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Magnetic fluid rheology and flows

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Abstract

Major recent advances: Magnetic fluid rheology and flow advances in the past year include: (1) generalization of the magnetization relaxation equation by Shliomis and Felderhof and generalization of the governing ferrohydrodynamic equations by Rosensweig and Felderhof; (2) advances in such biomedical applications as drug delivery, hyperthermia, and magnetic resonance imaging; (3) use of the antisymmetric part of the viscous stress tensor due to spin velocity to lower the effective magnetoviscosity to zero and negative values; (4) and ultrasound velocity profile measurements of spin-up flow showing counter-rotating surface and co-rotating volume flows in a uniform rotating magnetic field.

Recent advances in magnetic fluid rheology and flows are reviewed including extensions of the governing magnetization relaxation and ferrohydrodynamic equations with a viscous stress tensor that has an antisymmetric part due to spin velocity; derivation of the magnetic susceptibility tensor in a ferrofluid with spin velocity and its relationship to magnetically controlled heating; magnetic force and torque analysis, measurements, resulting flow phenomena, with device and biomedical applications; effective magnetoviscosity analysis and measurements including zero and negative values, not just reduced viscosity; ultrasound velocity profile measurements of spin-up flow showing counter-rotating surface and co-rotating volume flows in a uniform rotating magnetic field; theory and optical measurements of ferrofluid meniscus shape for tangential and perpendicular magnetic fields; new theory and measurements of ferrohydrodynamic flows and instabilities and of thermodiffusion (Soret effect) phenomena.

Keywords: Magnetic fluids; Ferrofluids; Ferrohydrodynamics; Magnetization; Magnetic susceptibility; Magnetic forces; Magnetic torques; Magnetoviscosity; Magnetic thermodiffusion; Magnetic Soret effect

1. Introduction to magnetic fluids

1.1. Ferrofluid composition

Magnetic fluids, also called ferrofluids, are synthesized colloidal mixtures of non-magnetic carrier liquid, typically water or oil, containing single domain permanently magnetized particles, typically magnetite, with diameters of order 5–15 nm and volume fraction up to about 10% [1••,2••,3•,4•,5•].

Brownian motion keeps the nanoscopic particles from settling under gravity, and a surfactant layer, such as oleic acid, or a polymer coating surrounds each particle to provide short range steric hindrance and electrostatic repulsion between particles preventing particle agglomeration [6•]. This coating allows ferrofluids to maintain fluidity even in intense high-gradient magnetic fields [7] unlike magnetorheological fluids that solidify in strong magnetic fields [2••,8]. Recent experiments and analysis show that magnetic dipole forces in strong magnetic fields cause large nanoparticles to form chains and aggregates that can greatly affect macroscopic properties of ferrofluids even for low nanoparticle concentration [9–12]. Small angle neutron

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scattering (SANS) distinguishes between magnetic and non-magnetic components of ferrofluids allowing density, composition, and magnetization profiles to be precisely determined [13,14]. Nanoparticle dynamics, composition, and magnetic relaxation affect magnetic fluid rheology which can be examined using magnetic field induced birefringence [15–19].

The study and applications of ferrofluids, invented in the mid-1960s, involve the multidisciplinary sciences of chemistry, fluid mechanics, and magnetism. Because of the small particle size, ferrofluids involved nanoscience and nanotechnology from their inception. With modern advances in understanding nanoscale systems, current research focuses on synthesis, characterization, and functionalization of nanoparticles with magnetic and surface properties tailored for application as micro/nanoelectromechanical sensors, actuators, and micro/nanofluidic devices [20•]; and for such biomedical applications as [20•,21••] nano-biosensors, targeted drug-delivery vectors [22], magneto-cytolysis of cancerous tumors, hyperthermia [23], separations and cell sorting, magnetic resonance imaging [24,25], immunoassays [26], radiolabelled magnetic fluids [27], and X-ray microtomography for three dimensional analysis of magnetic nanoparticle distribution in biological applications, a crucial parameter for therapeutic evaluation [28].

1.2. Applications

Conventional ferrofluid applications use DC magnetic fields from permanent magnets for use as liquid O-rings in rotary and exclusion seals, film bearings, as inertial dampers in stepper motors and shock absorbers, in magnetorheological fluid composites, as heat transfer fluids in loudspeakers, in inclinometers and accelerometers, for grinding and polishing, in magnetocaloric pumps and heat pipes [1••,2••,3•,4•,5•], and as lubrication in improved hydrodynamic journal bearings [29]. Ferrofluid is used for cooling over 50 million loudspeakers each year. Almost every computer disk drive uses a magnetic fluid rotary seal for contaminant exclusion and the semiconductor industry uses silicon crystal growing furnaces that employ ferrofluid rotary shaft seals. Ferrofluids are also used for separation of magnetic from non-magnetic materials and for separating materials by their density by using a non-uniform magnetic field to create a magnetic pressure distribution in the ferrofluid that causes the fluid to act as if it has a variable density that changes with height. Magnetic materials move to the regions of strongest magnetic field while non-magnetic materials move to the regions of low magnetic field with matching effective density. Magnetomotive separations use this selective buoyancy for mineral processing, water treatment [30], and sink-float separation of materials, one novel application being the separation of diamonds from beach sand.

2. Governing ferrohydrodynamic equations

2.1. Magnetization

2.1.1. Langevin magnetization equilibrium

Ferrofluid equilibrium magnetization is accurately described by the Langevin equation for paramagnetism [1••,2••,3•,4•,5•,31••]

$$M_0 = M_S\left[\coth\alpha - \frac{1}{\alpha}\right], \quad \alpha = \mu_0 mH/kT \tag{1}$$

where in equilibrium $\bar{M}_0$ and $\bar{H}$ are collinear; $M_s = Nm = M_d\phi$ is the saturation magnetization when all magnetic dipoles with magnetic nanoparticle volume V_p and magnetization M_d have moment $m = M_dV_p$ aligned with $\bar{H}$; N is the number of magnetic dipoles per unit volume; and ϕ is the volume fraction of magnetic nanoparticles in the ferrofluid. For the typically used magnetite nanoparticle ($M_d = 4.46 \times 10^5$ A/m or $\mu_0 M_d = 0.56$ T), a representative volume fraction of $\phi = 4\%$ with nanoparticle diameter $d = 10$ nm ($V_p = 5.25 \times 10^{-25}$ m^3) gives a ferrofluid saturation magnetization of $\mu_0 M_s = \mu_0 M_d \phi = 0.0244$ T and $N = \phi / V_p \approx 7.6 \times 10^{22}$ magnetic nanoparticles/m^3.

At low magnetic fields the magnetization is approximately linear with $\bar{H}$

$$\frac{\bar{M}_0}{\bar{H}} = \chi_0 = \mu_0 m^2 N/(3kT) = \left(\frac{\pi}{18kT}\right)\phi\mu_0 M_d^2 d^3 \tag{2}$$

where χ_0 is the magnetic susceptibility, related to magnetic permeability as $\mu = \mu_0(1+\chi_0)$. For our representative numbers at room temperature we obtain $\chi_0 \approx 0.42$ and $\mu/\mu_0 \approx 1.42$. When the initial magnetic permeability is large, the interaction of magnetic moments is appreciable so that Eq. (2) is no longer accurate. Shliomis [31••,1••] considers the case of monodispersed particles and uses a method similar to that used in the Debye–Onsager theory of polar fluids to replace Eq. (2) with

$$\frac{\chi_0(2\chi_0+3)}{\chi_0+1} = \mu_0 m^2 N/(kT) = \left(\frac{\pi}{6kT}\right)\phi\mu_0 M_d^2 d^3. \tag{3}$$

Langevin magnetization measurements in the linear low field region ($\alpha \ll 1$) provide an estimate of the largest magnetic particle diameters and in the high field saturation regime ($\alpha \gg 1$) gives an estimate of the smallest magnetic diameters [1••,32•]

$$\lim_{\alpha \gg 1} \frac{M_0}{M_S} \approx 1 - \frac{1}{\alpha} = 1 - \frac{6kT}{\pi\mu_0 M_d H d^3}$$

$$\lim_{\alpha \ll 1} \frac{M_0}{M_S} \approx \frac{\alpha}{3} = \frac{\pi\mu_0 M_d H d^3}{18kT} \tag{4}$$

This method allows estimation of the ferrofluid magnetic nanoparticle size range using a magnetometer. Other methods include transmission electron microscopy, atomic