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FLOW-THROUGH MAGNETIC SEPARATORS FOR WEAKLY-MAGNETIC ORES DESIGNED FOR SUPERCONDUCTING MAGNETS

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ABSTRACT

Two flow-through model ore separators have been constructed and tested. Both separators use the magnetic field of a straight wire conductor which deflects magnetic particles in toward the conductor. Nonmagnetic gangue particles in the water slurry are deflected away by gravity in one case and by centrifugal forces in the other case. Tests have been conducted with synthetic ore slurries made up of carefully screened sizes of magnetite and silica. These tests show that separation does take place and that the theoretical separation time expected for ferro-magnetic particles in a magnetic field is obtained.

INTRODUCTION

The scientific understanding of the nature of magnetic separation was known early in this century[1] and led to the early industrial magnetic separation of highly magnetic ores such as magnetite. Since that time considerable research has been done to develop new techniques capable of concentrating more weakly magnetic particles and to make such concentration commercially possible.[2,3] Many of the new concentrators can be classified as either "settling" or "flow-through" units. "Settling" separators have been very successful; some of those now used commerically are the Carpco high intensity magnetic separator,[2] the Jones separator,[4] and the M.I.T. high gradient separators.[5] The operation of settling or matrix separators involves three steps: (1) the settling out of magnetic particles on matrices of magnetized spheres, grooved plates, or wires while nonmagnetic particles flow straight through; (2) washing of the magnetics to remove any entrained nonmagnetic particles, thus giving a middlings product, and (3) scouring of magnetics to yield the magnetic product.

Flow-through units, which in general have not been widely used, are those in which magnetic particles are deflected continuously into exit channels. An early example of this type is the quadrupole experimental separator of Aubrey.[6] Aubrey achieved good separation of magnetite from a slurry with a 12 kilogauss quadrupole using iron pole tips. In an attempt to utilize higher field gradients for weakly-magnetic ores we have suggested a high field superconducting straight wire magnet.[7] The magnetic field and field gradient of a straight wire vary as $1/r$ and $-1/r^2$ respectively. A practical approximation to this field is obtained for low aspect ratio dipoles, that is, for dipole windings with small minor radii and large major radii.

If a slurry is directed to flow through a channel positioned near the conductor surface, then magnetic particles are deflected toward the conductor surface which causes the region beside that surface to become rich in magnetics. A divider at the end of the channel separates the concentrate from the tailings, provided that the nonmagnetic particles have been deflected away from the conductor by an opposite force. Examples of opposing forces are a gravity force and a centrifugal force.

The purpose of this work is to study high-speed, flow-through deflection type separators which would be useful for weakly-magnetic ores such as hematite. It is anticipated that high field, high field gradient configurations obtainable with superconductivity would be useful. A 100 kG straight wire magnet could provide a field gradient in the order of 10-15 kG/cm which corresponds to magnetic forces on hematite particles in the order of 20-30 times gravity. The first stage of this project, however, involves low field, non-superconducting magnet deflection experiments with magnetite to investigate this separation scheme.

THE STRAIGHT CHANNEL SEPARATOR[7]

The iron electromagnet shown in Fig. 1 has a cut out sector removed to give a field which is proportional to $1/r$ similar to the field of a straight wire. The magnet is positioned so that gravity forces oppose magnetic forces.

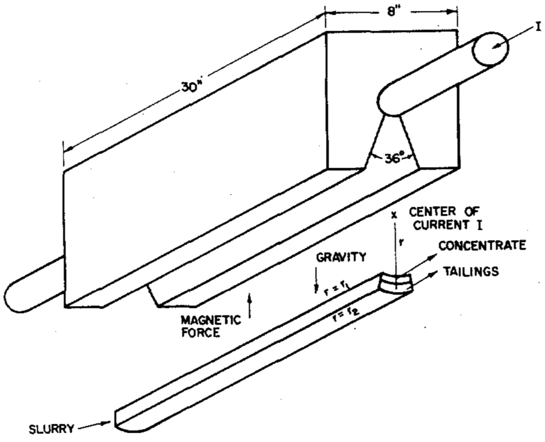

Fig. 1. The straight wire magnetic separator.

The separator design is based on the fact that there will be a particle concentration profile due to gravity and turbulence of the flow. When a magnetic field is applied the concentration profile of the magnetic particles can be reversed. That leaves the nonmagnetic distribution greater at the bottom of the channel. By means of a divider the two flows are then separated from each other at the channel exit. The velocity of the flow must be higher than a minimum velocity V_{min} which is defined as the velocity at which the solids settle freely. At the same time, the flow velocity should be less than a maximum velocity V_{max} above which there is a homogenous distribution of the solids due to strong turbulence.

Tests have been conducted with synthetic ore slurries made up of carefully screened sizes of magnetite and silica. Figure 2 shows recovery and grade plotted vs magnetic force for -200 + 300 mesh (40μ to 70μ dia) magnetite-silica mixtures. It can be seen that forces as small as 2 to 3 g are enough to separate magnetite. In this experiment, the particles do not stick to any channel surface because of turbulence which also tends to separate all particles from each other. However, magnetic particles do tend to agglomerate due to magnetic interparticle attraction and might entrap nonmagnetic particles. Such forces, which are called clustration forces, are proportional to M^2, where M is the

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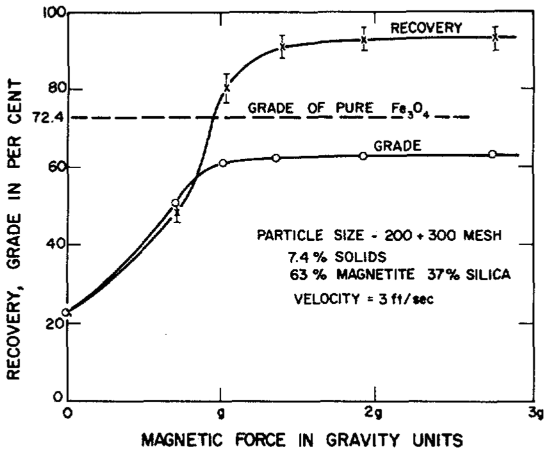

Fig. 2. Recovery and grade vs. magnetic force in gravity units for 40μm to 70μm particles.

particle magnetization, and therefore are much more severe for ferromagnetic magnetite than for antiferromagnetic hematite.[7]

Figure 3 is a grade recovery curve vs particle size. The grade and recovery are less for fine particles, especially below 150 microns, since gravity forces are not strong enough to overcome the turbulent forces on the finer particles.

According to the experiments with the straight channel separator, excellent grade and recovery can be achieved for two opposing forces which act in opposite directions on the magnetic and nonmagnetic particles.[7]

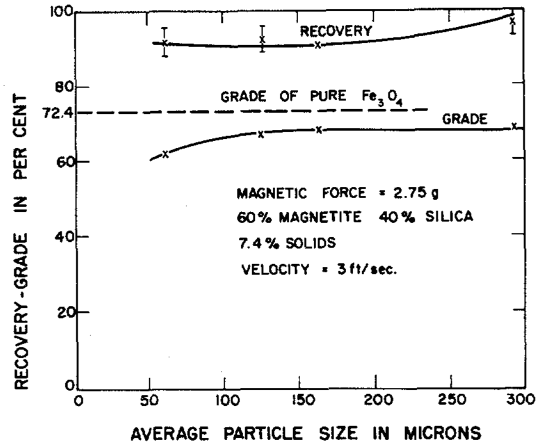

Fig. 3. Recovery and grade vs. particle size.

THE CENTRIFUGAL MAGNETIC SEPARATOR

For fine particles or for weakly magnetic ores forces of a few g are inadequate; in that case, a centrifugal separator such as is sketched in Fig. 4 might be used to provide forces up to 10 to 20 g. Due to the centrifugal force, the nonmagnetic particles will be deflected toward the outer surface while the magnetic particles will be deflected toward the inner surface. The slurry could be injected at one end and separated at the other end with a divider into magnetics and nonmagnetics.

A magnetic particle in a magnetic field experiences a force equal to

$$F_m = -\nabla U \tag{1}$$

where U is the particle energy due to an applied magnetic field H.

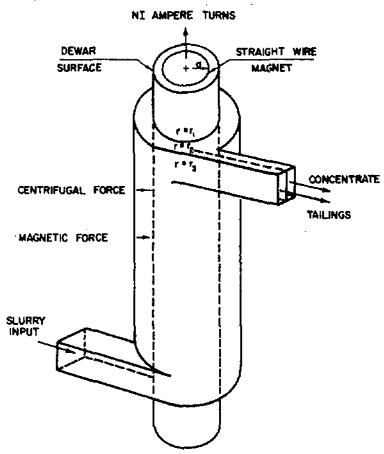

Fig. 4. The centrifugal magnetic separator.

For weakly-magnetic particles

$$U = -m[M_oH + \int H\, dM_1] \tag{2}$$

where m is the particle mass, M_o is the zero field magnetization in emu/gm, and M_1 is the induced magnetization due to H. By replacing M_1 with χH, where χ is the susceptibility, we get

$$U = -m[M_oH + 1/2\ \chi H^2]. \tag{3}$$

For an anti-ferromagnetic material such as hematite, the total magnetization M is

$$M = M_o + \chi H. \tag{4}$$

The values for hematite[7] are: $M_o = 0.4$ emu/gm, the zero field magnetization and $\chi = 2 \times 10^{-5}$ emu/gm-Oe, the anti-ferromagnetic susceptibility.

For a 100 kG field, $\chi H = 5\ M_o$, which allows the following approximation:

$$F_m \cong m\ \chi H \frac{dH}{dr}\ . \tag{5}$$

The drag force, F_D, on a spherical particle of diameter D is $3\pi D\mu u$ where μ is the viscosity and u the particle velocity relative to the flow, which in this case is predominantly laminar. This force is approximately correct if the Reynolds number $R_e = \rho u D/\mu$ is sufficiently small. The equation of motion in the radial direction r, for a magnetic particle and a nonmagnetic particle, is:

$$-\rho_m \frac{\pi D^3}{6} \frac{d^2r}{dt^2} = -\rho_m \frac{\pi D^3}{6} \chi H \frac{dH}{dr} + \frac{\pi D^3}{6} [\rho_m - 1]\omega^2 r + F_D \tag{6}$$

and $$\rho_n \frac{\pi D^3}{6} \frac{d^2r}{dt^2} = \frac{\pi D^3}{6} [\rho_n - 1]\omega^2 r - 3\pi D\mu \frac{dr}{dt} \tag{7}$$

where (see Fig. 4):

a is the radius of the current conductor, r_1 & r_3 are the inner and outer radii of the separator, r_2 is the radius of the divider, ρ_m & ρ_n are the density of magnetic and nonmagnetic particles, and ω is the angular velocity.

It can be easily shown that the left-hand side of Eqs. (6) and (7) can be neglected compared to the other terms. Then the time, T_m, that a magnetic particle travels from a radius r_3 to a radius r_2 is expressed in Eq. (8).

$$T_m(r_3 \to r_2) = \frac{18\mu}{4(\rho_m - 1)D^2\omega^2} \ln \frac{\chi H_o{}^2 a^2 - f\omega^2 r_2{}^4}{\chi H_o{}^2 a^2 - f\omega^2 r_3{}^4} \tag{8}$$

Similarly the time, T_n, that a nonmagnetic particle travels from a radius r_1 to a radius r_2 is

$$T_n(r_1 \to r_2) = \frac{18\mu}{(\rho_n - 1)D^2\omega^2} \ln \frac{r_2}{r_1} \tag{9}$$

where H_o is the field at $r = a$.

Equating Eqs. (8) and (9), we can get an expression for the angular velocity:

$$\omega^2 = \chi H_o{}^2 a^2 \left[\left(\frac{r_2}{r_1}\right)^{\beta} - 1\right] \Bigg/ f\left[r_3{}^4 \left(\frac{r_2}{r_1}\right)^{\beta} - r_2{}^4\right] \tag{10}$$

where $\beta = \dfrac{4(\rho_m - 1)}{\rho_n - 1}$ and $f = \dfrac{(\rho_m - 1)}{\rho_m}$.

Eq. (10) shows that the angular velocity is not dependent on particle size. Fig. 5 is a plot of deflection time T for hematite vs particle diameter in microns for different divider positions. Note that a 30 micron particle requires about one second for separation, which implies a separation length about 2 m long with about 10 traverses of flow around the central conductor.

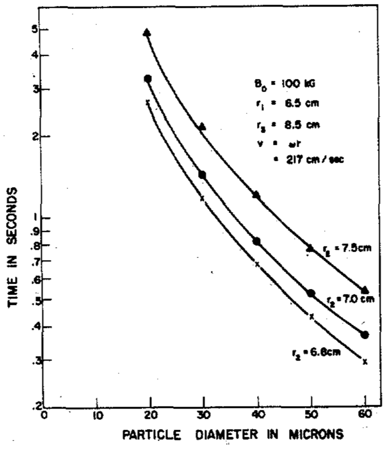

Fig. 5. Calculated time of deflection T vs. particle diameter D for hematite ore particles.

For smaller particles the length required for separation can be scaled from Fig. 5. For example, at 10 micron diameter the time required (and separator length) is 9 times larger than for 30 micron particles. Separation times are proportional to $1/D^2$.

CENTRIFUGAL EXPERIMENT

Assuming that a straight wire magnet could provide the basis for a superconducting centrifugal separator, a simulation experiment using magnetite at low fields is conducted because of the high cost of building a superconducting magnet. The object of this experiment is to provide design data for the eventual construction of a full-scale separator. In particular, several important hydrodynamic problems must be studied first.

An experimental channel similar to the sketch in Fig. 4 was mounted around a 10-turn straight conductor which can produce 800 gauss at r_1 = 7.5 cm. The channel, which is a cylinder 25 cm high by 1.87 cm thick, is transparent lucite in order to study the flow patterns. The experimental centrifugal separation of silica and magnetite particles from water (at zero applied magnetic field) is plotted in Fig. 6. Notice that above 6 g there is over 95% recovery for these 40-70μ dia. particles.

The preliminary tests with the magnetic field turned on showed that flocculation forces between magnetic particles are too large. When the magnet is turned on the magnetite particles start to flocculate and form larger pulp particles which rotate with the flow very close to the outer wall because of their larger mass. If the magnetic field is slowly increased then a field will be reached at which time the particles jump and stick to the inner wall. It is almost impossible find a range of forces in which these larger particles can rotate close to the inner wall without sticking, since the velocity, and centrifugal force, is zero at the inner wall. Recall that such sticking on the wall and the initial flocculation itself did not occur in the straight channel experiments due to a sufficient amount of turbulence.

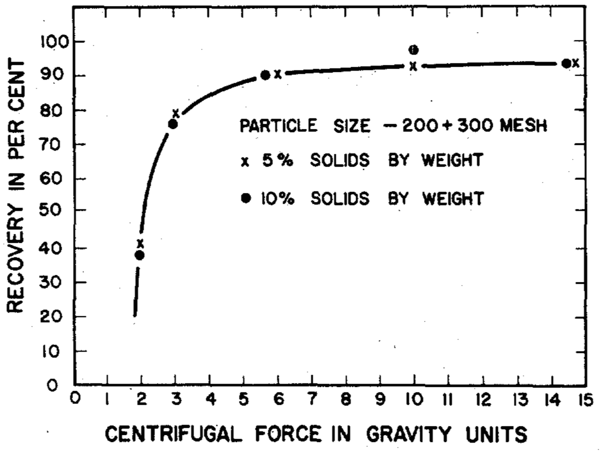

Fig. 6. Recovery vs. centrifugal force.

In summary, centrifugal separation of silica from water is satisfactory for 40μ particles; finer particles would require higher velocities. The centrifugal magnetic separation of magnetite from a slurry was not successful because of the flocculation forces, as described above. We expect that hematite or similar weakly magnetic ores could be separated in this centrifugal separator since, for them, the flocculation force between particles is smaller by a typical factor of ∿ 1/2500. It would seem that with superconducting turns producing 50 kG that the above experimental separator could provide a 12 g inward magnetic force to counteract the 6 g outward force. Thus good recovery for hematite ore would be possible. The general design feature is to provide opposite centrifugal and magnetic forces sufficiently large so that fine particles of weakly magnetic ores can be recovered.

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