CONF-740517--2

FERROFLUID VARIABLE DENSITY SEPARATIONS

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April 17, 1974

This paper is based on work performed under United States Atomic Energy Commission Contract AT(45-1)-1830.

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INTRODUCTION

In environmental problems as well as mineralogy it is often necessary to isolate a particular fraction of a mixture. One of the methods used for this is density separations. Density separations above a specific gravity of 3 are inconvenient, because they generally use thallium and mercury compounds. When a device appeared in the literature^{1,2} that allowed density separations of materials of specific gravity 2.5-22, a study was begun to determine feasibility of its use for laboratory separations of particulate materials. The device is called a Ferrofluid Variable Density Separator. AVCO Corporation is applying it to scrap metal separations and the Institute of Mineral Research at Michigan Technology University is developing methods of ore beneficiation.

EXPLANATION OF LEVITATION

If a magnetic fluid containing a non-magnetic particle is placed in a magnetic field, in addition to the usual Archimedes' principle effect there is the effect of the magnet and magnetic fluid.

To a first approximation the additional magnetic force is $\frac{MV}{4\pi} \left(\frac{\partial H}{\partial Z} \right)$.⁴ Therefore the Ferrofluid appears to have the density

$$\rho_A = \rho_f + \frac{M}{4\pi g} \left(\frac{\partial H}{\partial Z} \right)$$

where: ρ_A = Apparent density of ferrofluid
 ρ_f = Actual density of ferrofluid
 M = Magnetization
 g = Gravitational constant
 $\left(\frac{\partial H}{\partial Z} \right)$ = The gradient of H in the Z direction

Therefore if our particle has a density higher than the apparent density of the fluid (ρ_A) it will tend to sink.

ρ_A is a function of M and $\left(\frac{\partial H}{\partial Z} \right)$, since within the approximation ρ_f is not variable. $\left(\frac{\partial H}{\partial Z} \right)$ depends on the field while M is a complex function of both the field and the nature of the magnetic fluid.

FERROFLUIDS

Ferrofluids are suspensions of finely ground single domain magnetic particles in a suitable liquid. A single domain particle is defined as a particle that is in a state of uniform magnetization. See Figure 1.

For each material there is a critical size below which only single domain particles exist. For magnetite Stacey⁵ gives the value of .03 micrometers. Magnetite is the solid commonly used in ferrofluids.

This suspension leads to superparamagnetic behavior. Calculations of M have been made assuming a Gaussian distribution of sizes and using a Boltzman distribution for the particles in thermal equilibrium with the field and these calculations experimentally verified.⁴ See Figure 2.

FIG. 1. Single and Multi-domain Magnetic Particles.⁵

FIG. 2. Superparamagnetic Behavior of 27 Å Radius Cobalt Particles in a Copper - 2% Cobalt Alloy.⁹

The important point is that M reaches saturation in a high enough field. Therefore if the field is kept high enough M will be a constant throughout the fluid. This leaves the apparent density (ρ_A) dependent on only $\left(\frac{\partial H}{\partial Z}\right)$.

A typical ferrofluid is magnetite ground to a size of 10-30 A° and dispersed in kerosene with oleic acid as a stabilizing agent. The use of the surfactant keeps the suspension stable.⁶ See Figure 3.

Many other combinations have been developed and tested^{7,8}, some of which are commercially available. Most are magnetite dispersed in some suitable liquid.

After a choice of solid, liquid and surfactant are made, the materials are ground together in a ballmill for up to six months duration, although methods for shortening this time have been developed. The larger particles are then centrifuged out.

MAGNETIC FIELD

As stated earlier the apparent density of the ferrofluid depends only on $\left(\frac{\partial H}{\partial Z}\right)$.

Two approaches can be made.

1. $\left(\frac{\partial H}{\partial Z}\right) = \text{constant}$

This gives a uniform apparent density throughout the liquid. It therefore acts like a normal density liquid.

FIG. 3. Formation and Effect of Solvated Sheath on Interaction of Particles.⁶

$$2. \quad \frac{\partial H}{\partial Z} = f(Z)$$

In this case the apparent density changes throughout the system. The particles will then distribute themselves in the liquid according to their apparent density.

The first approach was taken in this study. Figure 4 shows the magnet and accessory equipment. The magnet is designed such that $\frac{\partial H}{\partial Z}$ can be varied by change in the voltage from the 40-volt, 250-amp power supply. Figure 5 is a close-up view of the magnet. Figure 6 shows the variation of H with the height above the magnet base at an amperage of 200. Within the sample volume the apparent density is reproducible within 5%.

RESULTS

A sample separations cell was fabricated from lucite which divided the fluid into two fractions. A kerosene based ferrofluid was chosen because of its availability, inertness and low viscosity.

One of the disadvantages of the system is that it depends on gravity for its separation. Figure 7 shows separation times versus particle size. This time gets very long for small particles.

Some artificial mixtures such as copper and quartz and some natural materials such as garnet sand from Emerald Creek, Idaho were screened and the fractions separated. In the 44 to 63 micrometer range a small amount of trouble was experienced with particle-wall interactions. The use of a mechanical stirrer

FIG. 4. Ferrofluid Variable Density Separator

FIG. 5. Magnet for the Ferrofluid Variable Density Separator

FIG. 6. The Magnetic Field of the Variable Density Separator at 200 Amps

FIG. 7. Settling Times (Hrs./cm) of Particles in Ferrofluid at Various Density Differences.

and an ultrasonic probe was successful in dislodging these particles. Little trouble was experienced with larger size fractions. These systems were chosen since the fractions were easily recognized under the microscope.

When 6-10 micrometer stainless steel balls were mixed with a very fine ash, much more trouble with wall-particle and particle-particle interactions were experienced. Although a concentration of the stainless steel balls did take place, the separations were far from complete. Changes in the cell material, dispersing agent or liquid may alleviate this problem and will be tested in the near future.

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