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 \( \phi = 0.50 \).

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.

SANS – QUALITATIVE OBSERVATIONS

Peaks correspond to high particle concentration. Structure saturates.

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

Increasing rate ->

SANS measurement with 0 shear subtracted: Structural rearrangements only.

Peaks correspond to high particle concentration.
CONCENTRATED SUSPENSION

MICROMECHANICS OF CONCENTRATED SUSPENSIONS FOR PROTECTIVE FABRICS

(Continued)

THERMODYNAMIC VISCOSITY FROM SANS

\[ \eta_{\text{Thermo}} \propto P_{21}^{1/\gamma} \]

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


HYDRODYNAMIC VISCOSITY FROM SANS

Total increased scattering at peak from hydrodynamics

\[ \eta_{\text{hydro}} \approx 2 \mu C(\gamma) \]

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


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

\[ \eta = (G_\mu)_{1/2} \gamma^{-1/2} \]

Limiting rheological behavior caused by compression of particles at high stresses

Particles produced to test theory. Left) PMMA spheres (1.05\(\mu\)m) in PEG. Right) SiO\(_2\) spheres (500nm) in PEG from Egres, 2005

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 hardnes 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

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