Wide-range density separation of mineral particles in a single fluid system

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Abstract

A number of experiments were carried out with a Ferrofluid Density Separator to determine the practicality of separating micrometer-size particles into density fractions. The separators are normally used on much coarser material. The experimentation demonstrated that density separations of nonmagnetic particles as small as 50 micrometers (μ m) were effective and reproducible and that the separator was easily operable far above the density of conventional liquid separation systems. Separations with smaller particle sizes were sometimes successful, but they could not be consistently reproduced.

Introduction

A device designed and described by Kaiser as a "Ferrofluid Density Separator" develops an apparent fluid density from nominally 1 to 20 g/cm³ dependent on the magnitude of an imposed magnetic field gradient. The ferrofluid retains other normal properties of a liquid. Descriptions of ferrofluid devices, principles of operation, and some applications have been published (Kaiser and Miskolczy, 1970; Rosenweig, 1970; Moskowitz, 1974).

A number of experiments were carried out with a separator to determine the practicality of separating micrometer-size particles into density fractions. A shaped pole-piece electromagnet was used to generate a constant field gradient of about 1000 oersted per centimeter. The magnet is water-cooled and is oper-ated with a continuously variable power supply up to about 250 amps. The volume applicable to sample processing is 50 cm³. There are larger devices.

A typical ferrofluid is a stable suspension of submicrometer magnetite particles in kerosene. Three ferrofluids with differing magnetite concentrations were used, covering an apparent density range of 2 to 15 g/cm³ when coupled with the magnet described. The three ferrofluids, with physical densities of 0.81, 0.86, and 0.95 g/cm³, were prepared by AVCO Corporation, Systems Division, Lowell, Massachusetts. A lucite sample cell was built to fit the magnet gap and contain the ferrofluid and sample. A central sliding valve in the cell isolates sink and float portions of separated samples. By varying the magnetic field gradient applied to a ferrofluid, it is possible to selectively sink or float a nonmagnetic solid object contained in the ferrofluid.

The ferrofluid force, F_m , on the object tends to move the object to the position of minimum field. When the field is aligned with the gravitational force, F_g , there is a point of equilibrium of the two forces such that (Kaiser and Miskolczy, 1970),

$$F_{\sigma} = (\rho_s - \rho_l)g = M\Delta H/4\pi = F_m$$

Here ρ_s is the density of the solid, ρ_i is the density of the liquid or fluid, g is the gravitational force, M is the magnetization of the ferrofluid and ΔH is the magnetic field gradient. Increasing or decreasing ΔH (by changing the magnet current) from the equilibrium condition will cause the solid to float or sink respectively. A more detailed description of principle is given by Rosenweig (1970).

Experimental

The experimental work involved a procedure for processing particle samples, and determining the effect of particle size, ferrofluid concentration, and sample concentration on separation efficiency. The technique was tested with synthetic and natural particle mixtures.

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Table 1. Floating glass spheres

Test number	Sphere	Separation results*	
	size		
	(µm)	Float Sink	
101	45-75	95 5	
119	25-35	90 10	
120	15-25	90 10	
123	10-15	85 15	
125	10-15	∿95 5	
124	3-8	~95 5	

*Conditions of these tests were expected to float all of the glass spheres. Conditions were: Ferrofluid physical density 0.86 and at an apparent density of 4.8 g/cm³; separation time, one hour, except test 124 which was three hours; and sphere concentration was below 0.00001 cm^3 per cm³ of ferrofluid.

Procedure

The sample is placed in the separation cell and the appropriate ferrofluid is added. The particles are dispersed by ultrasonic or mechanical mixing immediately before applying the magnetic field gradient. The cell remains in the magnetic separator for up to three hours. The sliding valve in the separation cell is inserted at the end of the magnetic separation period to divide the float and sink fractions. Each fraction is removed individually from the separation cell, filtered through a membrane filter and washed with heptane to remove the ferrofluid from the sample particles.

Ferrofluid concentration and sample concentration

Since the concentration-series of ferrofluids had overlapping separation ranges, tests were made to compare separation results with ferrofluids of different magnetite concentrations.

Ferrofluid with physical density 0.81 produced bet-

Test number	Sphere	Separation results*
	size	% %
	(µm)	Float Sink
90	50-60	99 1
91	50-60	96 4
93	50-60	96 4
88	24-48	14 86
94	24-48	36 64
95	24-48	29 71
96	24-48	24 76
126	12-20	50 50
127	6-12	25 75

Table 2. Floating stainless steel spheres

*Conditions for these tests were expected to float all of the stainless steel spheres. Conditions were: Ferrofluid physical density 0.95 and at an apparent density of 11.5 g/cm³; separation time, one hour; and sphere concentration was below 0.00001 cm³ per cm³ of ferrofluid.

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Test number	Sphere size (µm)	Sphere material	Separation % Float	results* % Sink
103	45-75 50-65	Glass s/s	95	99
106	25-35	Glass	85	70
110	24-48	s/s Glass	70	70
	24-48	s/s		95
111	15-25	Glass s/s	70	90
	12 20	57 5		50
112	10-15 6-12	Glass s/s	70	85
117	3-8 6-12	Glass s/s	No sep	aration

*Conditions for these tests were expected to float all of the glass spheres and sink all of the stainless steel spheres. Conditions were: Ferrofluid physical density 0.86 and at an apparent density of 4.8 g/cm³; separation time one hour except test ll? which was three hours; and sphere concentration was kept below 0.00001 cm³ per cm³ of ferrofluid.

ter separations than the ferrofluid with physical density 0.86 in all tests at the same separation apparent density. Experiments were conducted to determine the effect of sample concentration in the ferrofluid. Sample concentration was varied from nominally 0.001 to 0.01 cm³ of sample per cm³ ferrofluid with the sample materials quartz sand (<125 μ m) and stainless steel spheres (24–48 μ m). The lower sample concentrations yielded superior separations in all comparison tests. These comparisons were made by qualitative observation tests. The quantitative separation results in Tables 1–4 were carried out at lower concentrations in order to facilitate counting of particles in the float and sink fractions.

Table 4. Separation of garnet sand

Test number	Particle size		Separation results* % %	
	(µm)		Float	Sink
А	500-850 500-850	lights garnets	98	100
В	250 - 500 250-500	lights garnets	98	100
С	125-250 125-250	lights garnets	98	100

*Conditions for these tests were expected to float the quarts, feldspars and muscovite (lights) and sink the garmets. Conditions were: Ferrofluid physical density 0.81 at an apparent density of 3.4 g/cm³; separation time, 15 minutes; and sample concentration below 0.001 cm³ per cm³ of ferrofluid.

Table 3. Separation of stainless steel (s/s) and glass spheres

Standard particles

Two series of experiments with a single kind of particle were carried out. Commercial glass spheres in various size ranges were processed under conditions expected to float the spheres. The results are shown in Table 1. In a separation time of an hour, about 90 percent of the spheres in all size ranges were floated. In a second series of experiments, commercial stainless steel spheres were floated. In these tests only particles above 50 μ m were successfully floated, as shown in Table 2.

A series of experiments with mixed glass and stainless steel spheres was conducted under conditions expected to float the glass and leave the stainless steel in the sink fraction. The results of these tests are shown in Table 3. The separations were 70 to 95 percent efficient above 10 μ m, but again the nearly quantitative results occurred when the particles were 50 μ m and larger. The estimates of separation efficiencies were made by counting particles with a stereomicroscope.

Garnet sand

A sample of garnet sand was selected to demonstrate separation of minerals. Garnets have a density of about 4 g/cm³ and are easily recognized under the microscope. The sample consisted of approximately 10 percent garnet plus quartz, feldspar, and muscovite. The magnetic particles were removed, and the sample was screened into fractions 125-250 μ m, 250-500 μ m, and 500-850 μ m prior to the density separation. The sand was processed under conditions expected to float all but the garnets. No garnet was found in the light fraction, and about 2 percent of the light material was found with the garnet heavy fraction. The results are shown in Table 4.

Results

The experimentation demonstrated that density separation of particle groups with a ferrofluid separator is practical for particles as small as 50 μ m. The processing is easily handled at densities much above conventional density separation systems.

Certain conditions lead to improved separations. Mechanical stirring or ultrasonic mixing of sample and ferrofluid improves separations. The lowest concentration (in magnetite) ferrofluid that will produce a desired separation should be used. The lowest sample concentration practical in a given situation should be used.

Particles in the millimeter size range can be separated if $\Delta\rho$ is 0.1–0.2 of a density unit. The $\Delta\rho$ must be increased as particle size decreases, in order to achieve effective separations. A $\Delta\rho$ of 0.5–0.75 density unit is estimated to be necessary for separations of particles as small as 50 μ m.

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