CHAPTER 1

INTRODUCTION

At the last decades, the practical applications of fluid mechanics, in engineering and science, were confined to systems in which electric and magnetic fields play no role. However, the interaction of electromagnetic forces with fluid mechanics forces has been attracting increasing attention with the promise of applications in diverse areas as controlled nuclear fusion, chemical reactor engineering, medicine, and high-speed silent printing. Ferrohydrodynamics (FHD), the subject of this work, is the subject of a branch of fluid mechanics that deals with the mechanics of fluid motion influenced by strong forces of magnetic polarization. In FHD, there are no need of electric current flowing in the fluid. The body force in FHD is due to polarization force, which in turn requires material magnetization in the presence of magnetic field gradients or discontinuties. In this way, the hydrodynamic motion and magnetic phenomena are coupled. So, FHD equations of motion can be classified into two groups [1]. The first group, are the hydrodynamic equations and the second one corresponds to magnetic field equations. The coupling between the two sets of equations appears in the boundary conditions.

1.1. Magnetic fluids

1.1.1. Introduction

Unlike paramagnetics and diamagnetism, which can be gases, liquid or solid, ferromagnetics are almost exclusively solid. There exist, however, liquids with a susceptibility of roughly 1 , not as high as many ferromagnetics but still orders of magnitudes higher than that of paramagnets. Moreover, like ferromagnets these liquids can easily approach their saturation magnetization. These so-called magnetic fluids or ferrofluids are actually two-phase systems, comprised of small solid ferro-or ferrimagnetic particles dispersed in a liquid [1-3]. Because of, the size of the particles is in the colloidal range, i.e. between about 1 and 1000 nanometer (nm), these particles are often referred to as magnetic colloids.

Although intensive research on magnetic fluids did not start until the 1960s, the preparation of Elmore [4] were primarily used as a means to study magnetic domain structures in solids. Three decades later, Papell [5] and Rosensweig et al. [6] developed the synthesis of oil-based ferrofluids, which are still used up-till today. The most commonly used ferrofluid contains spherical magnetic particles with a typical size of 10 nm, dispersed in an apolar solvent. Sedimentation of these particles is sufficiently counteracted by their Brownian motion to keep them dispersed for years. A prerequisite for such long-term stability is that particles do not aggregate, since aggregates sediment faster and have slower Brownian motion to compensate for sedimentation. To prevent aggregation, the colloids can be covered with a thin layer of polymer, commonly a monolayer of oleic acid, which makes the particles soluble, in many organic solvents. Because of their small size, these magnetic colloids contain a single magnetic domain, and therefore have a permanent magnetic moment proportional to their volume. Although magnetic colloids are ferromagnetic on the molecular scale, they resemble a paramagnet on the colloidal scale, with the major difference that the magnetic moments of magnetic colloids are much large then the moments in a paramagnet (typical values are 10^{-19} Ampre meter^2 (Am^2) for magnetic colloids and 10^{-23} Am^2 for paramagnets). It is for this reason that ferrofluids are sometimes called super-paramagnetic. In order to be (super) paramagnetic, the dipole moment of each particle must be free to rotate on the time scale of experiments. Two modes of rotations are operative in magnetic colloids. One is Brownian rotation, with a relaxation time

$$\tau_B = \frac{3V\nu}{k_B\, T} \quad , \tag{1.1.1}$$

where V is the volume of the particle, ν is the viscosity of the solvent, k_B is the Boltzmann constant, and T the temperature. For $10-nm$ colloids in a solvent with $\nu 10^{-3}$ Pas, τ_B is $4 \times 10^{-7} s$. The other mode of rotation is Néel rotation, which involves rotation of the magnetization with respect to the crystal lattice of the magnetic colloid. The realization time for this process is

$$\tau_N = f_0^{-1}\, e^{\frac{3\breve{K}\nu}{k_B T}} \quad , \tag{1.1.2}$$

where $\breve{K}$ is the (material-dependent) anisotropy constant, and f_0 is the Larmor frequency, about 10^9 s^{-1}. Clearly, the Néel relaxation time strongly depends on the particle volume. For example, the τ_N of magnetite colloids ($\breve{K} = 1.1 \times 10^4 Jm^{-3}$ [2]) increases from 4×10^{-1} s to 7×10^{-5} s upon increasing the particle diameter from $10nm$ to $20nm$.

1.1.2. Applications of magnetic fluids

An important property of concentrated ferrofluids is that they are strongly attracted by permanent magnets, while their liquid character is preserved. The attraction can be strong enough to overcome the force of gravity. Many applications of ferrofluids are based on this property [2]. For example, ferrofluids are widely used as lubricating, airtight seals in rotary shafts. A magnetic field gradient keeps the ferrofluid in place, even in case of pressure differences between the two separated compartments. Today, many computer hard disk drives contain a ferrofluid -sealed shaft. Ferrofluids are also used to improve heat dissipation in loudspeaker coils, enabling higher output power.

When non-magnetic objects are immersed in a ferrofluid and subjected to the field gradient of a permanent magnet, the objects will be effectively repelled by the magnet (actually, the ferrofluid is attracted and drives away the object). When combined with a gravitational or centrifugal force opposing the magnetic force, this effective repulsion has the same effect as a density gradient in the solvent. This principle is used to separate materials into density fractions, for instance in the mining industry or waste processing. Because of the effective density of ferrofluids can be much higher than that of ordinary liquids, density-based separation with ferrofluids is also suitable for high density materials such as metals.

In the aforementioned applications, the ferrofluid was considered to be homogeneous. However, structural changes can occur on a microscopic level when magnetic fluids are subjected to a magnetic field. Because of an external field aligns the dipole moments of magnetic colloids, it can increase the average interaction strength between magnetic colloids sufficiently to induce aggregation of the colloids into concentrated, micron-sized droplets [7]. Because the size of such droplets is comparable to the wavelength of light, the optical properties of ferrofluids depend on the direction and strength of the external field. Optical devices employing the strong magneto-optical effects of magnetic fluids are still in development [2,8].

The use of magnetic fluids for biological applications has become widespread