MICROMECHANICS OF CONCENTRATED SUSPENSIONS FOR PROTECTIVE FABRICS

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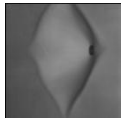
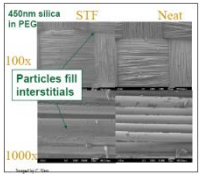
RESEARCH OVERVIEW

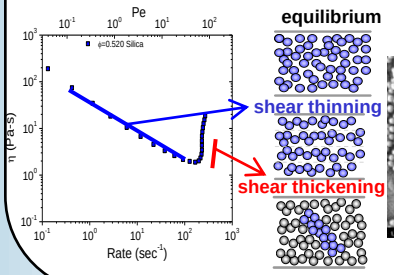
- Concentrated suspensions combined with protective fabrics improve stab protection
- Additional uses for these materials exist as damping materials in vehicle structures, hip protection, sporting goods, etc. are under investigation at UD or through technology licensed from UD
- Predictive understanding of suspension behavior necessary for use in applications

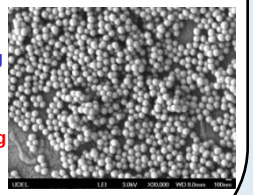




SUSPENSION INVESTIGATED

- Commercial spherical silica particles
- Near hard-sphere, surface stabilized
- ~120nm diameter (SEM, SANS)
- Suspended in Newtonian, partly deuterated ethylene glycol/poly(ethylene glycol) solvent mix
- Strongly, continuously shear thickening at ϕ~0.50

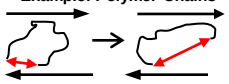




GOAL – DEVELOP STRUCTURE/ PROPERTY RELATIONSHIPS

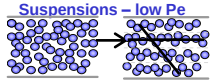
- **Polymers**
  - Controlled by thermodynamics
    - Displacement from equilibrium requires energy
    - Stretching/disentangling polymers requires work
    - Fully stretched structure cannot support more stress
    - Shear Thinning!
- **Low Pe – Brownian Suspensions**
  - Controlled by thermodynamics
    - Displacement from equilibrium requires work
    - Brownian motion, Van der Waals forces, electrostatics
    - Structure saturates – additional rearrangements cannot support more stress
    - Shear Thinning!
- **High Pe – Suspensions**
  - Controlled by hydrodynamics
    - Motion of particles within fluid requires displacement of fluid
    - Forces become much larger at very thin gaps – lubrication
    - Viscosity related to structural growth AND shear rate
    - Saturating structure leads to power-law thickening

Example: Polymer Chains



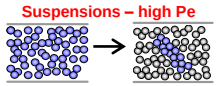
$$\tau_p \propto \langle \underline{RR} \rangle$$

Suspensions – low Pe



$$\eta_{Thermo} \propto P_{21} / \dot{\gamma}$$

Suspensions – high Pe



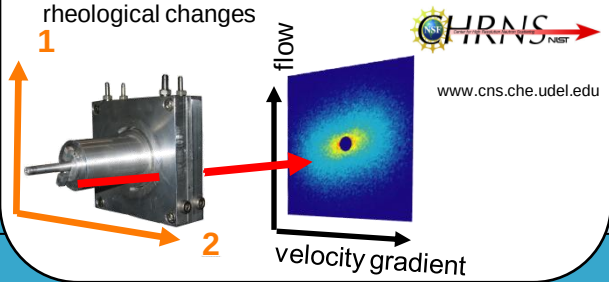
$$\eta_{hydro} \approx 2\mu C P_1(\dot{\gamma})$$

Suspension: See Wagner and Ackerson, J. Chem. Phys, 1992

Polymer Scaling: See Larson, The Structure and Rheology of Complex Fluids 1999.

FLOW-SMALL ANGLE NEUTRON SCATTERING (FLOW-SANS)

1-2 Plane SANS can measure structure directly in shear plane. Now we can measure in all 3 planes of shear to match microstructural changes to rheological changes



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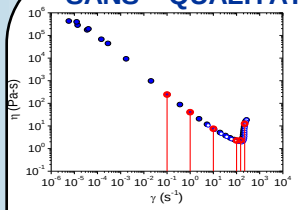
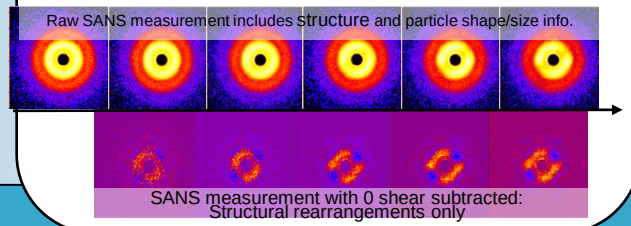
SANS – QUALITATIVE OBSERVATIONS



Peaks correspond to high particle concentration.

Structure saturates.

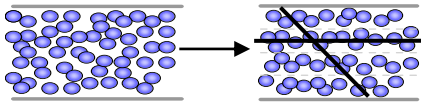
Increasing rate ->



MICROMECHANICS OF CONCENTRATED SUSPENSIONS FOR PROTECTIVE FABRICS

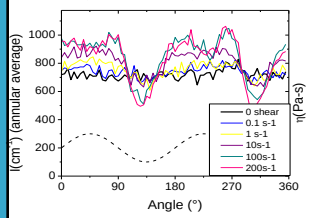
(Continued)

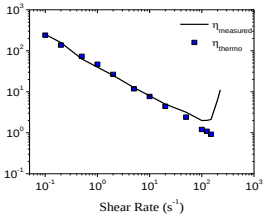
THERMODYNAMIC VISCOSITY FROM SANS



$$P_{21} = \int_0^{2\pi} \left(\frac{I(q,\theta,\dot{\gamma})}{I(q,\theta,\dot{\gamma}=0)} - 1 \right) \cdot \cos\theta \cdot \sin\theta \, d\theta$$

$$\eta_{Thermo} \propto P_{21} / \dot{\gamma}$$

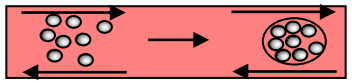




Note: First microstructural measurements of thermodynamic stress that drives shear thinning.

Wagner and Ackerson, J. Chem. Phys., 1992

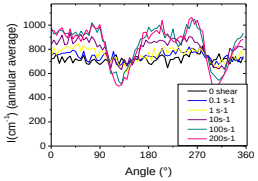
HYDRODYNAMIC VISCOSITY FROM SANS

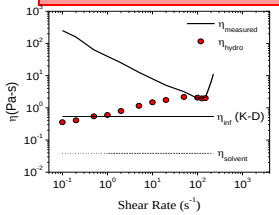


Total increased scattering at peak from hydrodynamics

$$P_1 = \int_0^{2\pi} \left(\frac{I(q,\theta,\dot{\gamma})}{I(q,\theta,\dot{\gamma}=0)} - 1 \right) d\theta$$

$$\eta_{hydro} \approx 2\mu C P_1(\dot{\gamma})$$



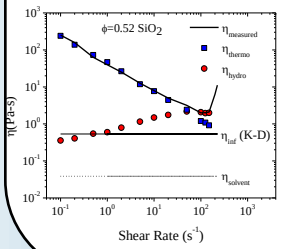


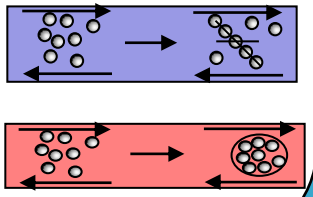
Challenge: Need data at high stresses in strongly shear-thickened state. Future work to measure this.

Maranzano and Wagner, J. Chem Phys., 2002

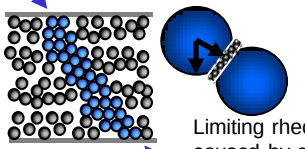
CONCENTRATED SUSPENSION MICROSTRUCTURE

1-2 Plane SANS allows for microstructural measurements of concentrated suspensions under shear
Micromechanical theories allow for measurement of rheological properties via SANS
Hydrodynamic viscosity increases even while dominant behavior is shear-thinning



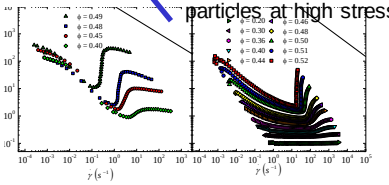


ELASTOHYDRODYNAMIC LIMIT TO SHEAR-THICKENING

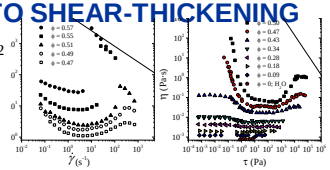


$$\eta \cong (G_s \mu_s)^{1/2} \dot{\gamma}^{-1/2}$$

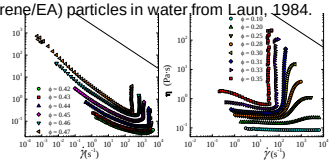
Limiting rheological behavior caused by compression of particles at high stresses



Particles produced to test theory. *Left)* PMMA spheres (1.05μm) in PEG. *Right)* SiO_2 spheres (500nm) in PEG from Egres, 2005)



Concentrated suspensions of polymer particles. *Left)* PVC (1.25μm) in DOP from Hoffman, 1972). *Right)* Poly (styrene/EA) particles in water from Laun, 1984.



Concentrated suspensions of mineral particles. *Left)* Kaolin in water from Egres, 2005 (thesis). *Right)* Precipitated $CaCO_3$ in water from Egres 2005 (JOR)

CONCLUSIONS

- ♦First structural measurements on suspensions performed in shear plane
- ♦Structure anisotropy in shear plane agrees with simulations and theory at low and moderate Pe
- ♦Structure-property relations work to compare SANS measurements to rheology
- ♦Shear thickening stresses limited by particle hardness from elastohydrodynamics
- ♦Future work to develop scaling laws into constitutive model based on independently measurable parameters
- ♦Improved understanding of microstructures allows for elastohydrodynamic limit of shear thickening

ACKNOWLEDGEMENTS

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