Small Angle Neutron Scattering from Magnetic Inks

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Introduction

• Heterogeneous liquids such as ferrofluids and magnetic dispersions have technological applications.
• They exhibit interesting rheological properties (viscosity etc.) under the influence of shear, electric field and magnetic field.
• The particles form aggregates and clusters in a magnetic field.
• Theoretical studies and computer simulations indicate that these clusters vary from the simple chains, planes, rods and other complex structures.
• The structure of the dispersion depends on the composition of particles.
Beamline NG7 at NIST Center for Neutron Research

Measurement Conditions
- Radial Scan
- sample-detector distance = 15.5 m
- neutron wavelength \( \lambda = 6 \, \text{Å} \)
- Couette shear cell
- magnetic field: 0-180 Oe
- room temperature
- shear rate: 0-4000 s\(^{-1}\)
Small Angle Neutron Scattering

Scattering vector: \( \mathbf{Q} = \mathbf{k}' - \mathbf{k}; |\mathbf{k}'| = |\mathbf{k}| \\
\[ Q = \frac{4\pi}{\lambda} \sin \theta \] \\
\[ 2\theta = \arctan \left( \frac{R}{SD} \right) \]

Scattering vector \( \mathbf{Q} \), scattering angle \( 2\theta \) and radial distance \( R \) in the small angle scattering geometry. The vectors \( \mathbf{k}, \mathbf{k}' \) and \( \mathbf{Q} \) are all in the same plane.
Data Analysis

• We assume that there is no magnetic contribution to the scattering (the particle composition is small).

• Only nuclear scattering is considered. Scattering intensity is fitted with:
  \[ I(\theta) = A + B \sin^2(\theta + \phi) \]

B/A is anisotropy

\( \theta \) is the scattering angle

\( \phi \) is the phase or tilt angle
Scattering Anisotropy

- Scattering is isotropic in zero field and zero shear conditions.
  \[ \Rightarrow \text{Particles are randomly oriented in zero field and zero shear} \]
- Anisotropic scattering is observed either in applied field or under the influence of shear.
  \[ \Rightarrow \text{Particles could be aligned along the field or shear} \]
Shear Rate Dependence of Tilt Angle

- Tilt angle follows a power law behavior of shear rate:
  \[ \psi = c \gamma^{-z} \]

- \( z \) dynamic exponent
- \( z \) depends on
  - (i) the dimensionality
  - (ii) type of aggregation process

- observed field dependence of \( z \)
Modeling of Nanoparticle Dynamics

The behavior of Fe nanoparticles in the magnetic dispersion under the influence of steady shear flow and static magnetic field is theoretically studied using the constitutive model.

The constitutive model (Anand Bhandar-John Wiest 02)

• single-part mean-field approach
• the particles as rigid dumbbells dispersed in a solvent.
• incorporates
  Brownian motion
  anisotropic hydrodynamic drag
  a steric potential
  magnetic forces (dipolar)
Comparison of the SANS Results with the Constitutive Model Calculations

- the tilt angle (90 deg.) at low shear and its dependence on shear at high shear rates is qualitatively similar to SANS observations.
- The transition from field oriented state to shear oriented state is abrupt in the model.
- Mean-field approach, does not account for the fluctuations.
Summary

- The structure and dynamics of iron nanoparticles in a magnetic dispersion has been investigated by Small angle neutron scattering measurements at NIST beamline NG7.
- The particles can be oriented along the shear or along the magnetic field.
- A second-order-like phase transition from field oriented state to shear oriented state takes place at critical shear rate $\gamma_c (H)$.
- The tilt angle of particles w.r.t. shear flow exhibits a power law scaling. The exponent $z$ depends on the applied magnetic field.
- The results are in qualitative agreement with the constitutive model calculations.
- Future experiments will focus on particle dynamics at higher fields ~500 Oe.