Effect of viscosity ratio on the behaviour of ferrofluid droplet emulsions

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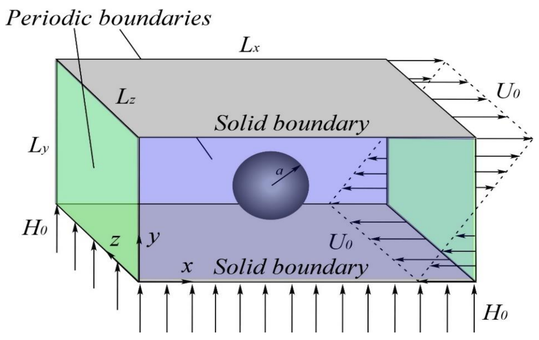
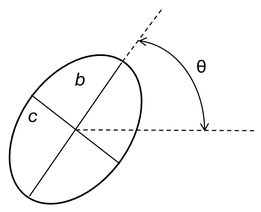
Introduction

The behaviour of a ferrofluid droplet in a non-magnetisable immiscible liquid of different viscosity was investigated using a Hybrid Volume of fluid – Level Set approach [1]. We consider the droplet is subjected to simple shear flow and study the effect of viscosity ratio in the presence of magnetic field. The accuracy of the code was first assessed against existing experimental and numerical data in the absence of a magnetic field. We then study the effects produced by a uniform magnetic field applied normal to the flow direction for a range of capillary and Bond numbers. Using the approach of [2], the results are then used to infer the rheology of a dilute emulsion, showing that even relatively small magnetic fields can significantly affect the rheological properties such as the effective viscosity of the emulsion.

Problem Statement

The shear rheology of a dilute emulsion made of the ferrofluid droplets suspended in a non-magnetizable immiscible liquid was investigated numerically





$$D = \frac{b-c}{b+c}, \quad \theta' = 45^o - \theta$$

Dimensionless parameters:

$$\mathrm{Re} = \frac{\rho \dot{\gamma} a^2}{\eta} \ll 1$$

$$\mathrm{Ca} = \frac{\eta \dot{\gamma} a}{\sigma}$$

$$\mathrm{Bo}_m = \frac{\mu_0 H_0^2 a}{\sigma}$$

$$\rho = \frac{\rho_d}{\rho_m} = 1$$

$$\lambda = \frac{\eta_d}{\eta_m} = (0.08\ ,\ 1,\ 6.4\ ,\ 10)$$

Numerical Method

- Simulations using a Hybrid Volume of fluid – Level Set approach implemented in OpenFOAM [1].
- The fluid flow obeys the isothermal and incompressible conservation of mass and Navier–Stokes equations for magnetizable fluids in the presence of a magnetic vector field.

$$\nabla \cdot \mathbf{u} = 0\ , \qquad \rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\,.\,\nabla \mathbf{u}\right) = -\nabla p + \nabla\,.\,(2\eta \mathbf{D}) + \mathbf{F}_\sigma + \mathbf{F}_H$$

- Maxwell's magnetostatic equations for a non-conducting ferrofluid:

$$\nabla .\ \mathbf{B} = 0\ , \qquad \nabla \times \mathbf{H} = \mathbf{0}$$

B being the magnetic induction, which is related to the magnetic field by a specific constitutive relationship:

$$\mathbf{B} = \begin{cases} \mu_0(\mathbf{H} + \mathbf{M}) & \text{in the ferrofluid phase} \\ \mu_0 \mathbf{H} & \text{in the surrounding phase} \end{cases}$$

- The magnetization **M** is assumed to be proportional to the magnetic field

$$\mathbf{M} = \chi \mathbf{H}\ , \qquad \mathbf{B} = \mu \mathbf{H}$$

- The magnetic permeability of the ferrofluid phase: $\mu = \mu_0 \chi$
  where μ_0 denotes the permeability of the vacuum
- Introducing the magnetic scalar potential ψ in the Maxwell's magnetostatic equations leads to

$$\nabla \cdot [\boldsymbol{\mu}(\mathrm{x}) \nabla \psi] = 0, \qquad \mathbf{H} = -\nabla \psi$$

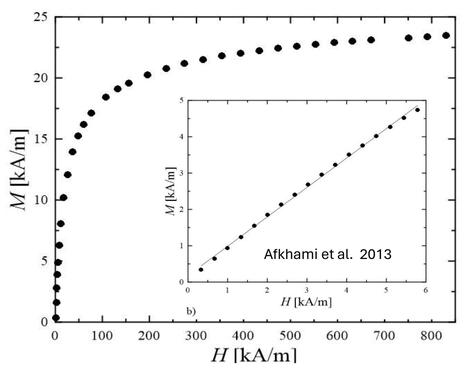
- **Volume of Fluid Approach**

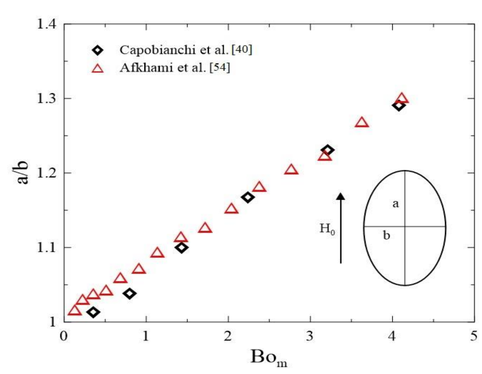
$$D\alpha(\mathbf{x})/Dt = 0\ , \qquad \zeta(\mathbf{x}) = \alpha(\mathbf{x})\zeta_\mathrm{p} + (1 - \alpha(\mathrm{x}))\zeta_a$$

Here α denotes volume fraction and ζ is a generic fluid property

Implementation Validation

Magnetic Field: Effect of Bo_m in the absence of imposed shear flow

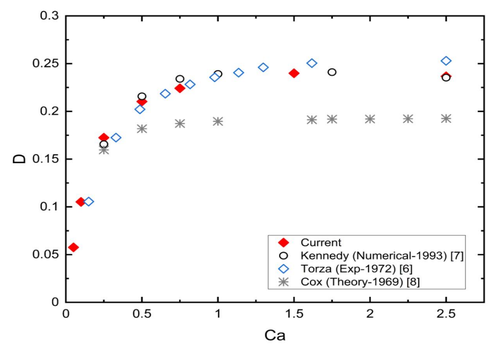


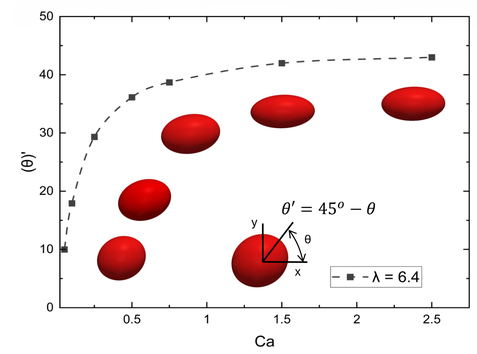


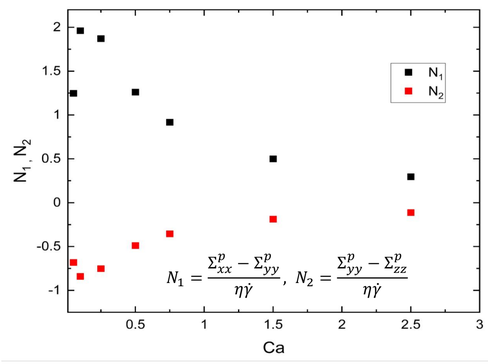
$$\mathrm{Bo}_m = \frac{\mu_0 H_0^2 a}{\sigma}$$

Effect of shear flow for viscosity ratio different than λ = 1

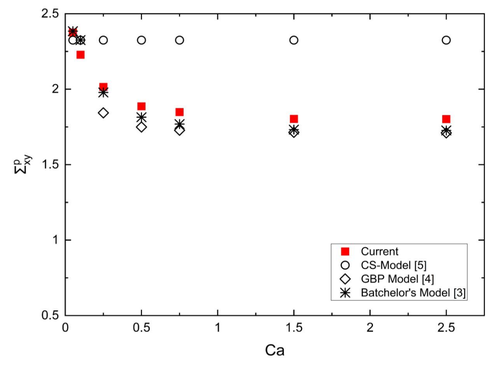
Viscosity jump across the interface in the absence of a magnetic field (λ=6.4)



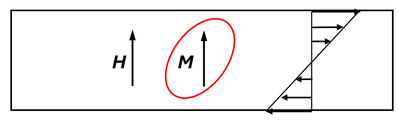




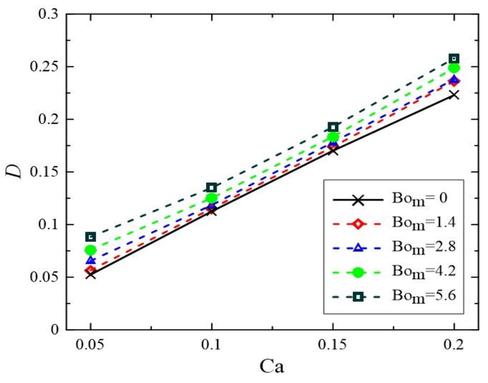
$$N_1 = \frac{\Sigma^p_{xx} - \Sigma^p_{yy}}{\eta\dot{\gamma}},\ N_2 = \frac{\Sigma^p_{yy} - \Sigma^p_{zz}}{\eta\dot{\gamma}}$$

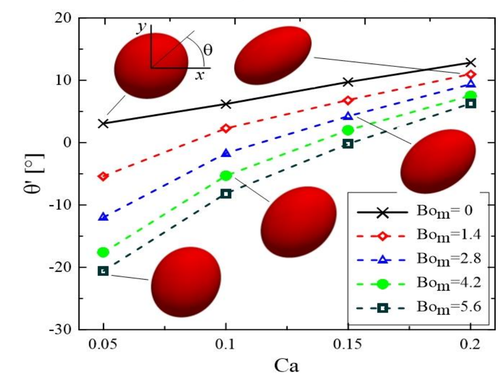


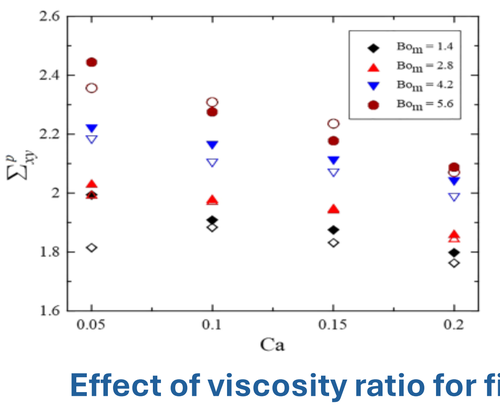
Combined effects of shear flow and magnetic field

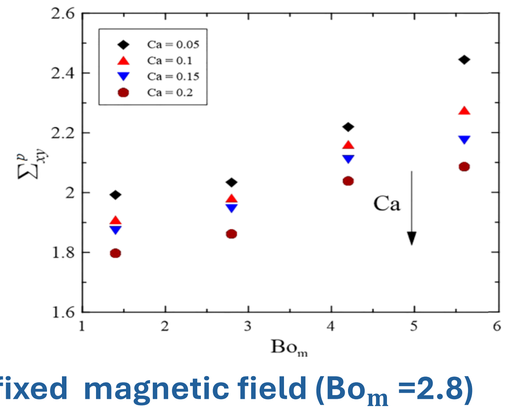


Effect of magnetic field for fixed viscosity ratio (λ=1)

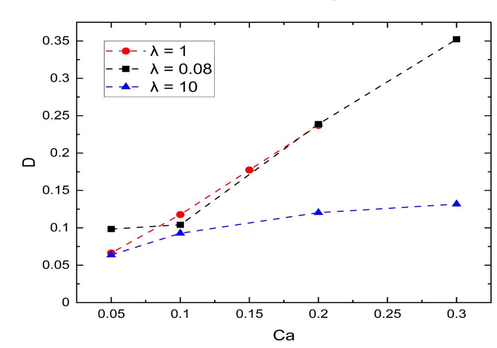


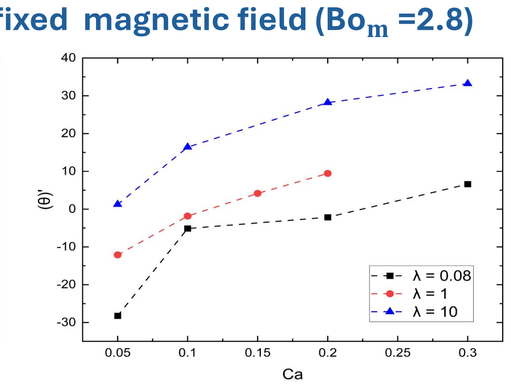


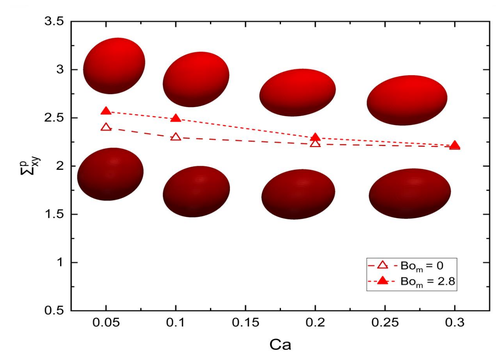


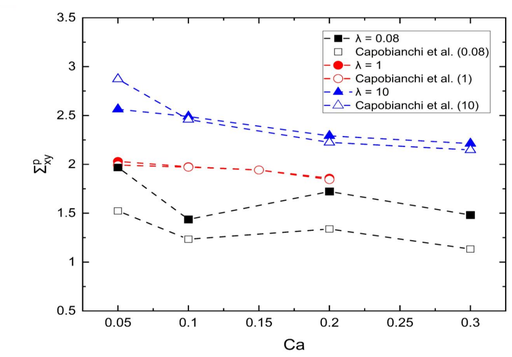


Effect of viscosity ratio for fixed magnetic field (Bo_m =2.8)









Conclusions and Future Work

- Numerical simulations for dilute ferrofluid emulsions in the absence and presence of uniform vertical magnetic fields were performed.
- Implementation validated using experiments and/or Batchelor's, CS, and GBP-YB Models.
- The model predicted an increase of the shear viscosity for increasing strengths of the magnetic field (magneto-thickening behaviour) and for increasing viscosity ratios.
- Magnetic stresses contribute to deform and orient the drop toward the direction of the magnetic field.

References and Acknowledgment

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