Floating Diamonds with Nanomagnetic Particles

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Summary: In the diamond industry, ferrofluids are used in ferrohydrostatic separators for the density separation of diamonds from gangue material. The size of the magnetic core of the coated particles forming the ferrofluid suspension is vital in ensuring the stability of the fluid. The particle size must be small enough such that sedimentation does not occur in a magnetic field gradient and under the influence of a gravitational field and such that magnetic agglomeration can be overcome. This paper discusses the particle size requirements for fluid stability under the influence of these effects.

Keywords: gravitational field; magnetic agglomeration; magnetic field gradient; magnetic nanoparticle; stability

Introduction

A ferrofluid or magnetic liquid consists of a stable colloidal dispersion or suspension of single domain nanometre-sized magnetic particles coated with a surfactant and suspended in a carrier liquid as shown schematically in Figure 1 [1]. The magnetic core could, for example, consist of magnetite, nickel, maghemite or cobalt. Surfactants such as oleic acid and lauric acid and different types of oils, fluorocarbons or even water may be used as carrier liquids.

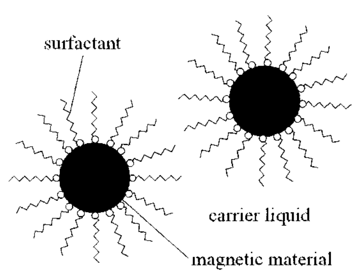

Figure 1. Components of a ferrofluid.

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The history of ferrofluids dates back to the 1700s when Gowan Knight in 1779 attempted to disperse iron filings in water. He obtained a suspension of small particles after several hours of mixing, but the fluid was not stable over long periods of time. In 1932, Bitter produced a suspension of magnetite of particle size 10^3 nm in water. Elmore (in 1938) as well as Craik and Griffiths (in 1958) produced suspensions containing smaller particles (20 nm) which closely resembled ferrofluids. The first ultrastable ferrofluids containing ferrite particles in a non-conducting liquid carrier were prepared by Papell at NASA in the 1960s [2, 3, 4].

Magnetic suspensions were first used to detect microscopic-magnetic patterns on ferromagnetic tools (through deposition of the fluid on the surface and evaporation of the carrier liquid) and later for the identification of flux change on magnetic tapes. NASA manufactured ferrofluids for investigations into its use as a pumpable rocket propellant in microgravity conditions (controlling fuel flow under conditions of weightlessness). Ferrofluids can be manipulated to flow or remain immobilized via application of an external magnetic field. One of the most common applications is the use of ferrofluid in the voice coils of loudspeakers. In this case, the ferrofluid functions as a coolant and damping medium and keeps the voice coil concentric with the magnet. Ferrofluid has also been used to form airtight seals in rotating machinery [2, 4].

The use of ferrofluid has been investigated as a variable density fluid for the separation of scrap metals. Magnetic paints have been developed and magnetisable liquids have found application in the fields of biology and medicine (e.g. enzyme fixing, immunoanalysis, cell separation of bacteria cultures and drug delivery to specific points in the body by application of a magnetic field) [3, 4].

Ferrohydrostatic Separation in the Diamond Industry

Ferrofluid has become important in the diamond industry as a result of developments in ferrohydrostatic separation. This is a sink-float technique and is used for the recovery of diamonds from gangue material.

The ferrohydrostatic separator consists of an electromagnet and a separation chamber in which a pool of ferrofluid is held. Material is introduced into the separation chamber via a vibratory feeder (see Figure 2).

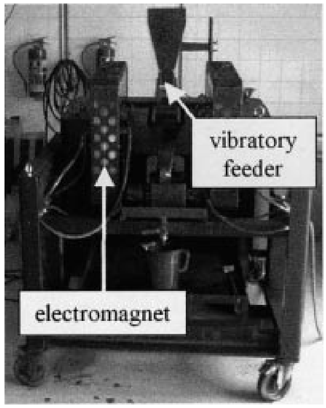

Figure 2. Ferrohydrostatic separator.

A particle entering the chamber is suspended in the ferrofluid and is acted upon by a gravitational and magnetic traction force in the downward direction and a gravity-related and magnetically induced buoyancy force in the upward direction. If the sum of the forces exerted on a particle fed to the separation chamber is such that the sum of the forces in the upward direction is greater than the sum of the forces in the downward direction, the particle will float. If the sum of the forces exerted on a particle is such that the sum of the magnetic and gravity-related buoyancy forces is less than the gravitational and magnetic forces, the particle will sink.

The magnetically induced buoyancy force leads to a situation where the density of the ferrofluid appears to the particles to be higher than the natural density of the fluid, called the apparent density of the fluid. This apparent density can be changed by varying the field gradient to which the fluid is exposed [5, 6]. Gangue material can be separated from diamonds in two stages by judicious setting of the apparent density. Diamond density is approximately 3.53 g/cm^3. In the first stage, for example, the ferrofluid apparent density could be set at 3.5 g/cm^3 to float and separate off the material lighter than diamond. In the second pass, the fluid density could be set at 3.6 g/cm^3 to float and separate off diamond from the denser minerals.

Ferrofluid Requirements for Ferrohydrostatic Separation

Some properties of the ferrofluid are critical for fluid stability and for achieving separation in a ferrohydrostatic separator.

Firstly, the viscosity of the fluid in a ferrohydrostatic separator is important for the separation of small particles. Hydrodynamic effects become much more important in the separation of small particles and therefore it is essential to keep the viscosity as low as possible [5].

Secondly, a vital requirement of a ferrofluid is that the fluid possesses the correct magnetic properties. Ferrofluids when exposed to an external magnetic field must be magnetisable, but should exhibit no remanent magnetism once the magnetic field is removed i.e. they must be superparamagnetic. Superparamagnetic materials consist of single domain particles [7]. In addition, a high saturation magnetisation is desired for the ferrofluid as this allows the ferrohydrostatic separators to operate at lower magnetic fields. At lower field strength, interaction with magnetic material in the feed should be minimized and this in turn should lead to an improved selectivity in separation.

The magnetite particle size is not only important in terms of the magnetic properties of the fluid, but is vital in ensuring stability. A magnetite particle must be small enough such that the fluid is stable in a magnetic field gradient, in a gravitational field and stable against magnetic agglomeration [1]. This will be discussed in the following sections. (Although the magnetite particles are small enough to be stable colloidally, London-type Van der Waals attractive forces may result in agglomeration which will lead to fluid instability. Coating the particles with a suitable surfactant will minimise this interaction and should ensure fluid stability [1, 2].)

Fluid Stability in a Magnetic Field Gradient

Magnetic particles exposed to a magnetic field are attracted to the higher intensity regions of the magnetic field. According to the kinetic theory of matter, a particle that is denser than the fluid in which it is found can remain suspended in the fluid as long as the particle size is sufficiently small. Molecules in the liquid collide continuously with the particles and transfer their kinetic energy to the particles keeping them suspended. The energy carried by these particles is equal to kT where k is the Boltzmann constant (1.38x10^{-23} J/K) and T is the temperature (K). For a particle in a magnetic field to remain in suspension, the ratio of the thermal energy to the magnetic energy must be greater than or equal to 1 [1, 8].

$$\frac{thermal\ energy}{magnetic\ energy} = \frac{kT}{\mu_0 M_s HV} \geq 1 \qquad (1)$$

If the volume of a sphere is substituted in eq. (1), the maximum particle size can be determined [1].

$$\frac{kT}{\mu_0 M_s H} \frac{6}{\pi d^3} \geq 1 \qquad (2)$$

and therefore

$$d \leq (6kT / \pi\mu_0 M_s H)^{1/3} \qquad (3)$$

At ambient temperature (298 K), with M_s (the saturation magnetisation of magnetite) equal to 480000 A/m, μ_0 (the magnetic permeability of a vacuum) equal to 4πx10^{-7} N/A^2 and H (the magnetic field strength) equal to 100 kA/m for a ferrohydrostatic separator, the particle size is found to be smaller than or equal to approximately 5 nm. This value is used as a guideline for the particle size as other effects in the environment in which the fluid is located will also influence the allowable particle size perhaps resulting in the allowable particle being larger. It is thought that particles of too small a size may possess a lower saturation magnetisation and would thus be less effective for use in ferrohydrostatic separators. It could therefore probably be stated that the maximum magnetite particle size required for a particle in a magnetic field to remain in suspension is in the range of 10 nm [1, 8].

Fluid Stability in a Gravitational Field

In a similar manner, the relative effect of the gravitational to the magnetic energy can be calculated to determine whether this force is significant or not.

$$\frac{gravitational\ energy}{magnetic\ energy} = \frac{\Delta\rho VgL}{\mu_0 M_s HV} = \frac{\Delta\rho gL}{\mu_0 M_s H} \tag{4}$$

Typical values for the ferrofluid are substituted into eq. (4) with L equal to 0.1 m (as the approximate height in a magnetic separation chamber), and the difference in density between the solid and liquid equal to 4400 kg/m^3 (with magnetite density equal to 5180 kg/m^3 and kerosene density equal to 780 kg/m^3). It is found that gravity is less of a threat than the magnetic energy to the settling out of particles in ferrofluid as the ratio of the gravitational energy to the magnetic energy is equal to 0.07 [1].

This is further confirmed by determining what the allowable size of a magnetite particle is to prevent settling in a gravitational field. For a particle in a gravitational field to remain in suspension, the ratio of the thermal energy (kT) to the gravitational energy must be greater than or equal to 1:

$$\frac{thermal\ energy}{gravitational\ energy} = \frac{kT}{\Delta\rho VgL} \geq 1 \tag{5}$$

If the volume of a sphere is substituted in eq. (5), the maximum particle size can be determined.

$$\frac{kT}{\Delta\rho gL}\frac{6}{\pi d^3} \geq 1 \tag{6}$$

and therefore

$$d \leq (6kT / \pi\Delta\rho gL)^{1/3} \tag{7}$$

At ambient temperature (298 K) it is found that for the ratio of the thermal to the gravitational energy to be greater than or equal to one, the particle size should be smaller than or equal to approximately 12 nm. The magnetic field gradient is of more of a threat to the settling out of particles than the gravitational energy as the gravitational energy allows for a larger particle size before settling will take place.

Stability against Magnetic Agglomeration

Collisions between particles are frequent in a typical colloidal magnetic fluid as such a fluid contains in the order of 10^{23} particles per cubic metre. A magnetic attractive force can exist between two particles that approach one another. Each particle can be treated as a magnetic dipole which generates a magnetic field. The ratio of the thermal energy to the dipole-dipole contact energy gives an indication of the likelihood of particles agglomerating and the possibility of their settling out from suspension [1].

$$\frac{\textit{thermal energy of two magnetite particles}}{\textit{dipole}-\textit{dipole contact energy}} = \frac{2kT}{\dfrac{\mu_0 M^2 V}{12}} \tag{8}$$

Solving for d, again with the substitution for the volume of a sphere, gives (M is the magnetisation of the fluid (A/m)):

$$\begin{aligned} &\frac{24kT}{\mu_0 M^2}\frac{6}{\pi d^3} \geq 1 \\ &d \leq (144kT/\pi\mu_0 M^2)^{1/3} \end{aligned} \tag{9}$$

For magnetite particles at room temperature it is found that particles less than approximately 9 nm in size are not likely to experience magnetically induced agglomeration and the subsequent settling of agglomerates is not expected from ferrofluids with particles of diameter of the order of 10 nm.

Conclusions

Ferrofluids have been used for a variety of different applications over the last few decades including density separation in the diamond industry. Some properties of ferrofluids are vital for the use of the fluid in ferrohydrostatic separators. At the heart of the process are the nanometre-sized magnetic particles. Particles of approximately 10 nm in size are critical in providing a stable fluid and allowing for the density separation of diamonds from gangue material.

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