Engineering the viscoelastic flow of frac'ing fluids via computer simulation

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Collaborators, Graduate Students, Funding

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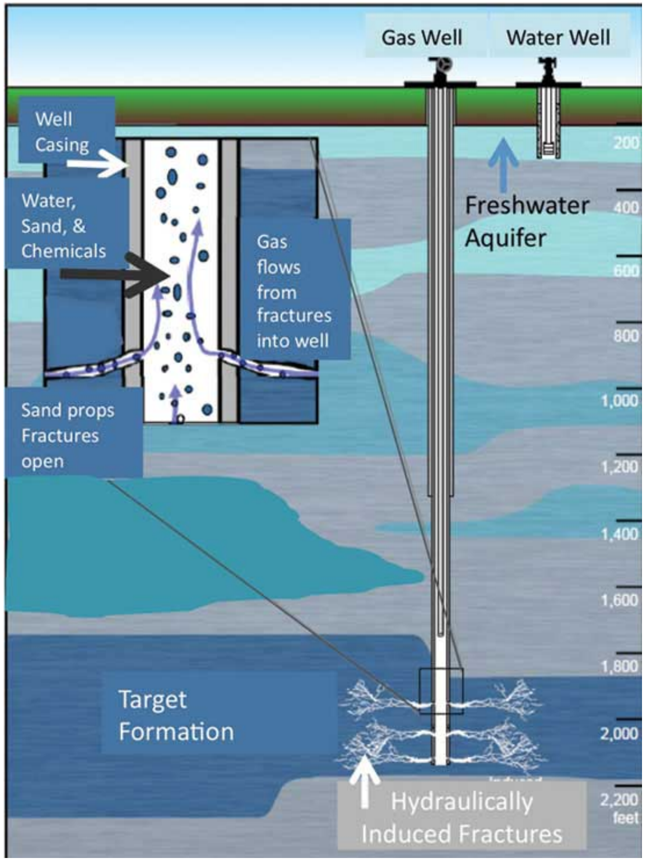
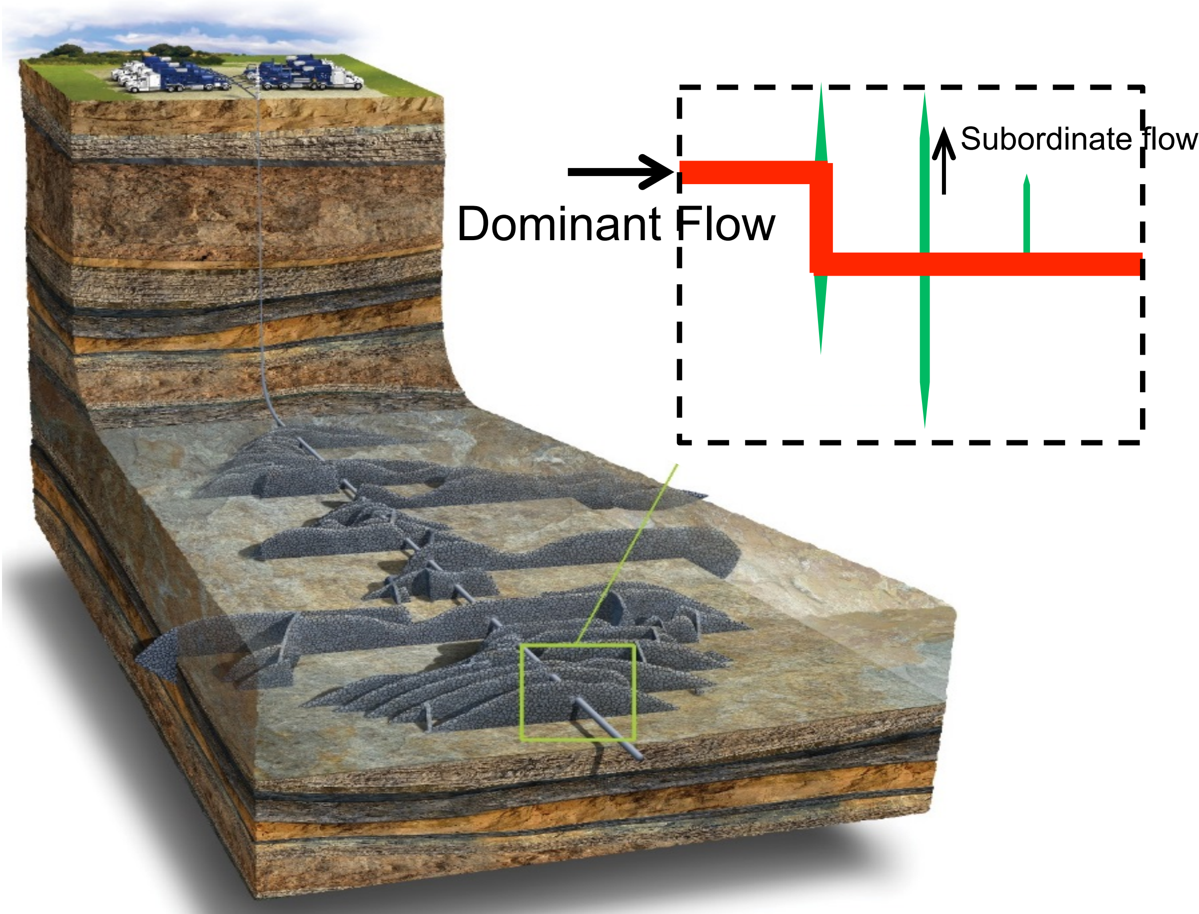
FUNDING

Motivation: Proppant Support!

- Suspensions of solids in *polymeric* solutions

are pumped to help prop open the fracture (frac'ing fluid)

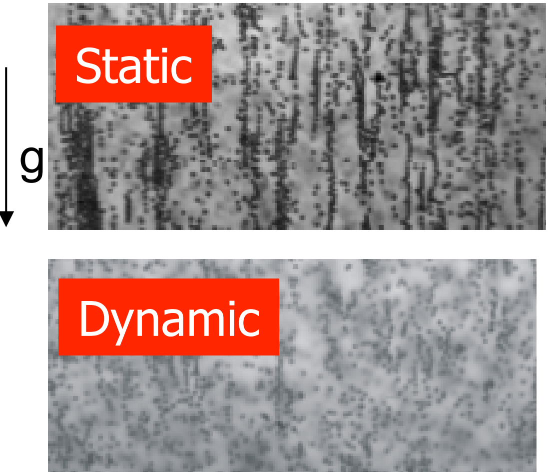


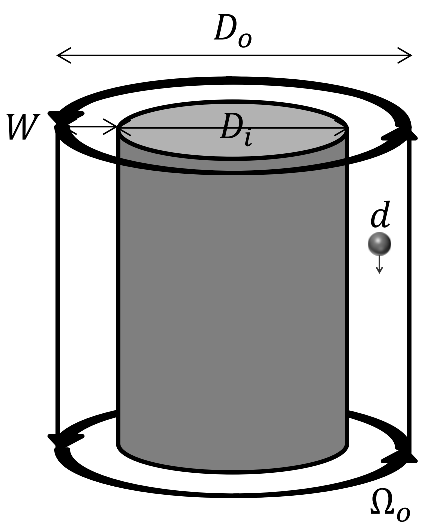


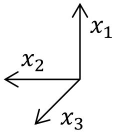
Barbati, A. C., Desroches, J., Robisson, A., McKinley, G. H. "Complex Fluids and Hydraulic Fracturing" (submitted, 2015)

“Good” proppant support vs. “Bad” proppant support

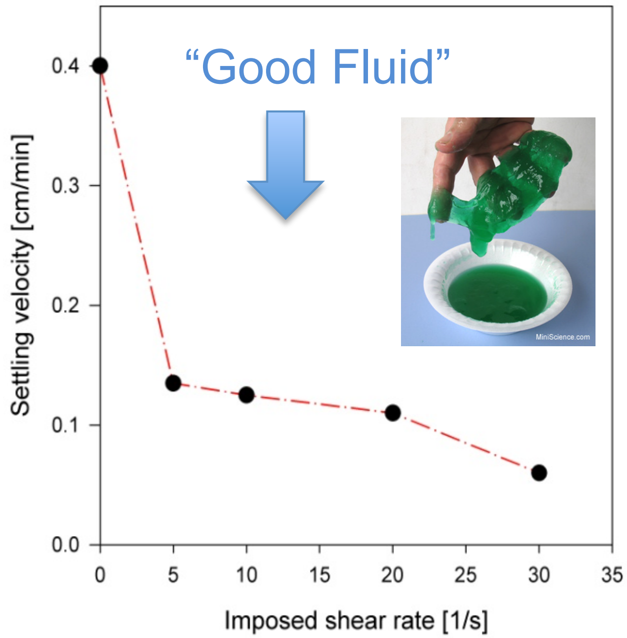
- *Guar gum solutions: (Tonmukayakul et al. 2008)*





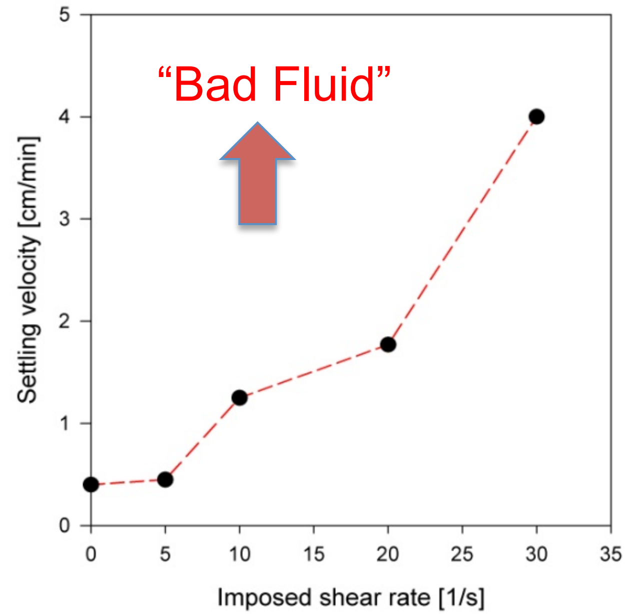


93 ppm borate cross linked



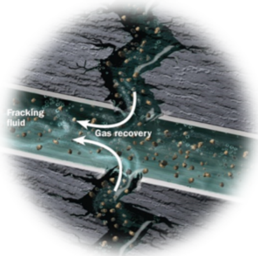
Highly Elastic

31 ppm borate cross linked

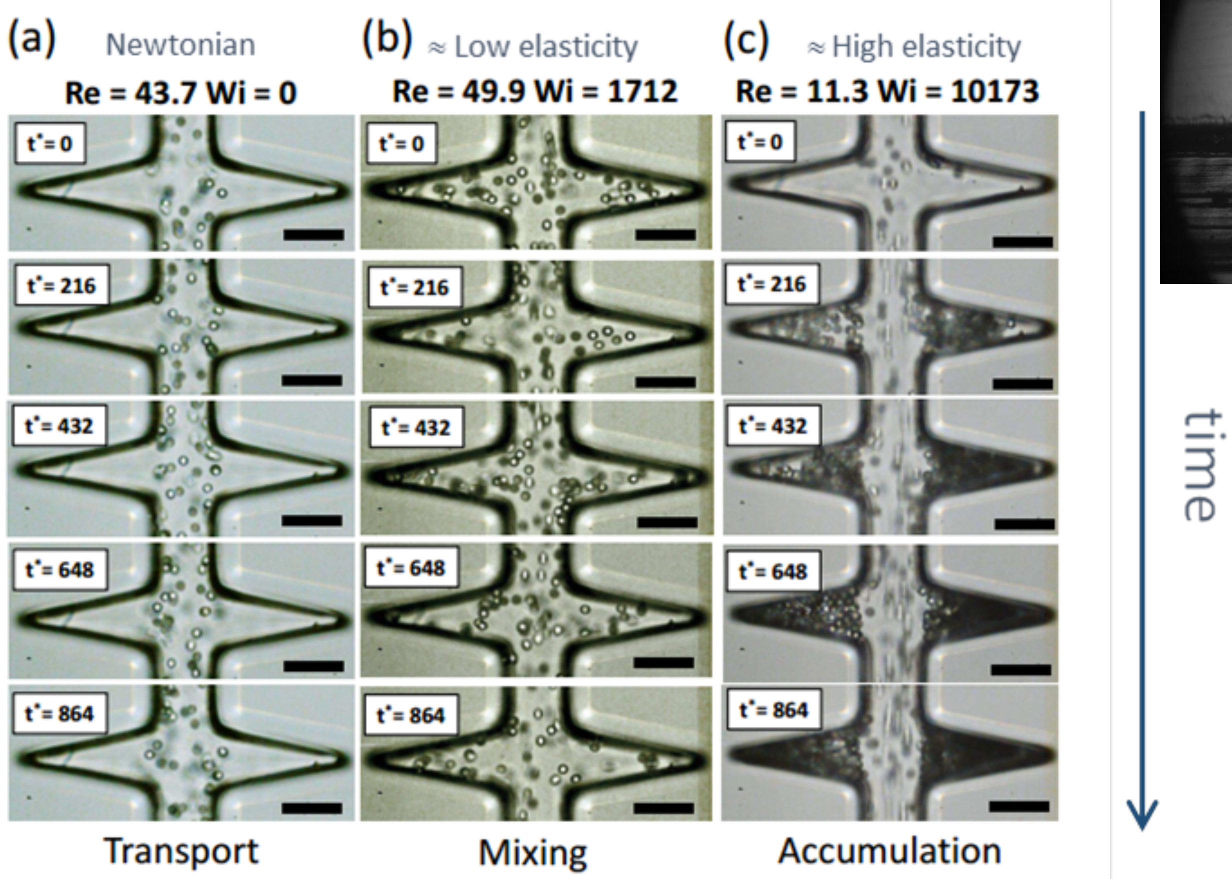


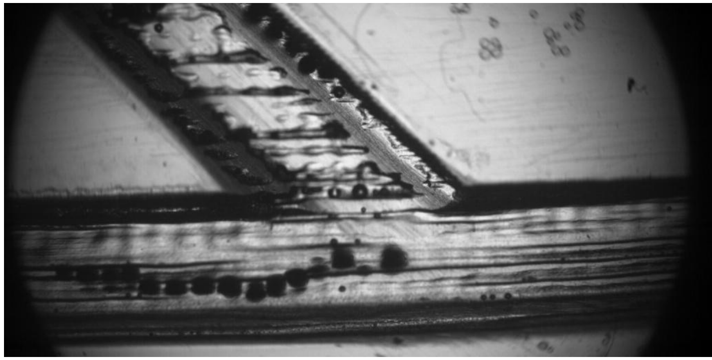
Weakly Elastic

Other Issues: Proppant Trajectory



Experiments (left) conducted by Barbati et al. MIT, (right) by Morris & Manoorkar, CCNY)





Re= 115, 35%

Goals of Project

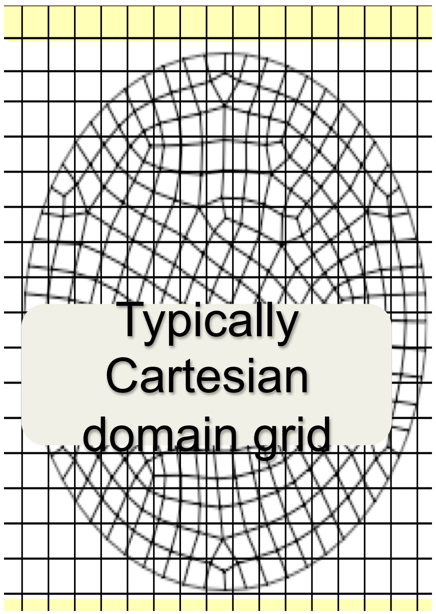
- *Develop a computer simulation tool to simulate particulate flows of viscoelastic frac'ing fluids in realistic crack geometries*
- *Use this tool to understand the operation of these fluids and, thus, engineer their associated proppant transport for predicted downhole conditions.*

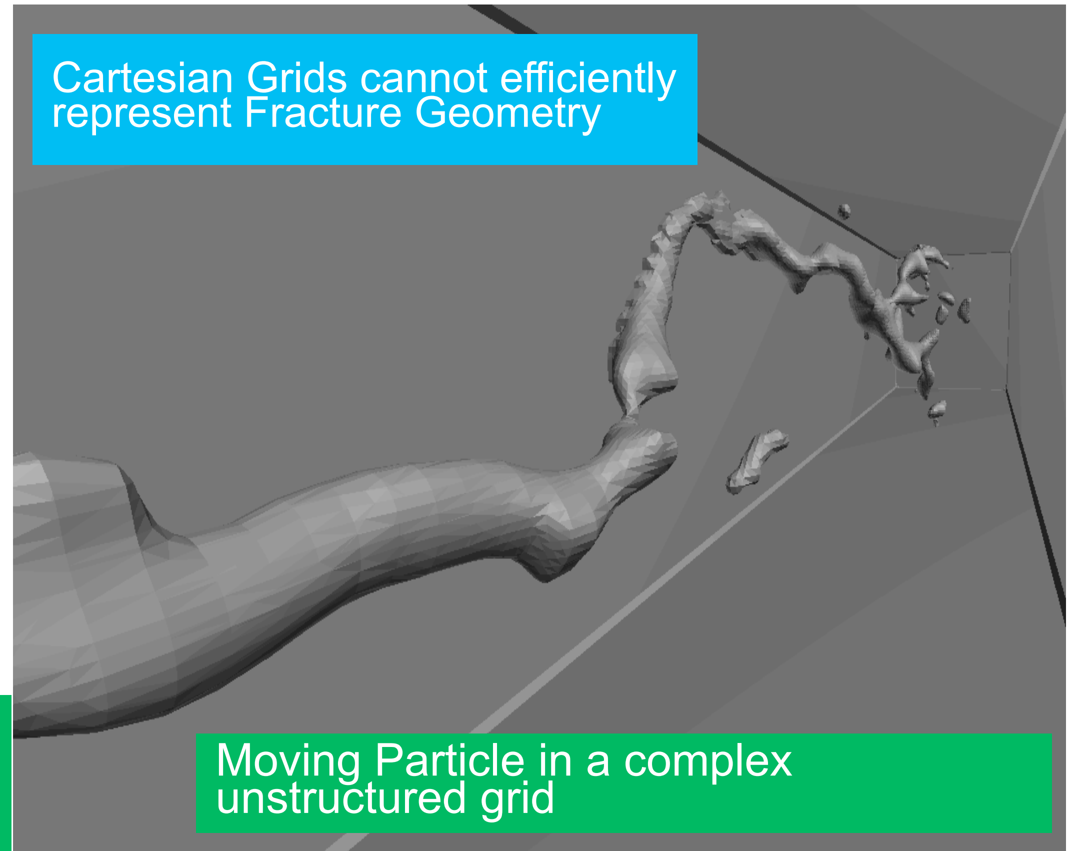
Challenges

- *Evolving, Complex Geometries*
  - *Must be massively parallel code!*
- *Time Dependent, Highly NonLinear Flow Problem*
  - *Must be careful with stability and accuracy of numerical method!*
- *Rheology of Suspending Fluids Only Beginning to be Understood.*
  - *Must be flexible and coupled to experimental program!*

Immersed boundary (IB) method

Simulate flows on grids that do not conform to the shape of the boundaries





Simplifies **mesh generation**

No re-meshing when particles move

Key ideas

VARIABLE DENSITY FLUID

Particle regions are "fluids" with density equal to particle density

Body Forces

$$\frac{\partial u_j}{\partial x_j} = 0$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial[\rho u_i u_j]}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i + \rho \mathcal{R}_i$$

NAVIER – STOKES (N-S) eqn. FOR THE ENTIRE DOMAIN

Additional force to impose rigid body motion for the "fluid" occupying the particle regions

RIGIDITY CONSTRAINT FORCE

- $\rho = \rho_f(1 - \Theta) + \rho_p \Theta$
- Θ is the indicator function that has a value 1 inside the particle region and zero outside

Apte et at, 2009, JCP

Governing equations

Polymer Concentration

Additional Stress due to elasticity of polymers

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\beta}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{1-\beta}{Re}\frac{1}{Wi}\frac{\partial \tau_{ij}^p}{\partial x_j} + F_i$$

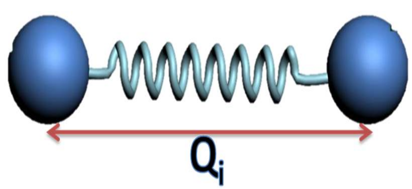
Weissenberg number

Ratio of characteristic polymer relaxation timescale and flow timescale

Rigidity Constraint force

FENE-P Model

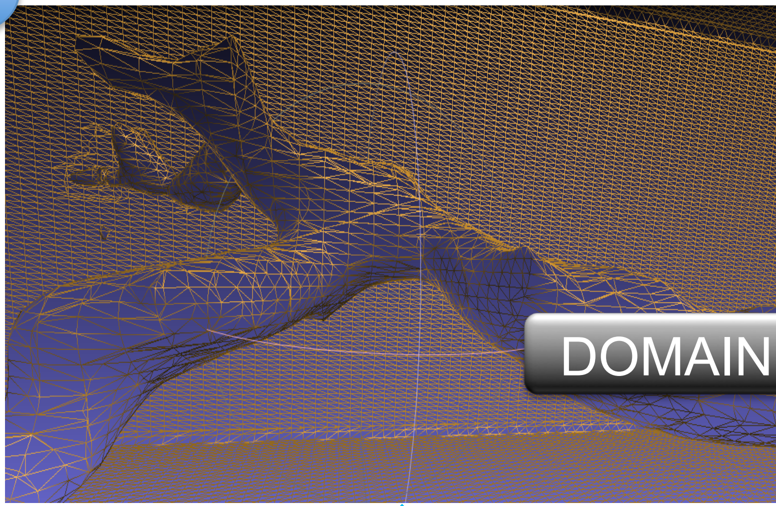
Non – linear Spring

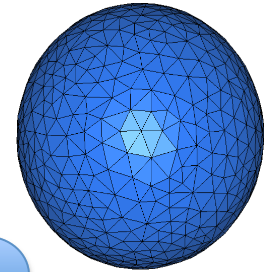


$$\frac{\partial c_{ij}}{\partial t} + u_k \frac{\partial c_{ij}}{\partial x_k} - c_{ik}\frac{\partial u_j}{\partial x_k} - c_{kj}\frac{\partial u_i}{\partial x_k} = \frac{1}{Wi}\tau_{ij}^p$$

$$\tau_{ij}^p = \frac{c_{ij}}{1 - c_{kk}/L^2} - \delta_{ij} \qquad c_{ij} = \langle Q_i Q_j \rangle$$

1 SOLVE N-S eqns IN THE DOMAIN





IMMERSED PARTICLE

2 PROJECT VELOCITY TO PARTICLE MESH

3 ESTIMATE LINEAR/ANGULAR VELOCITY

Conserve linear and angular momentum in the particle grid

4 ESTIMATE RIGIDITY FORCE

From the difference between projected velocity and rigid body motion

5 PROJECT RIGIDITY FORCE TO DOMAIN

6 CORRECT VELOCITY IN THE DOMAIN

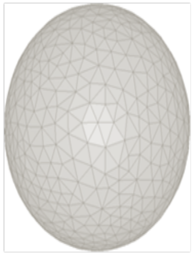
Also, move the particle

Eulerian

Lagrangian

1 SOLVE N-S eqns IN THE DOMAIN

INTERPOLATION



IMMERSED PARTICLE

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From the difference between projected velocity and rigid body motion

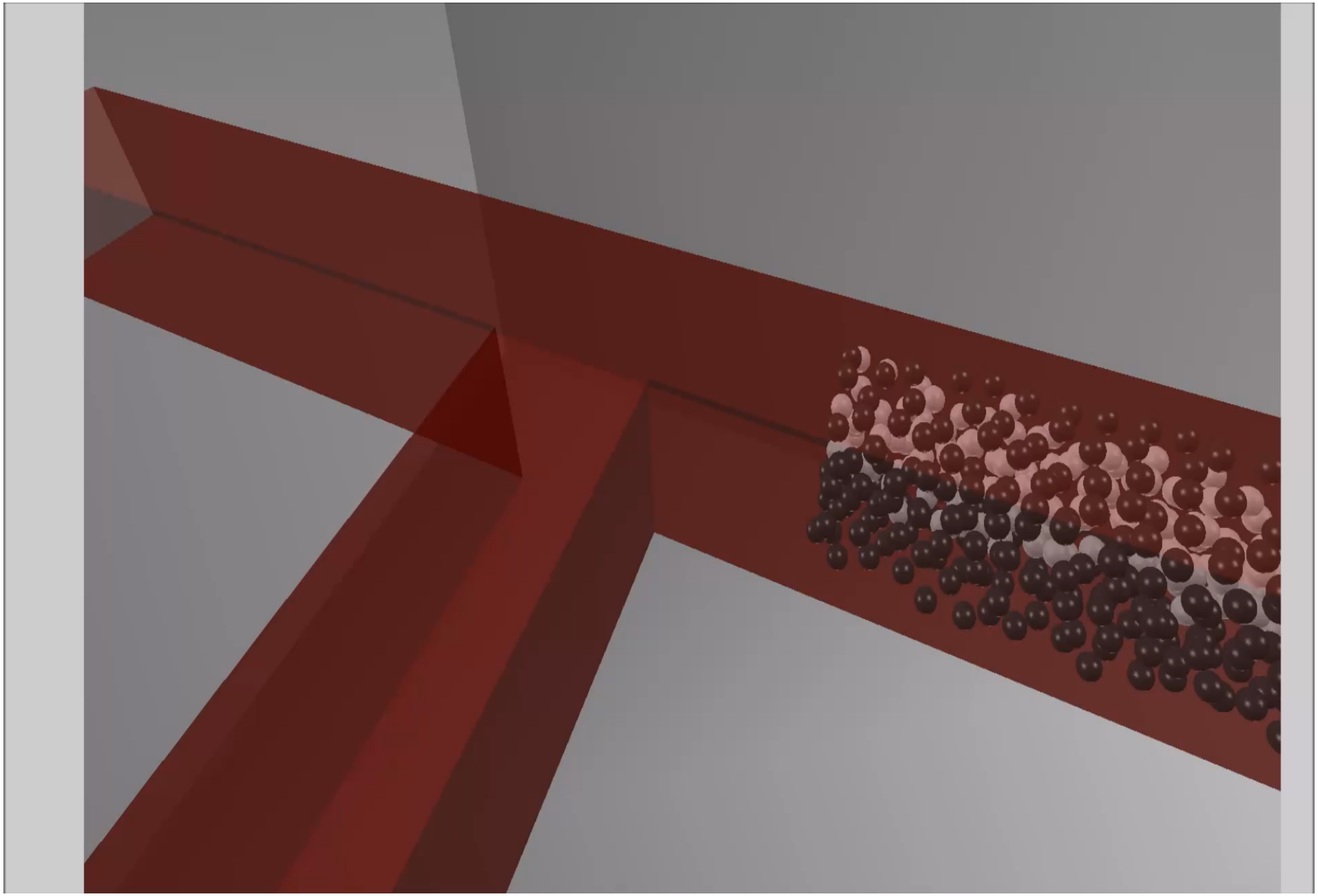
PROJECTION

5 PROJECT RIGIDITY FORCE TO DOMAIN

6 CORRECT VELOCITY IN THE DOMAIN

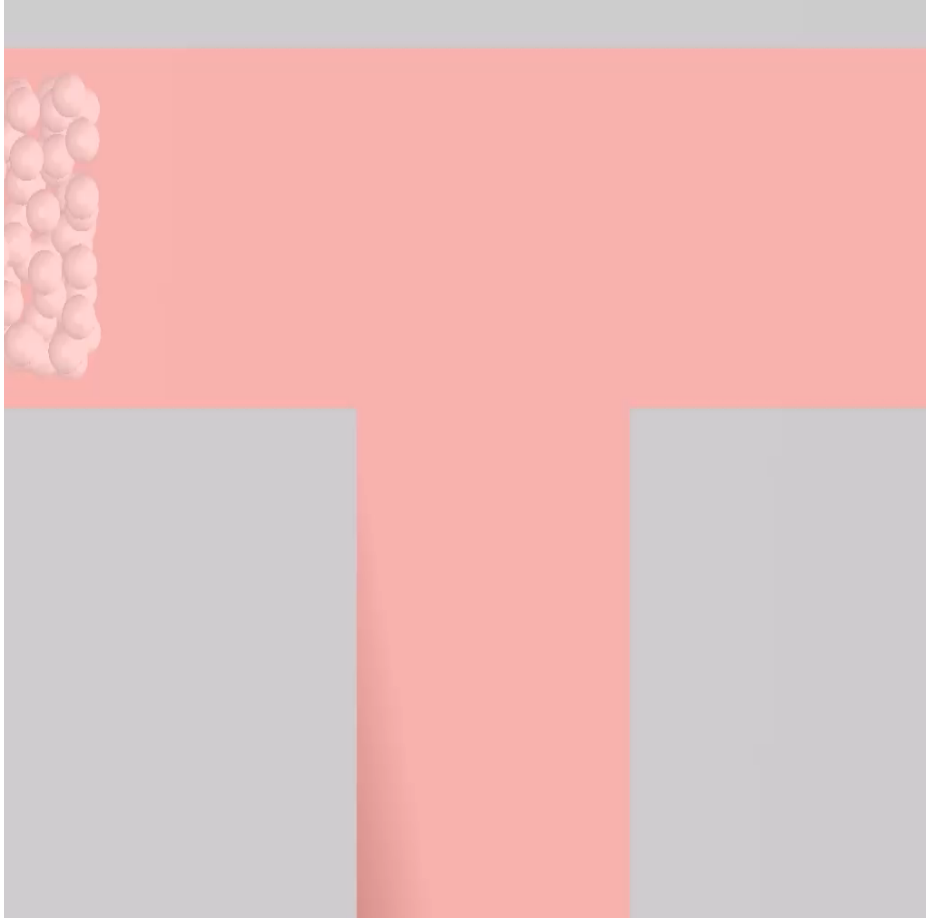
Also, move the particle

Results for Particle “Split”



Results for Particle "Split"

Simulation



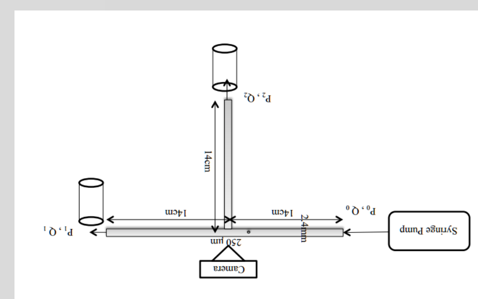
Experiment

Re 100, 14.5% *Different frame rates Re 115, 35%

Results for Particle "Split" – *The Full Geometry*

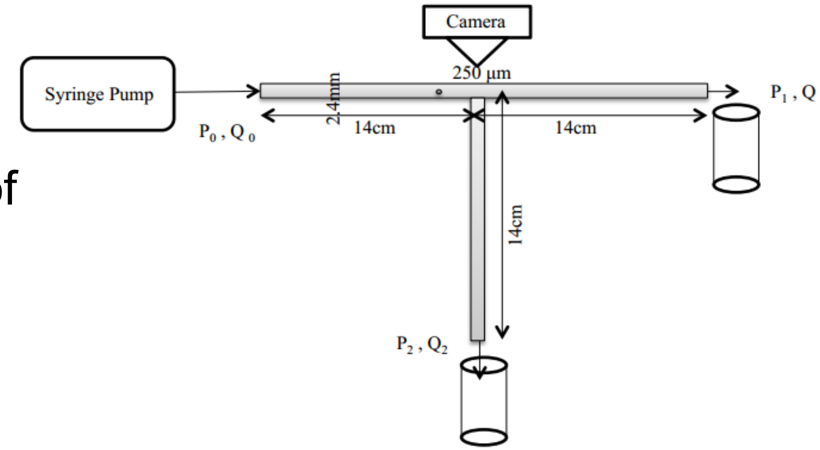
- Channel with square cross section
- Sphere radius is 1/10th of the wall separation
- Reynolds number = 10
- Neutrally buoyant particles
- 5% Volume fraction
- 1:1 correspondence between experiment and simulation geometry

0.05

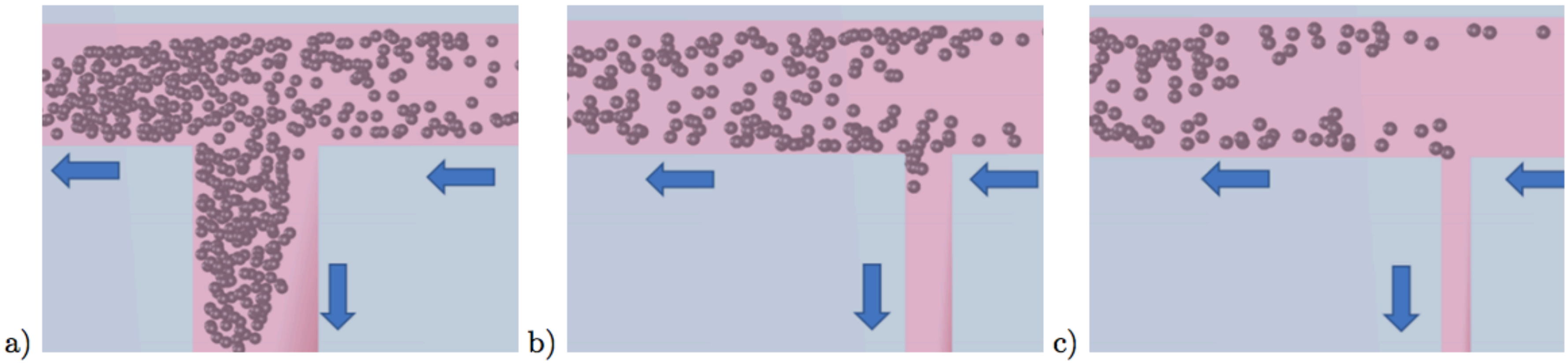


Particle split comparison with experiments – Newtonian

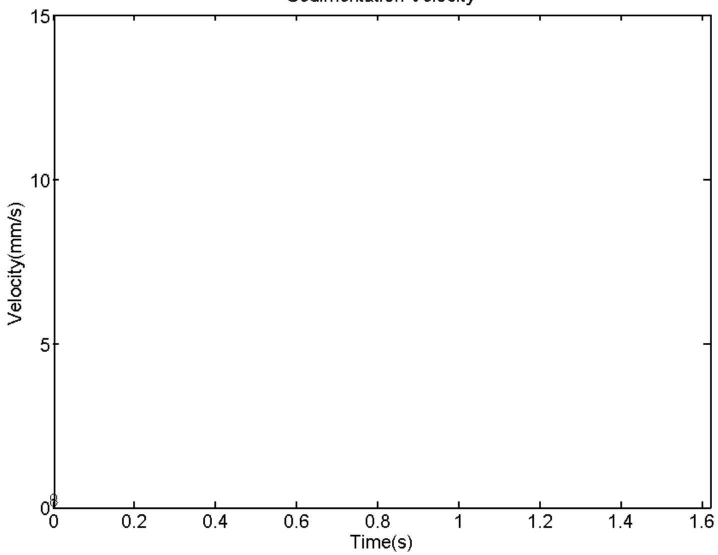
Experiments conducted at The City College of New York (Jeff Morris, Sojwal Manoorkar)

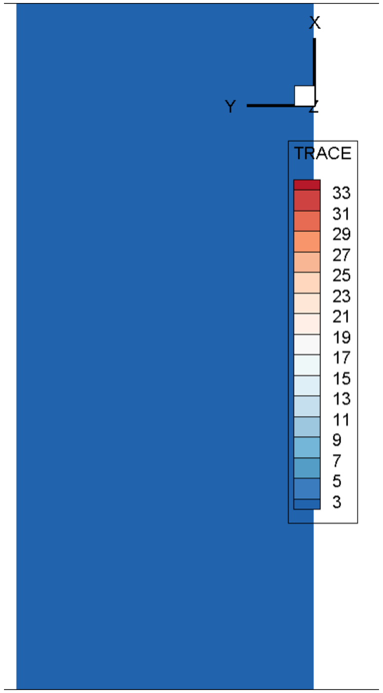


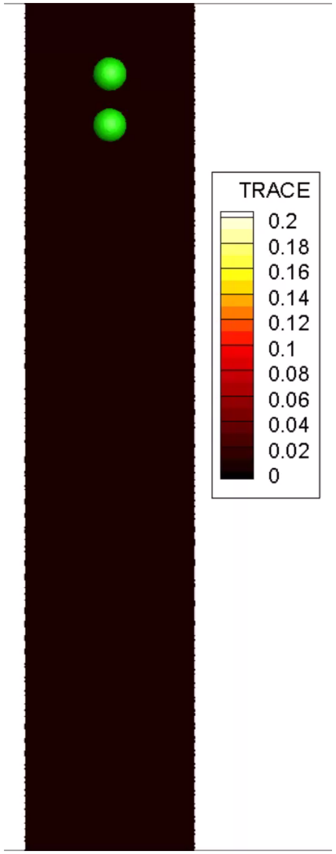
Sl No.	T-Junction	Particle Diameter / Main Channel width	Concentration	No. of particles in the simulation	Particle Split (Experiment)	Particle Split (Simulation)
1	1:1	0.1	14.5%	500	50%	53%
2	1:3	0.1	15%	250	3.6%	4.4%
3	1:5	0.1	10%	250	0%	0%



Particle Sedimentation in Elastic Fluids







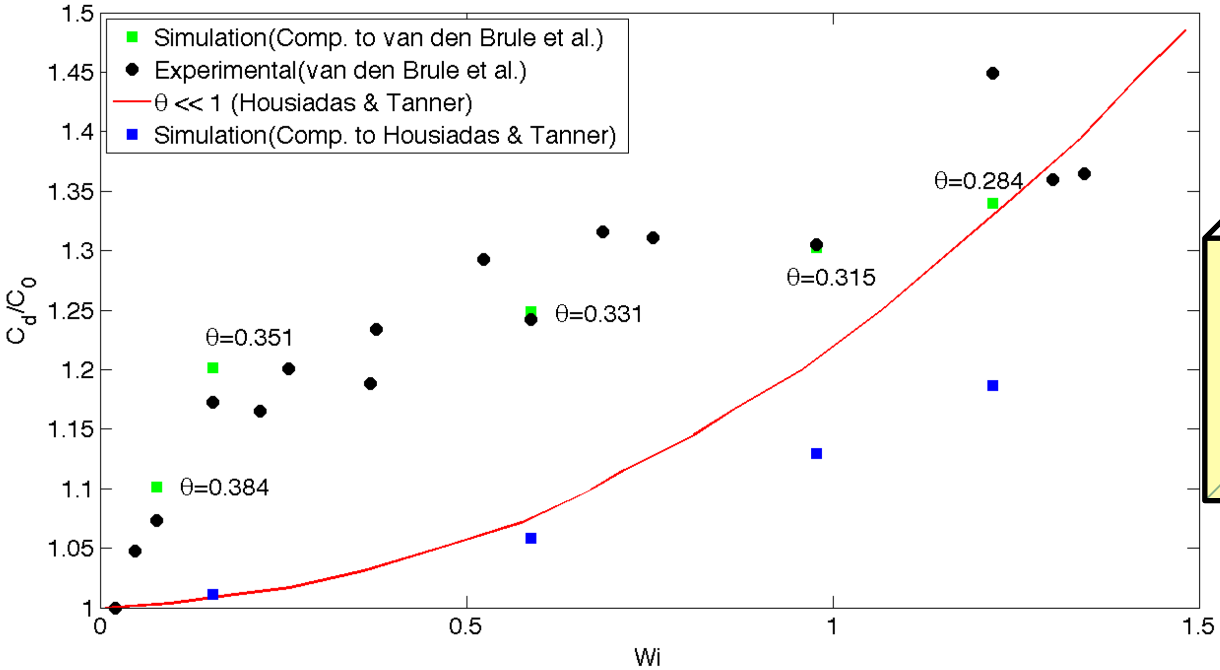
Results: Experimental Comparison to Literature Values

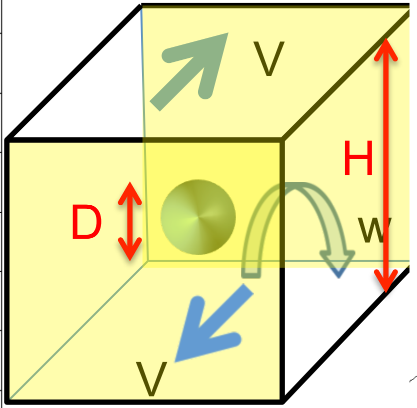
0.01 % ppm PAA (van den Brule et al.1993)

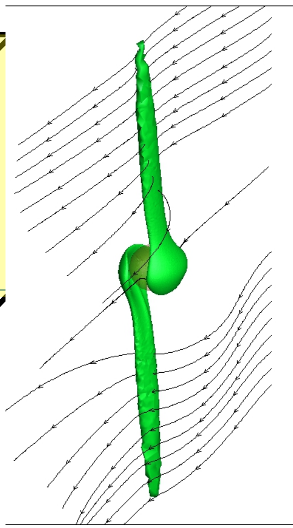
- *The drag coefficient is given by :* $C_d = \dfrac{2F_1}{(\mu_P + \mu_S)UD}$
- *Settling Rate* ⬇ *or Drag Coefficient* ⬆

$U_0/U = C_d/C_{d0}$

U_0 - Sedimentation velocity at Wi = 0







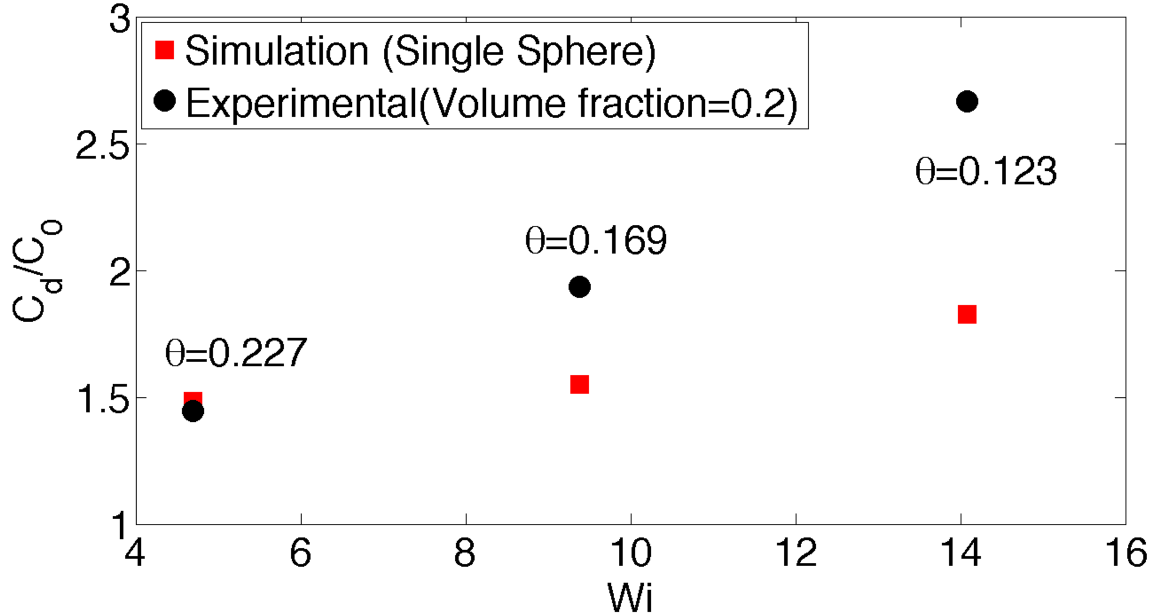
Results: Experimental Comparison at finite volume fraction

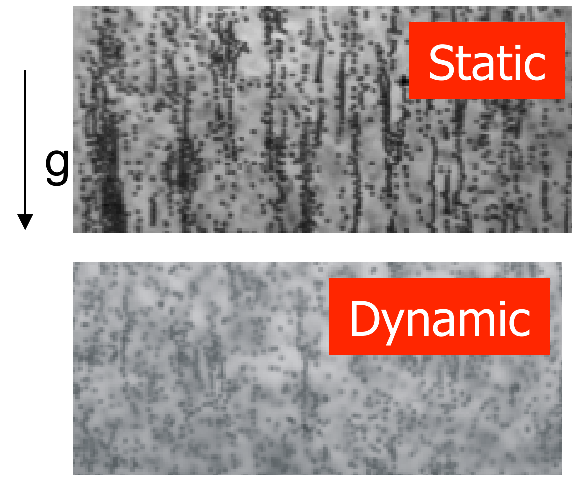
1% PAA solution (Tonmukayakul et al. 2008)

- *Re=0.01 for all simulation results again*
- *Simulation results are in qualitative agreement with experiments*

Direct comparison to Tonmukayakul et al.2008

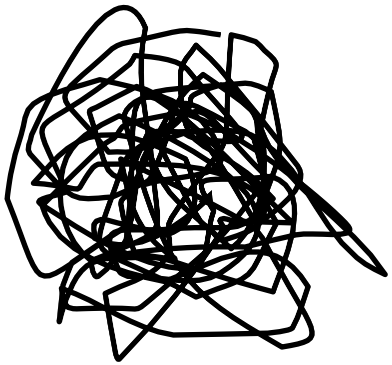
Is the interpretation that interparticle interactions Increase the effect?



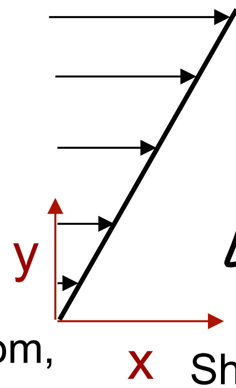


Elastic Fluid Rheology

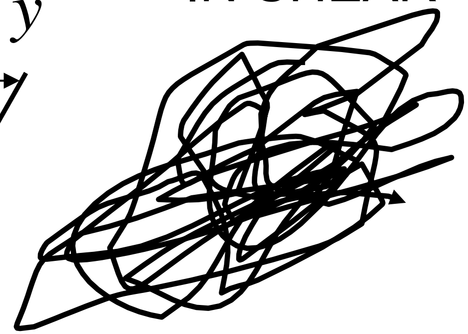
EQUILIBRIUM COIL



$U = \dot{\gamma} y$

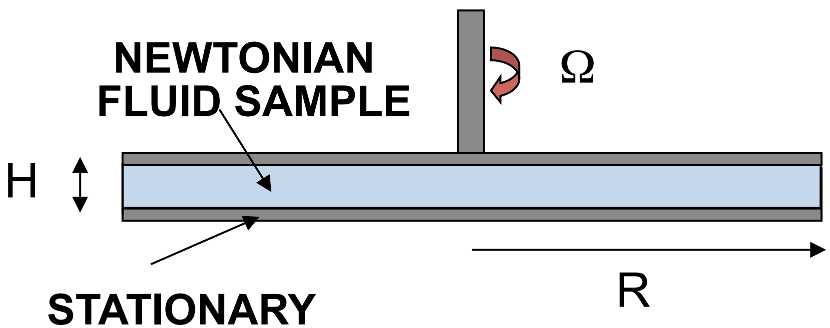


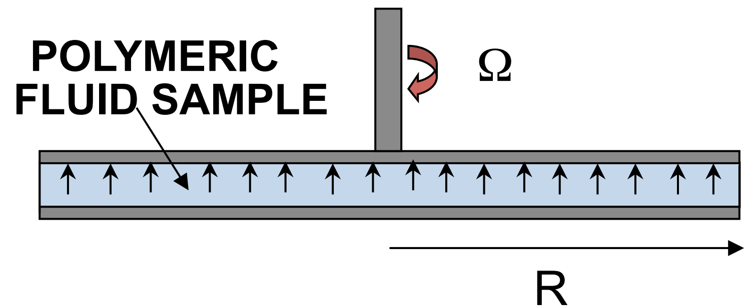
IN SHEAR



Diffusion makes coil random, isotropic

Shear causes stretch. Configurational or Entropic restoring force causes stress !





Torque = constant $\mu R\Omega/H$

μ = shear viscosity

Torque = constant $\mu R\Omega/H$

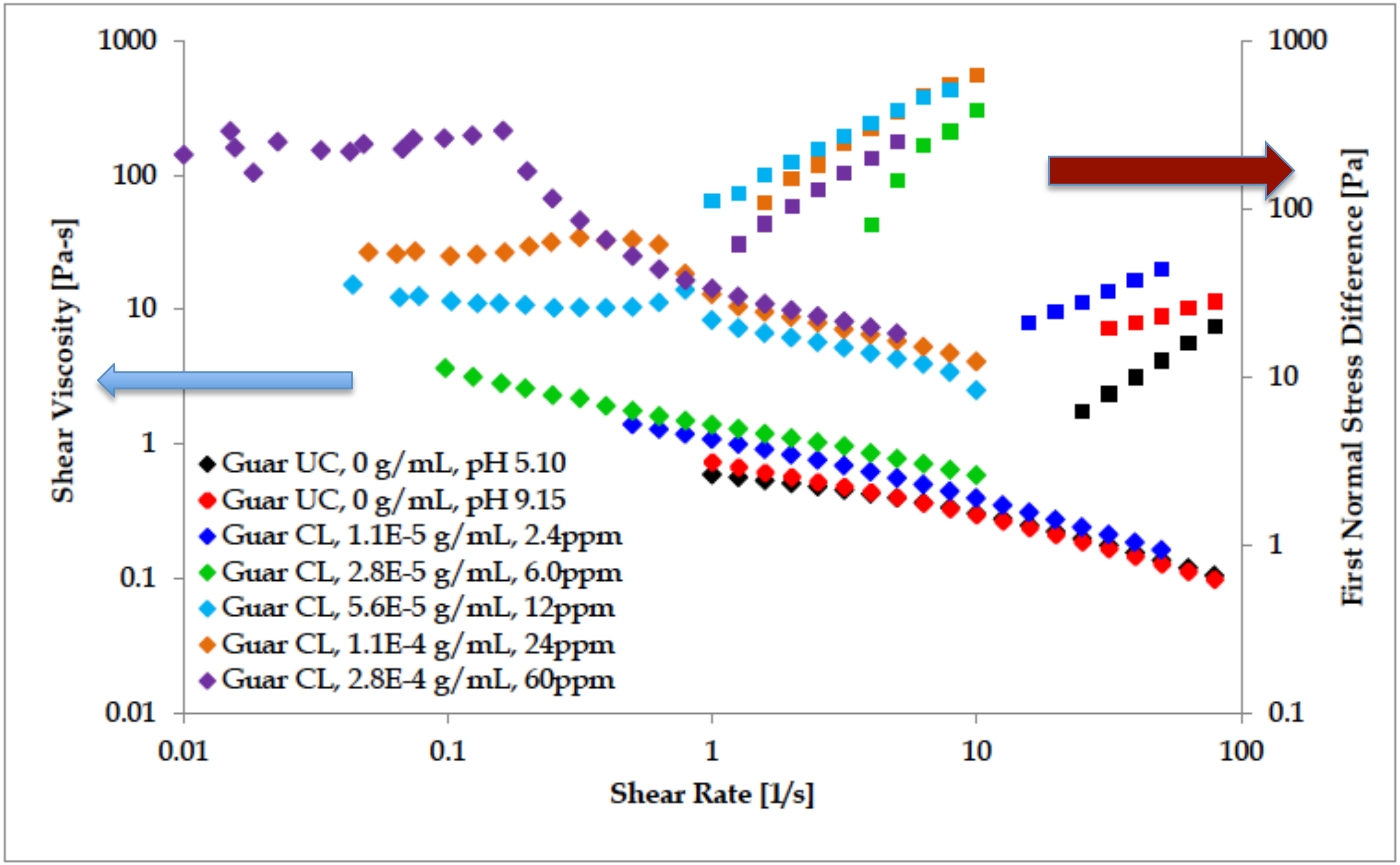
μ = shear viscosity

Normal Force = constant $\Psi(R\Omega/H)^2$

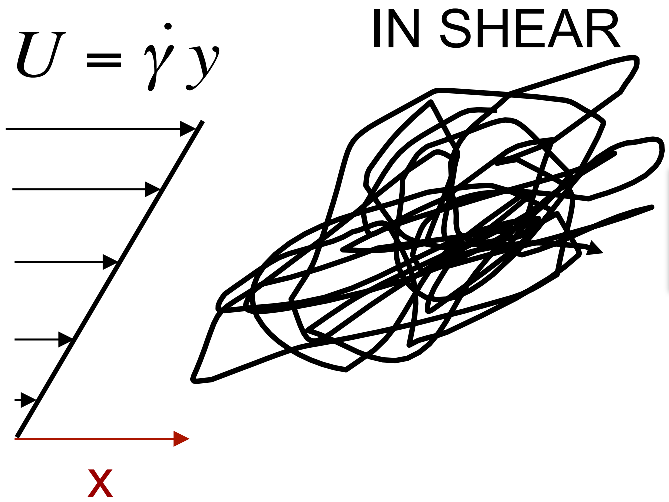
Ψ = primary normal stress coeff.

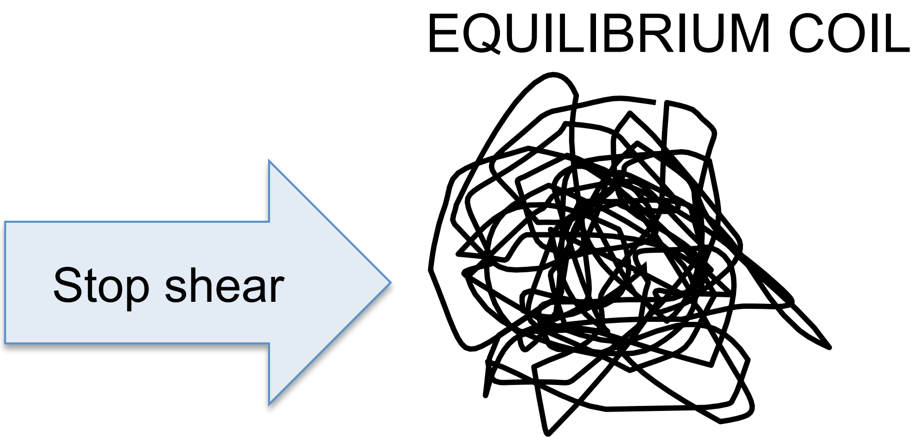
Frac'ing Fluid Rheology

- Effect of increased crosslinker concentration observed in shear viscosity and N1
  - Significant increase in N1 above 1.1e-5 g/mL sodium tetraborate (2.4 ppm boron)



Relaxation Times for Frac'ing Fluids





Diffusion makes coil random,
Isotropic again !

Relaxation occurs at time λ intrinsic to polymer solution

- CL guar fluid relaxation times estimated from crossover frequencies and transient step-relaxation tests

$[Na_2B_4O_7]$ (g/mL)	λ_{SAOS} (s)	λ_{N1} (s)	λ_{G} (s)
0.00E+00	0.25	--	0.29
0.00E+00	0.25	0.22	0.25
1.10E-05	0.63	0.77	1.1
2.80E-05	3.1	1.1	1.5
5.60E-05	25	4.3	4.0
1.10E-04	57	4.9	5.7
2.80E-04	>60	7.8	10

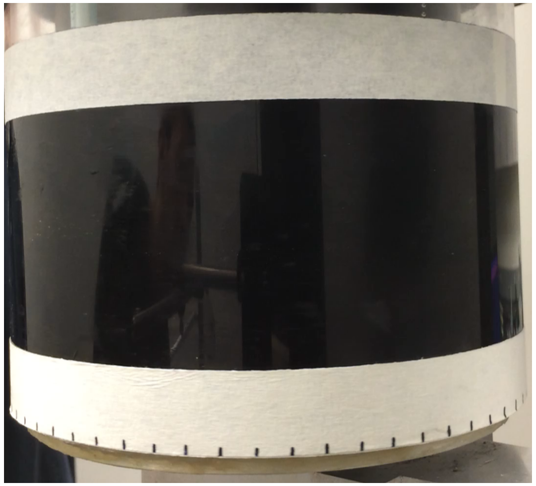
New Experiments: Sed. In Frac'ing Fluids

- Orthogonal shear experiments using a Taylor-Couette cell
  - Gap, W = 1.0 cm
  - **0 < Wi < 10**

U_0 - Sedimentation velocity at Wi = 0

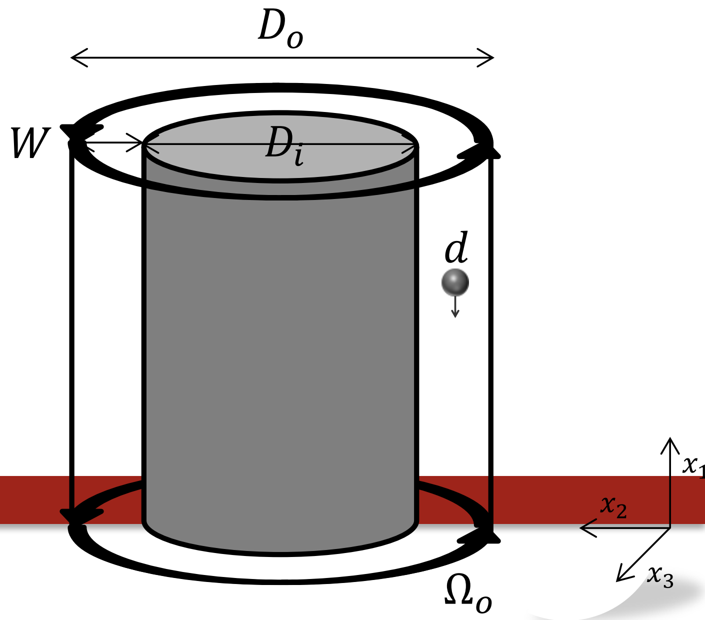
- Model Elastic Fluids and
- Real Guar Gum Solutions!

$U_0/U = C_d/C_{d0}$

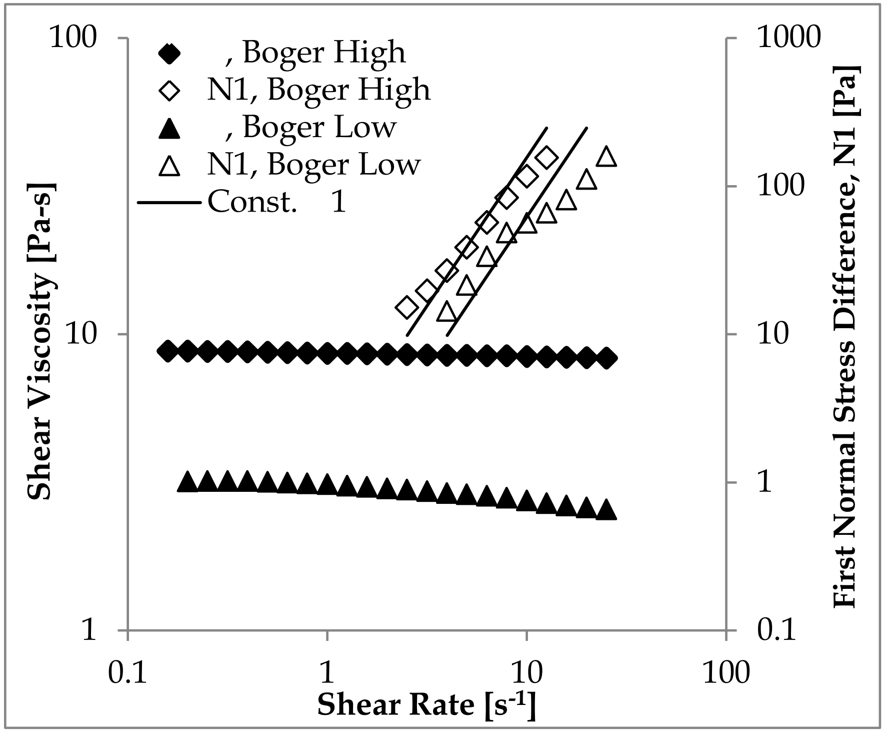


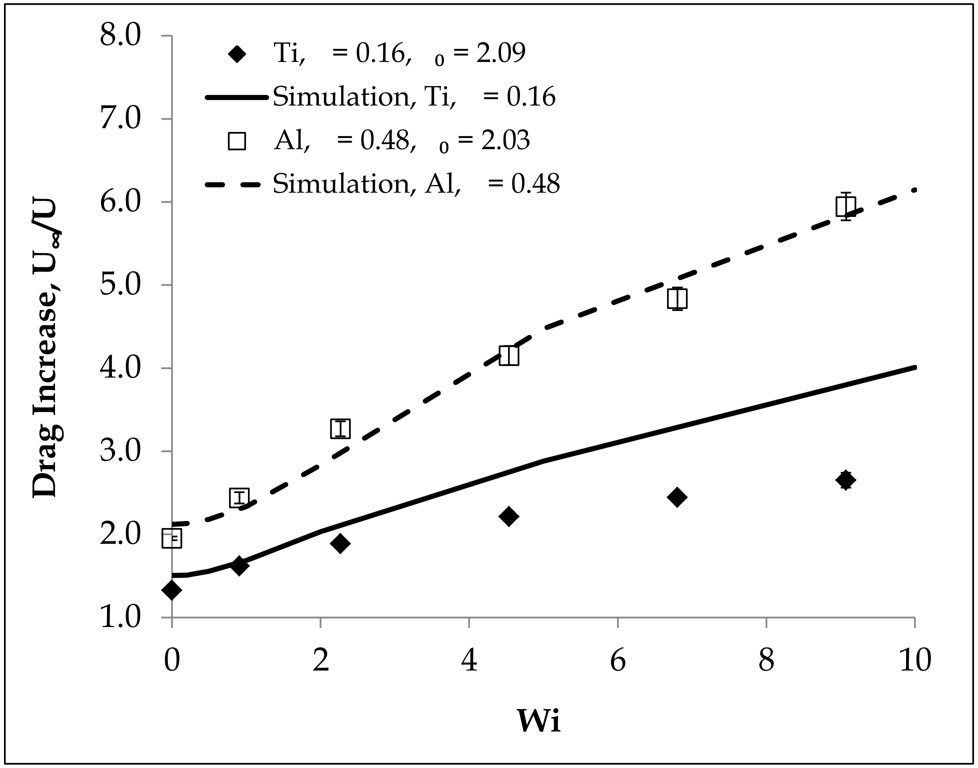
- Stainless steel (8.00 g/cm^3)
- Titanium spheres (4.43 g/cm^3)
- Aluminum spheres (2.79 g/cm^3)

- Sphere size:
  - $\varepsilon = d/W = 0.16,\ 0.32,\ 0.48$



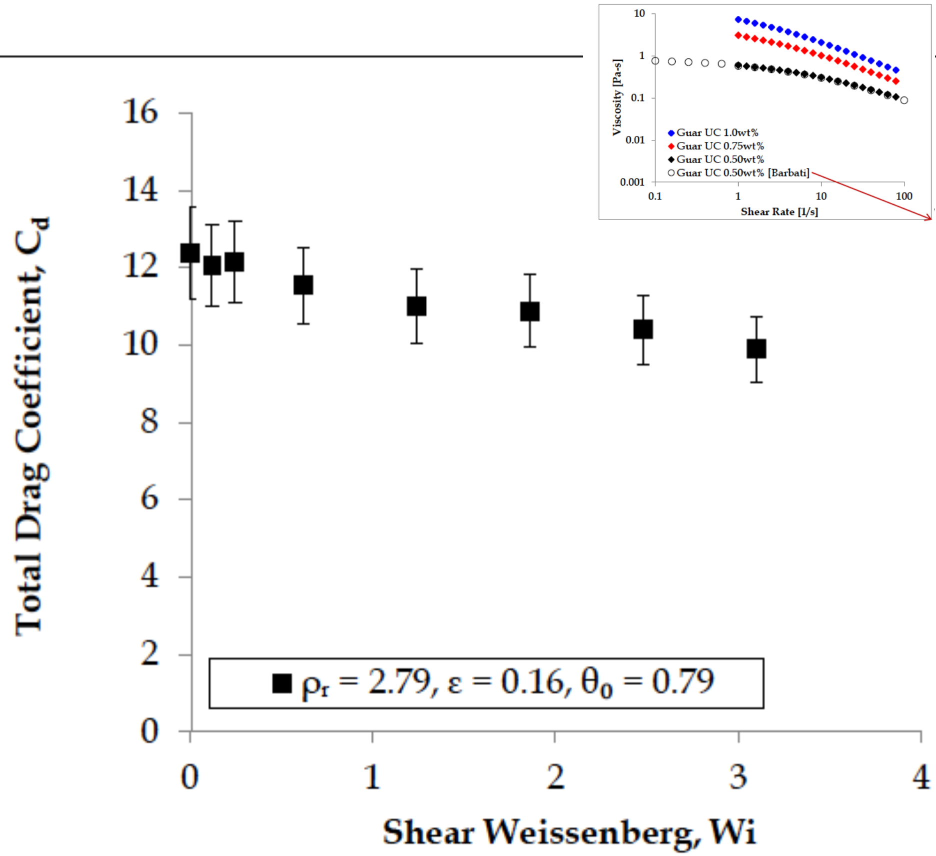
Model Highly Elastic, Constant Viscosity Fluids





“Weakly” Cross-linked Guar Gum Solutions

- Drag reduction in *weakly crosslinked* guar gum solutions (0.3wt% guar, 31 PPM borate) under orthogonal shear was predicted qualitatively using numerical simulation by Padhy et al. [2], and attributed to a decrease in polymer stresses



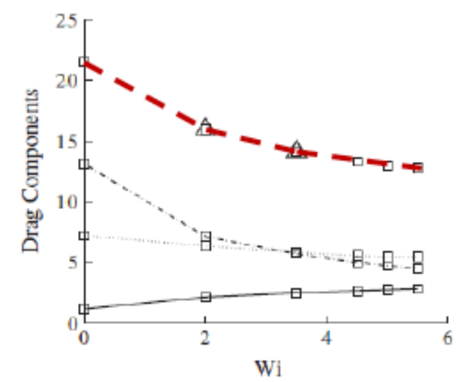


Fig. 5. Drag coefficients and components (θ = 0.15). □, total drag (finer mesh); △, total drag (coarser mesh); – · · □ · · –, polymer drag; · · · · □ · · · ·, form drag; –□–, viscous drag.

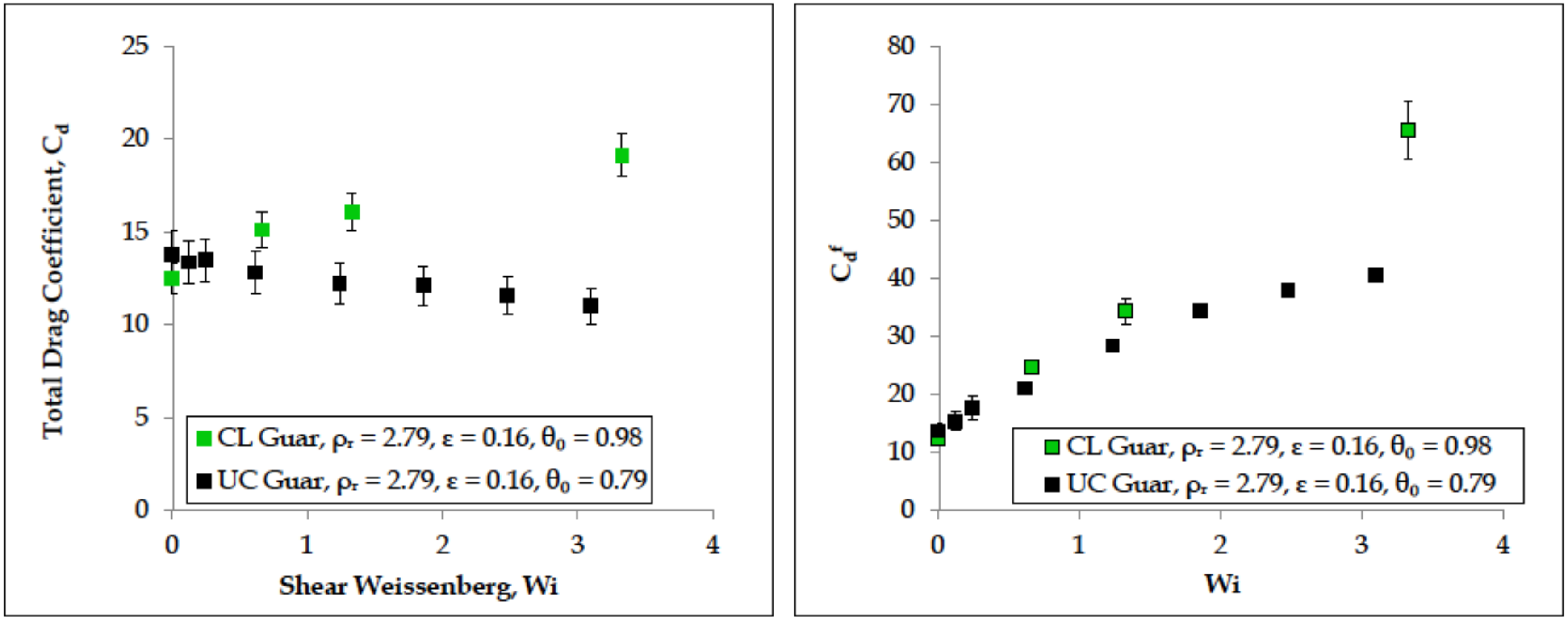
Figure from Padhy et al. [2]; guide-to-eye drawn for total drag (red)

$$C_d = \frac{F_d}{\eta U r} = \frac{4\pi r^2(\rho_f - \rho_s)g}{3\eta_0 U}$$

[2] *Padhy et al., J Non-Newton Fluid Mech (2013): 201*

Increased Cross-linking in Guar Gum Solutions

- Addition of even a modest amount of crosslinker (2.8E-5 g/mL sodium tetraborate) changes the fluid behavior (left) from ***decreasing* total drag (uncrosslinked guar)** to ***increasing* total drag (crosslinked guar)** as a function of shear Weissenberg number, Wi for low Wi:



Where:

$$C_d = \frac{F_d}{\eta U r} = \frac{4\pi r^2(\rho_f - \rho_s)g}{3\eta_0 U}$$

$$C_d^f = \frac{F_d}{\eta_f(Wi)\,Ur} = \frac{4\pi r^2(\rho_f - \rho_s)g}{3\,\eta_f(Wi)\,U}$$

- Rescaled drag shows a **drag *increase*** for both fluids (right)

Overall Computational Project

- *Develop a computer simulation tool to simulate particulate flows of viscoelastic frac'ing fluids in realistic crack geometries*
- *Use this tool to understand the operation of these fluids and, thus, engineer their associated proppant transport for predicted downhole conditions.*

Related Experimental Goals

- *Develop a Constitutive Equation for Frac'ing Fluids at different degrees of crosslinking, as input to computational simulation.*
- *Verify and Validate Constitutive Equation and Simulations with Orthogonal Shear Sed. Experiments Using "Real" Frac'ing Fluids*

FUNDING