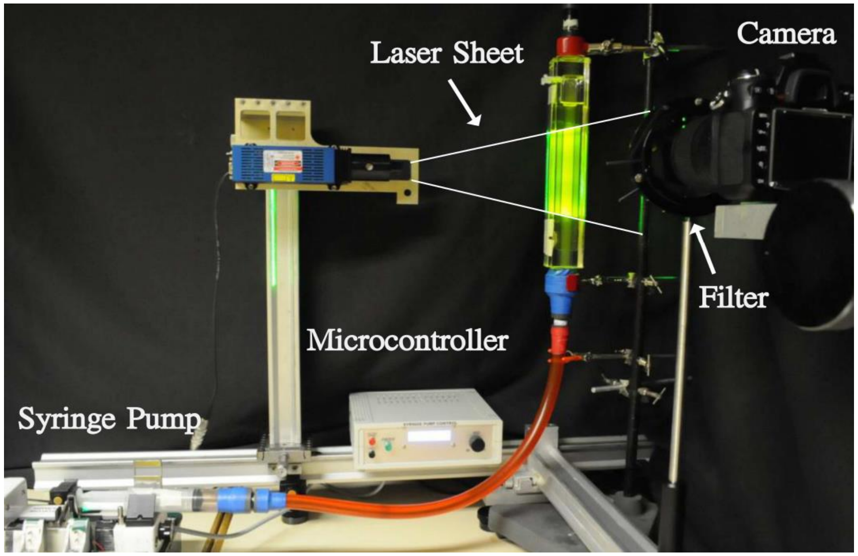
Objective:

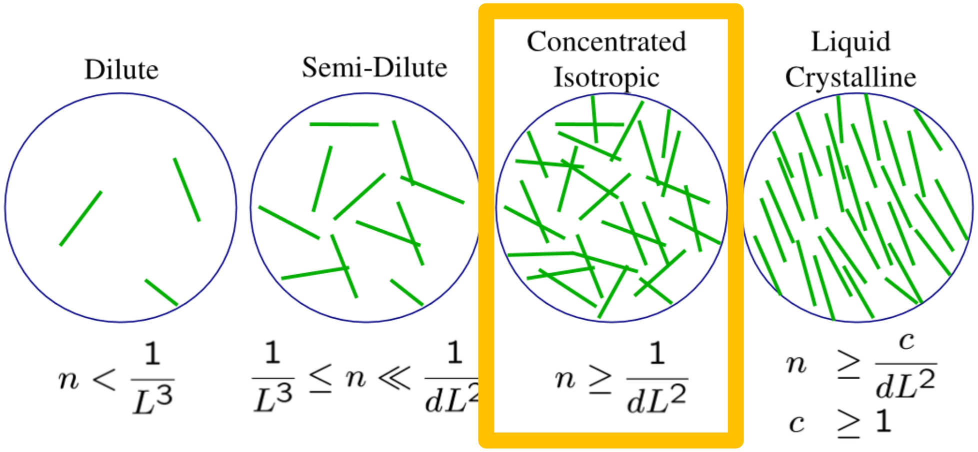
Measure the spatial and orientation distribution in pipe flow using refractive indexed matched particles, fluorescence and direct imaging.

Particles: PMMA, ($\rho \sim 1.19$ g/cm^3), **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 ($n_0L^2d = 0.42$ 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.

Summary/Challenges – Tube Experiments

Previous Findings:

- Experimental evidence of shear-induced migration of concentrated fiber suspensions.
- Migration of fibers scales with φA ($\propto nL^2d$), instead of φ.
- 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.

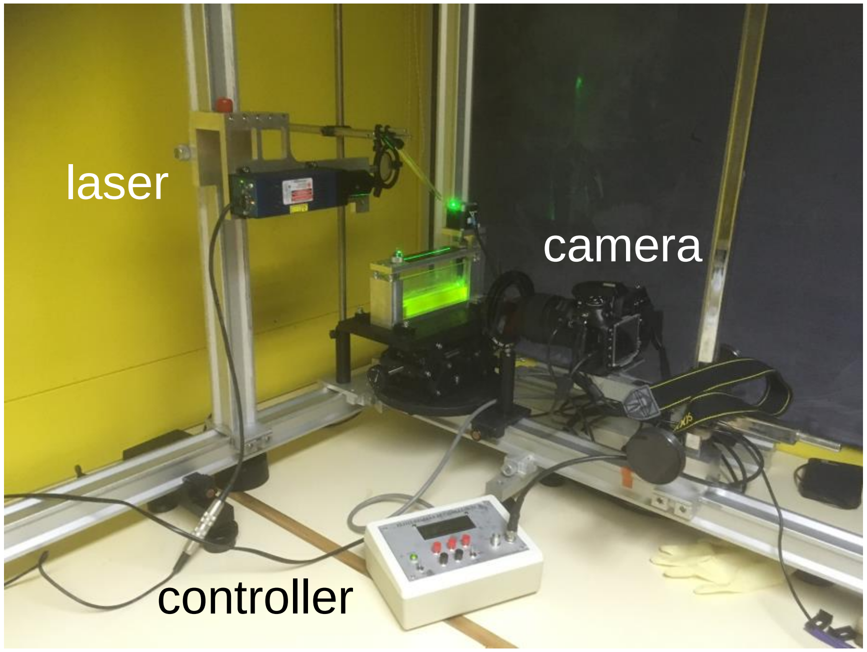
Shear Cell Experiments - Setup

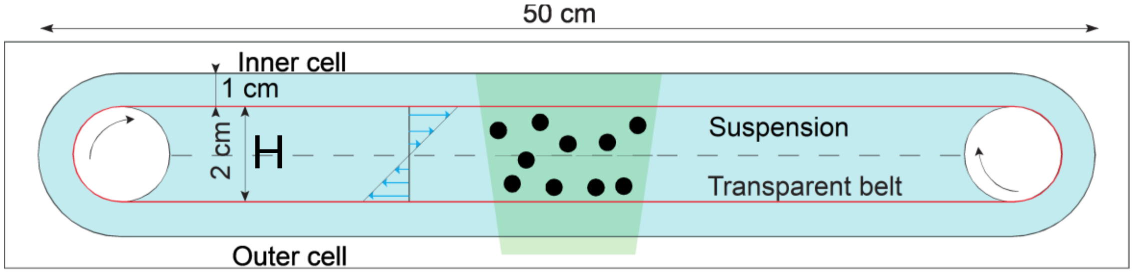
Objective:

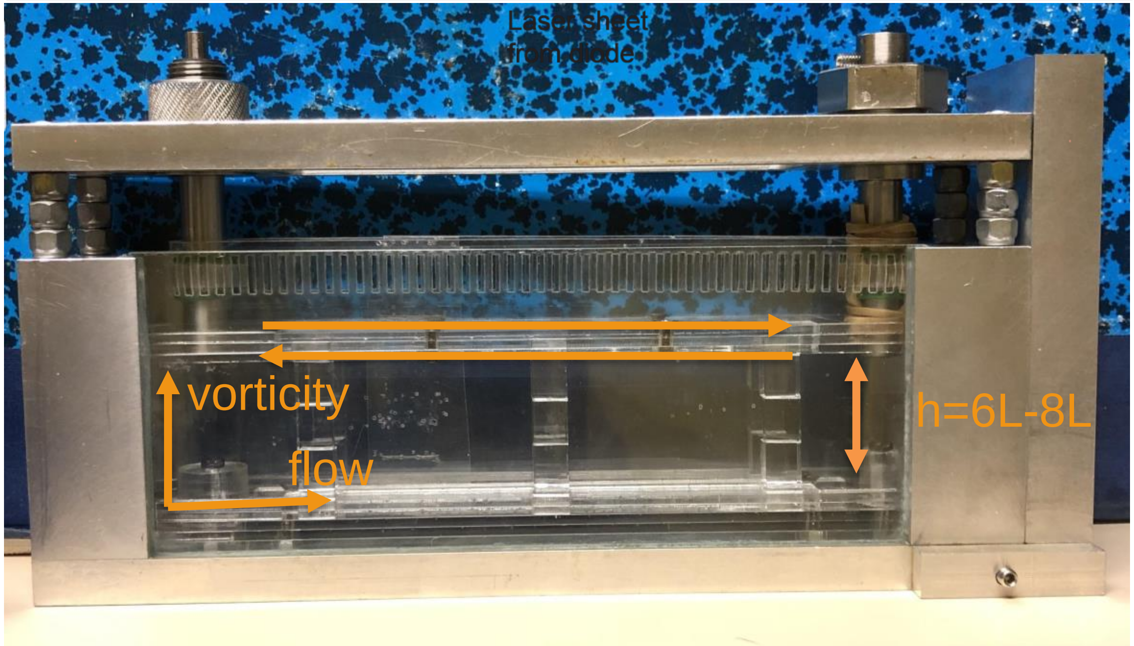
Measure the orientation distribution in shear flow using refractive indexed matched particles, fluorescence and direct imaging.

Particles: PMMA, (ρ ~ 1.19 g/cm^3), **A=L/d=11.3 & 22.6, d=0.23 & 0.46 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.

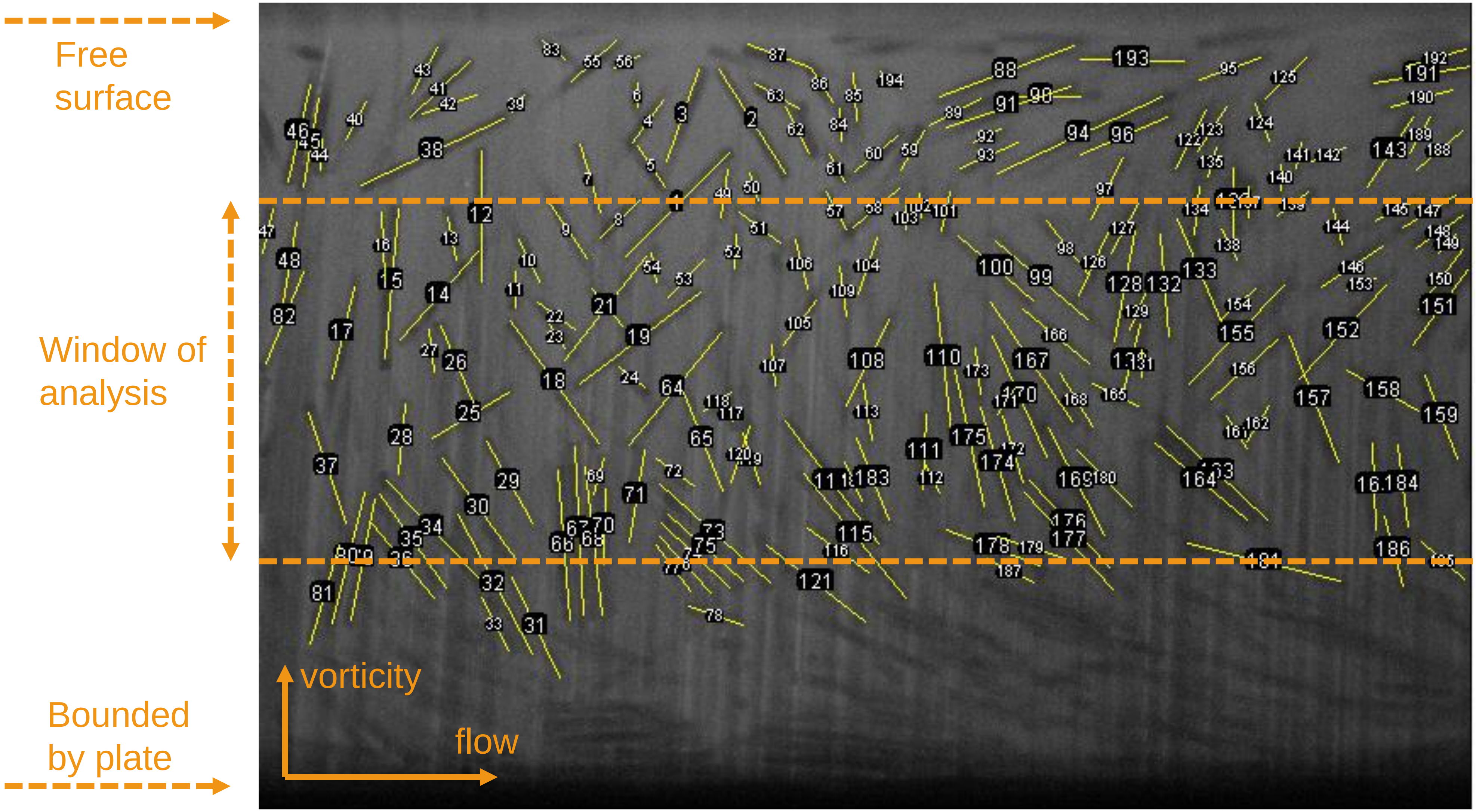
Shear Cell Experiments - Videos

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

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

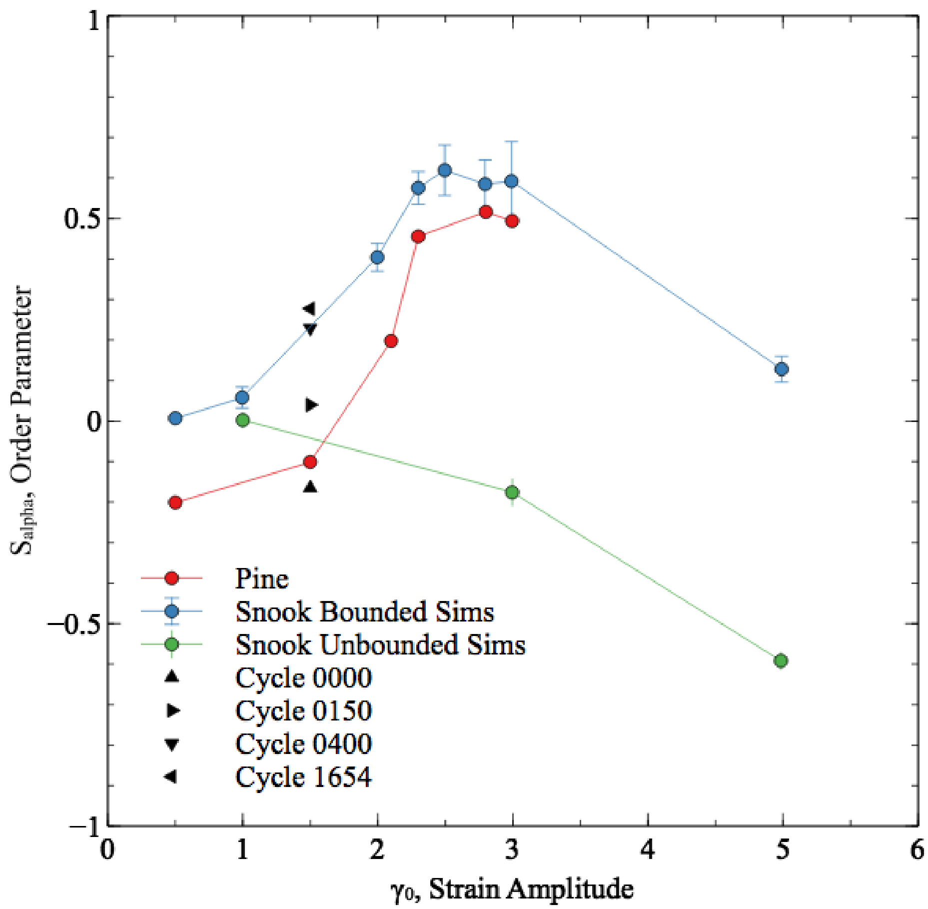
Or maybe I’ll just show one video. I have not decided.

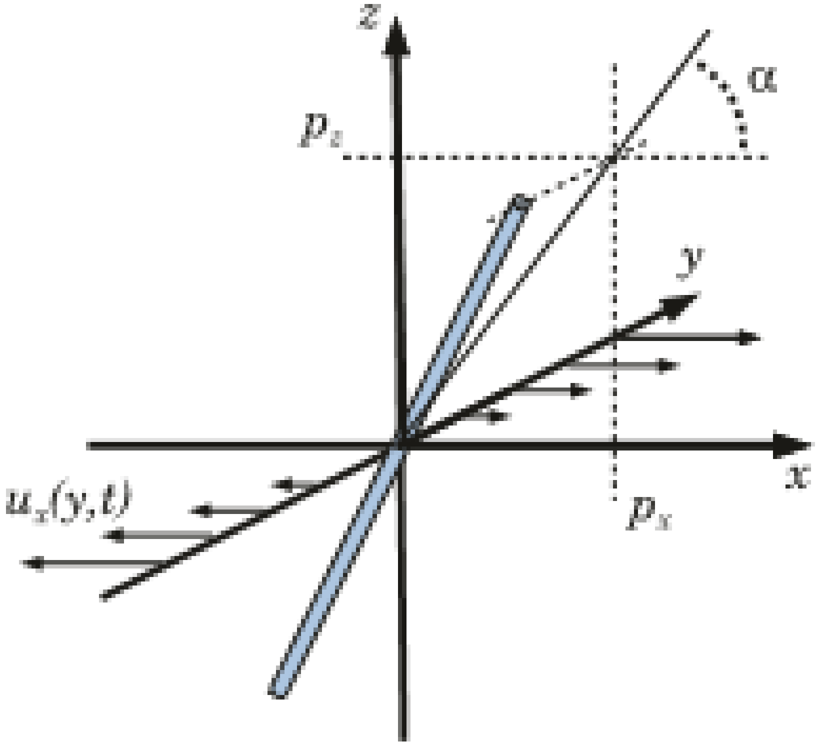
Shear Cell Experiments - Processing



- Free surface diffracts laser, making image quality difficult to process systematically.
- Exclude particles in analysis that are within one particle length of the boundaries.

Shear Cell Experiments - Results

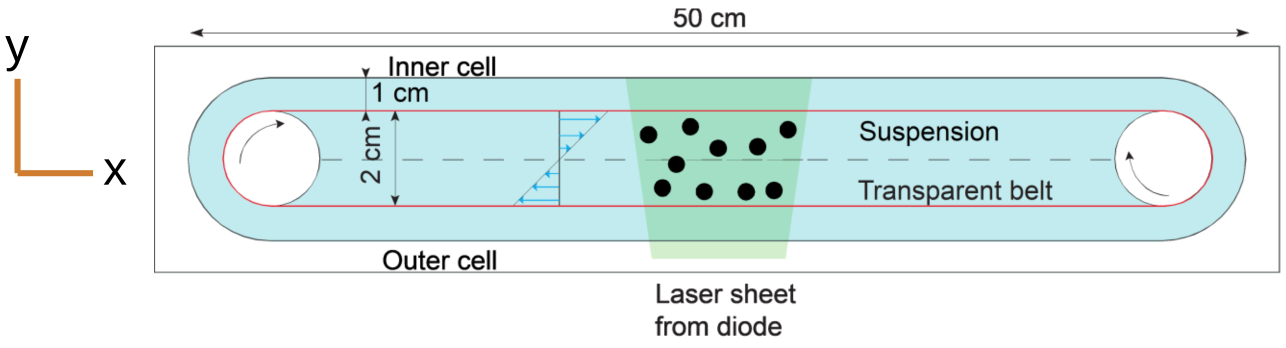




- Order parameter: $S_\alpha = 1 - 2\langle\cos^2\alpha\rangle$
- α is the angle between the fiber's projection in the flow-vorticity plane and the flow direction
- $S_\alpha = 1$: alignment in the vorticity direction
- $S_\alpha = -1$: alignment in the flow direction

Shear Flow Simulations

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

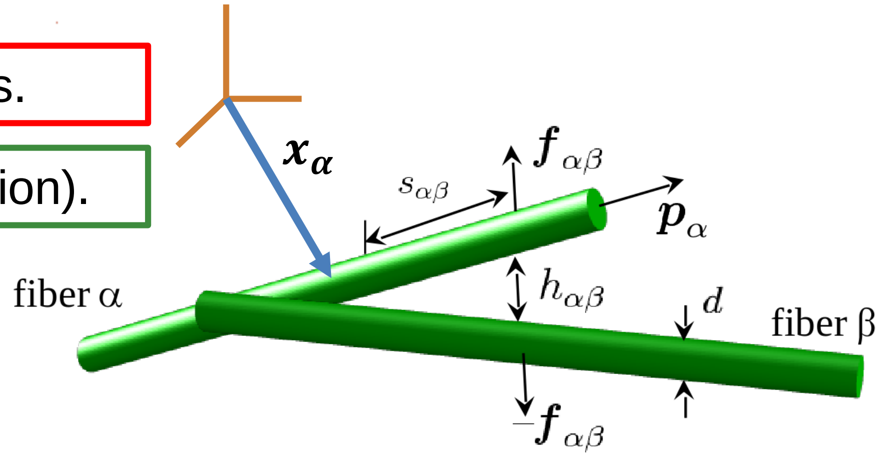


$$\boxed{\boldsymbol{u}(x) = \dot{\gamma}(t)\,y\,\boldsymbol{e}_x}$$

- 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).



$$\dot{\boldsymbol{x}}_\alpha = \boxed{\boldsymbol{u}\left(\boldsymbol{x}_\alpha\right)} + \boxed{\xi^{-1}\left(\boldsymbol{I}+\boldsymbol{p}_\alpha\boldsymbol{p}_\alpha\right)\cdot\boldsymbol{F}_\alpha}$$

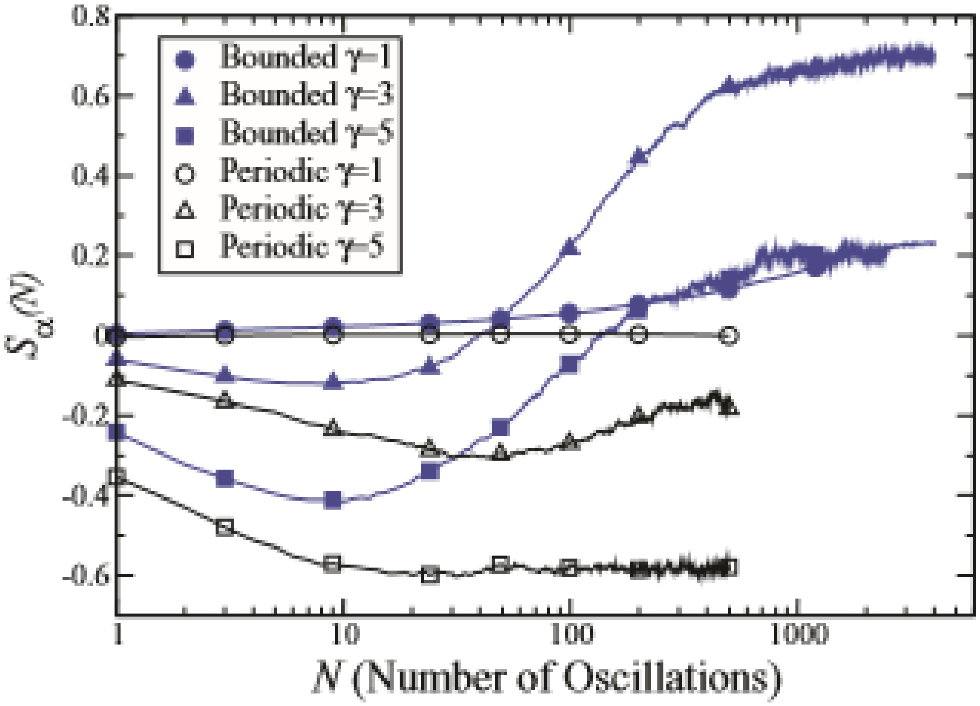
$$\dot{\boldsymbol{p}}_\alpha = \boxed{\boldsymbol{\Omega}\cdot\boldsymbol{p}_\alpha + B\left(\boldsymbol{I}-\boldsymbol{p}_\alpha\boldsymbol{p}_\alpha\right)\cdot\boldsymbol{E}\cdot\boldsymbol{p}_\alpha}$$
$$\boxed{+\frac{12\xi^{-1}}{L^3}\left(\boldsymbol{I}-\boldsymbol{p}_\alpha\boldsymbol{p}_\alpha\right)\cdot\tilde{\boldsymbol{F}}_\alpha}$$

$$B = \frac{A_e^2-1}{A_e^2+1} \qquad \xi^{-1} = \ln\left(2A\right)/4\pi\mu L$$

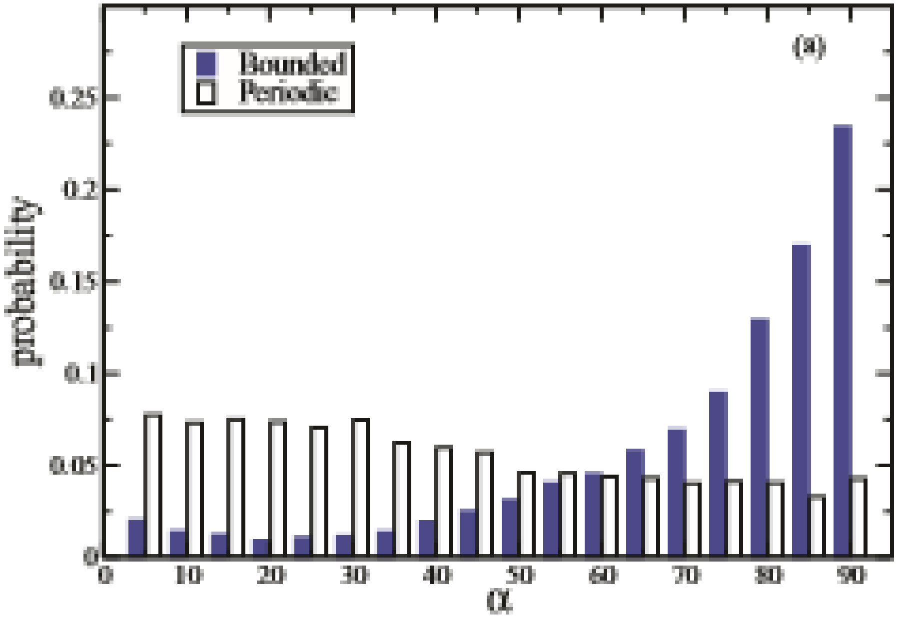
$$\boldsymbol{F}_\alpha = \sum_{\beta=1}^{N_f}\boldsymbol{f}_{\alpha\beta} \qquad \tilde{\boldsymbol{F}}_\alpha = \sum_{\beta=1}^{N_f} s_{\alpha\beta}\boldsymbol{f}_{\alpha\beta}$$

$$\boldsymbol{f}_{\alpha\beta} = \begin{cases} 0 & \text{if } h_{\alpha\beta} > \epsilon \\ f_0\boldsymbol{n}_{\alpha\beta} & \text{if } h_{\alpha\beta} \leq \epsilon \end{cases}$$

Simulation- Results/Comparisons

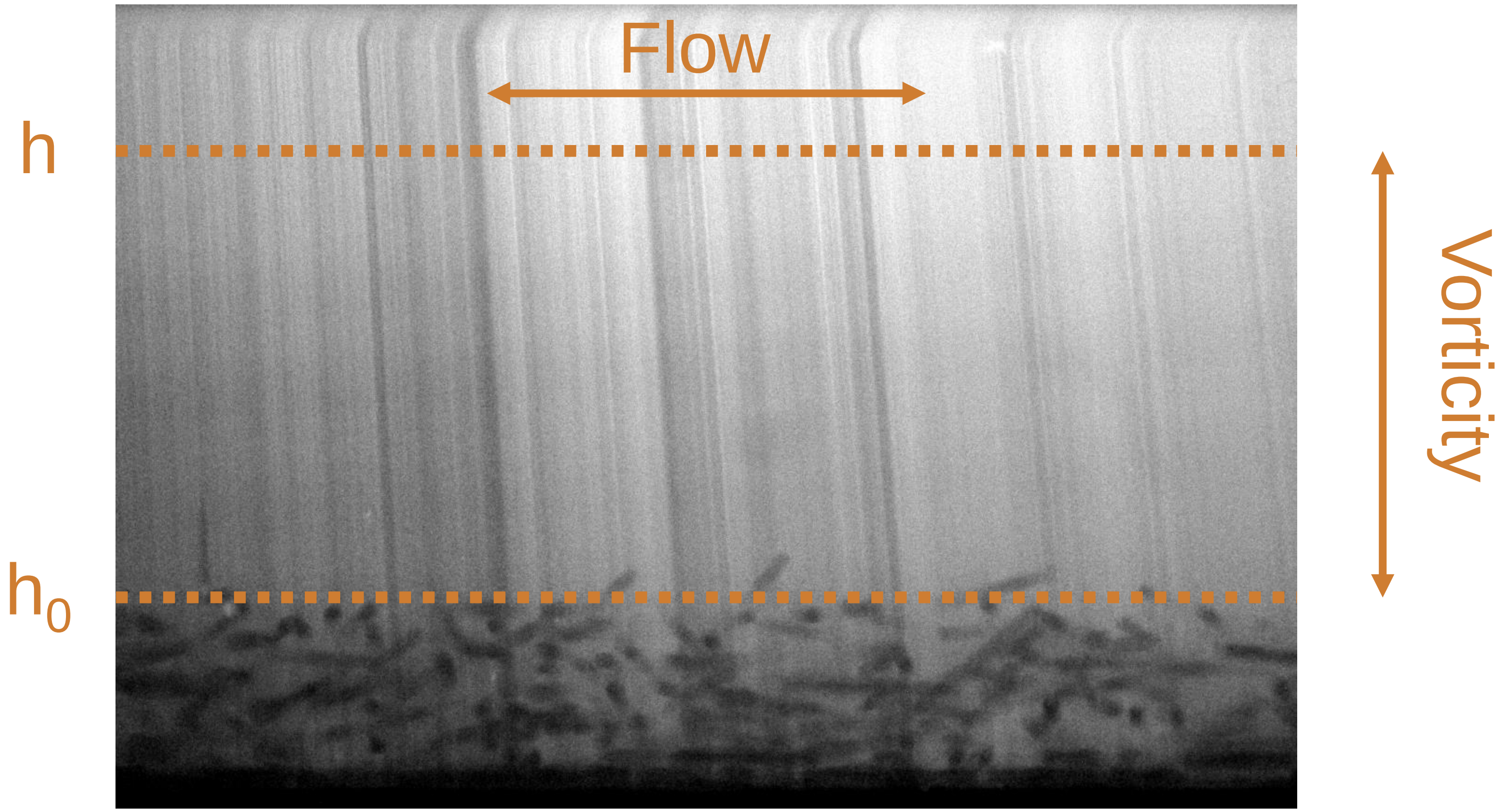


- Volume fraction of 20%
- Vorticity alignment in simulations at strain amplitude of 3



- Steady state orientation distribution
- Vorticity alignment observed for system in confinement (bounded)

Shear Cell Experiments – Resuspension



Objective:

Measure resuspension of settled fibers in suspension. Using refractive indexed matched particles, fluorescence and direct imaging.

Particles: PMMA, ($\rho \sim 1.19$ g/cm^3), **A=L/d=11.3**
Fibers are rigid, non-colloidal, non-inertial, and **heavy**.
Fluid: *Newtonian* mixture of Triton X-100, $ZnCl_2$, and water.

- 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!

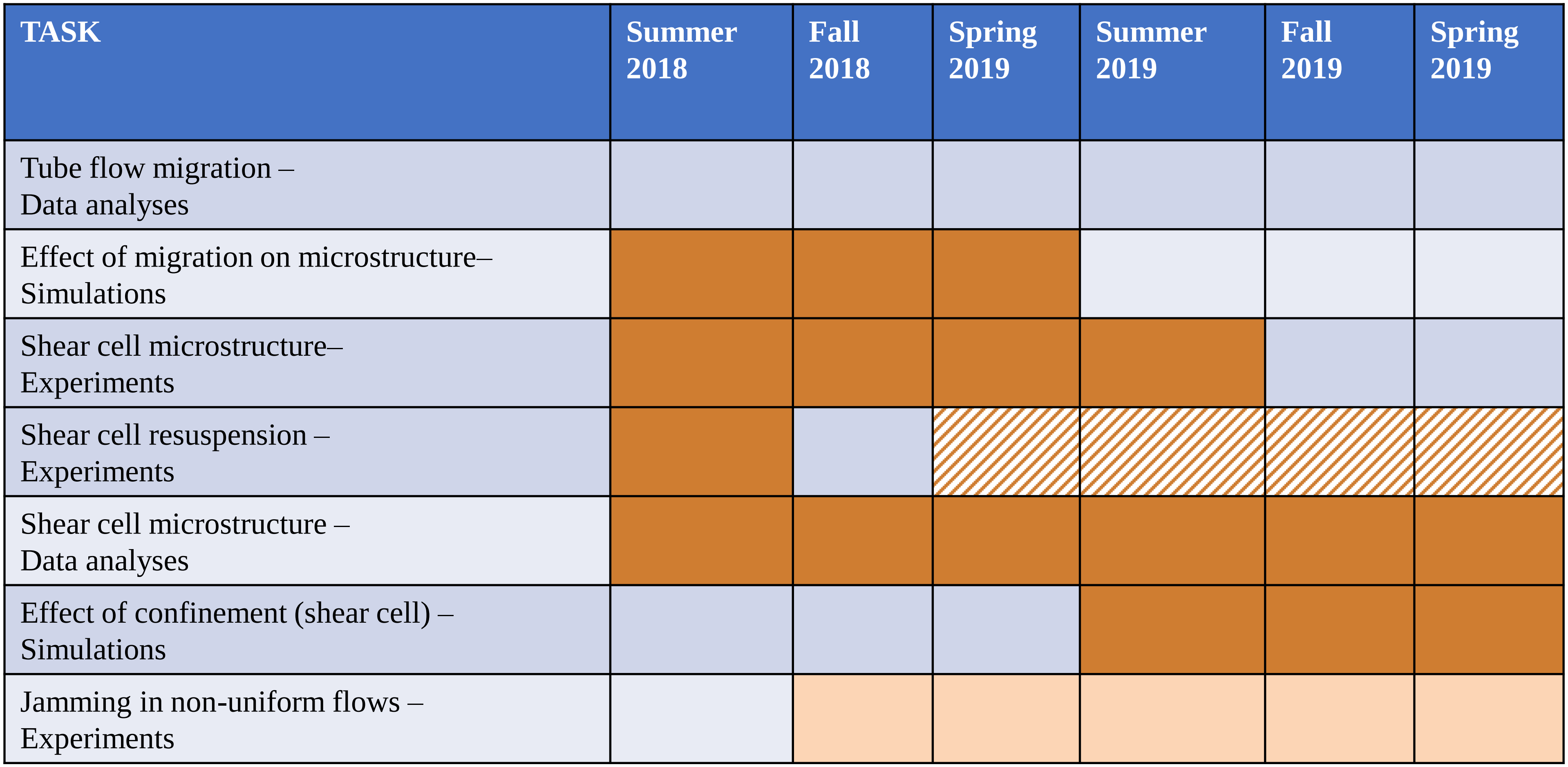
Project Summary

	Spheres	Rods
Experiments	• Shear-induced migration of spheres Snook, B., Butler, J., & Guazzelli, É. (2016) • Particle dispersion: role of contacts Pham, P., Metzger, B., & Butler, J. (2015) • Rheology of concentrated suspensions of spheres Boyer, F., Guazzelli, E., & Pouliquen, O. (2011)	• Rheology of concentrated suspensions of rigid fibers Tapia, F., Shaikh, S., Butler, J., Pouliquen, O., & Guazzelli, É. (2018) • Shear-induced migration of rods Strednak, S., Shaikh, S., Butler, J., & Guazzelli, É. (2018)
Simulations	• Irreversibility and chaos in suspensions Metzger, B., Pham, P., & Butler, J. (2013)	• Vorticity alignment of fibers Snook, B., Guazzelli, É., & Butler, J. (2012) • Normal stress differences Snook, B., Davidson, L., Butler, J., Pouliquen, O., & Guazzelli, É. (2014)

- 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.

Project Progress



TASK	Summer 2018	Fall 2018	Spring 2019	Summer 2019	Fall 2019	Spring 2019
Tube flow migration – Data analyses						
Effect of migration on microstructure– Simulations	🟧	🟧	🟧			
Shear cell microstructure– Experiments	🟧	🟧	🟧	🟧		
Shear cell resuspension – Experiments	🟧		▨	▨	▨	▨
Shear cell microstructure – Data analyses	🟧	🟧	🟧	🟧	🟧	🟧
Effect of confinement (shear cell) – Simulations				🟧	🟧	🟧
Jamming in non-uniform flows – Experiments		░	░	░	░	░

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*:

AICHE Conference, "Fiber Alignment in Confined Shearing Flows," Orlando, FL November 13, 2019.

"Microstructural Dynamics and Rheology of Suspensions of Rigid Fibers" by Jason E. Butler and Braden Snook, published in the *Annual Review of Fluid Mechanics (2018)*.

"Shear-induced migration and orientation of rigid fibers in an oscillatory pipe flow" by Scott Strednak, Saif Shaikh, Élisabeth Guazzelli, and Jason E. Butler, *Phys. Rev. Fluids (2018)*.

IUTAM Symposium on Dynamics and Stability of Fluid Interfaces, "Shear-induced dynamics of rigid fibers in an oscillatory pipe flow," Gainesville, FL April 2 – 5, 2018

71st Annual Meeting of the APS-DFD, "Shear-induced migration and orientation of rigid fibers in an oscillatory pipe flow," Atlanta, GA November 18 - 20, 2018.

Acknowledgment

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Disclaimer