LA-UR- 93-2516

Title:

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ENVIRONMENTAL REMEDIATION

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Submitted to:

Cryogenic Engineering Conf.
Albuquerque, NM
July 12-16, 1993

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Form No. 836 R5
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HIGH GRADIENT MAGNETIC SEPARATION APPLIED TO ENVIRONMENTAL REMEDIATION

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ABSTRACT

High Gradient Magnetic Separation (HGMS) is an application of superconducting magnet technology to the separation of magnetic solids from other solids, liquids, or gases. The production of both high magnetic fields (>4 T) and large field gradients using superconducting magnet technology has made it possible to separate a previously unreachable but large family of paramagnetic materials. This is a powerful technique that can be used to separate widely dispersed contaminants from a host material and may be the only technique available for separating material in the colloidal state. Because it is a physical separation process, no additional waste is generated. We are applying this technology to the treatment of radioactive wastes for environmental remediation. We have conducted tests examining slurries containing nonradioactive, magnetic surrogates. Results from these studies were used to verify our analytical model of the separation process. The model describes the rate process for magnetic separation and is based on a force balance on the paramagnetic species. This model was used to support bench scale experiments and prototype separator design.

NOMENCLATURE

A_o	= Superficial flow area, m^2	h_s	= Separation coefficient, Kg/m^2-s
A_s	= Matrix surface area, m^2	L	= Matrix length, m
B_o	= Applied magnetic flux density, T	S	= Matrix spacing, m
C	= Correlation coefficient	S_p	= Separation parameter
c	= Contaminant concentration, Kg/m^3	U_m	= Magnetic velocity, m/s
c_o	= Initial contaminant concentration, Kg/m^3	U_o	= Superficial velocity, m/s
D_m	= Matrix element diameter, m	z	= Coordinate in flow direction, m
D_p	= Particle diameter, m	λ	= Capture cross section
e	= Matrix void fraction	μ	= Fluid viscosity, N-s/m ²
F_m	= Magnetic force, N	χ_p	= Particle susceptibility, (SI)
F_o	= Competing forces, N	χ_f	= Fluid susceptibility, (SI)
H_m	= Modified Hartmann number		
H_s	= Magnetic field at saturation, A/m		

INTRODUCTION

High gradient magnetic separation (HGMS) is a form of magnetic separation where large magnetic field gradients are used to accomplish separations of micron-sized paramagnetic particles. HGMS separators usually consist of a high-field solenoid magnet the bore of which contains a fine structured, ferromagnetic matrix material. The matrix material locally distorts the magnetic field and creates large field gradients in the vicinity of the matrix elements. These elements then become trapping sites for paramagnetic particles and is the basis for the magnetic separation.

Much work¹⁻⁷ has been done to model the behavior of the paramagnetic particles as they interact with the magnetized matrix. Dynamic effects have been investigated by analyzing particle trajectories in homogeneous materials and the influence of particle buildup on the matrix elements and their effect on the flow field have also been studied. These studies, although requiring simplifying assumptions, provide useful insight into important aspects of this complex problem. In particular they identify appropriate independent variables that form the basis for this investigation.

The matrix materials currently used for HGMS are inhomogeneous and are of complex cross section. In addition the paramagnetic particles are nonspherical and include a range of particle sizes. All of these factors preclude precise analytical treatment.

If the particles are physically liberated from the host material and are not electrically charged, the principal forces governing their behavior are magnetic, viscous and gravitational. The performance of the magnetic separator is modeled using a static force balance on an individual paramagnetic particle in the immediate vicinity of a matrix element as shown in Fig. 1. The model assumes that if the magnetic capture forces are greater than the competing viscous drag and gravity forces, the particle is captured and removed from the flow stream. We propose a rate model for this process that depends on a separation coefficient, which we define in terms of a capture cross section, and a potential function defined by the force balance on the particle.

Figure 1. Force balance on a paramagnetic particle in the vicinity of a matrix element.

A series of tests was performed to evaluate separator performance as a function of the independent variables in the separation process. The results were used to determine the separation coefficient in the proposed rate model and are correlated using physically meaningful dimensionless groups. This model provides a predictive tool for further magnetic separator development and can be used for the design of both prototype and full scale units.

MODEL

Our model of the high gradient magnetic separator is based on a rate equation which includes an empirically determined separation coefficient, h_s as follows:

$$U_o A_o dc = -h_s A_s \left(\frac{F_m - F_o}{F_m} \right) d\left(\frac{z}{L}\right) \quad (1)$$

where the contaminant concentration is given in terms of h_s and the force balance on the particle. Writing in dimensionless form by using c_o gives

$$\frac{d(c/c_o)}{d(z/L)} = - \frac{h_s A_s}{U_o A_o c_o} \left(\frac{F_m - F_o}{F_m} \right) \quad (2)$$

Let

$$S_p \equiv \frac{h_s A_s}{U_o A_o c_o} \quad (3)$$

be the separation parameter. In general

$$S_p = f(c) \quad (4)$$

and

$$0 \leq S_p \leq 1.0 \quad (5)$$

If S_p is known, Eq (2) can be integrated and the separation efficiency can be calculated once the forces are determined. S_p can be determined empirically but because of Eq (4) a correlation is difficult to obtain. A more fundamental measure of separator performance is needed, one that is independent of concentration.

Assume there exists for each matrix element a capture height, wherein, each magnetic particle entering the window defined by the capture height and the matrix element length will be captured by the matrix element. Then define a capture cross section, λ for a matrix element to be the ratio of the capture height to the matrix element height as shown in Fig. 2. Recognizing that the separation parameter is the ratio of capture rate to feed rate, it can be written in terms of λ as follows:

$$S_p = \frac{\text{Capture Rate}}{\text{Feed Rate}} \quad (6)$$

$$\lambda = \frac{\text{capture height}}{\text{element diameter}}$$

Figure 2. The matrix capture cross section, λ defined as the ratio of capture height to matrix element diameter.

Because of the importance of matrix length in the formulation of λ , we express the capture rate in terms of the swept area of particle capture, or

$$\text{Capture Rate} = \left[\frac{\text{Capture Rate}}{\text{Length}} \right] \left[\frac{\text{Matrix Element Volume}}{\text{Element Cross Section}} \right] \quad (7)$$

and for a circular matrix element

$$\text{Capture Rate} = \left[\frac{\lambda D_m U_o c}{e} \right] \left[\frac{L A_o (1-e)}{\frac{\pi D_m^2}{4}} \right] \quad (8)$$

and the feed rate is

$$\text{Feed Rate} = c_o A_o U_o \quad (9)$$

then the separation parameter becomes

$$S_p = \left[\frac{4 \lambda L}{\pi D_m} \right] \left[\frac{c}{c_o} \right] \left[\frac{1-e}{e} \right] \quad (10)$$

It remains to empirically determine λ , which is independent of the contaminant concentration. Once λ is known, then the separation parameter, S_p be calculated with Eq (10) and the separation efficiency can be determined using Eq (2).

EXPERIMENTS

A comprehensive series of experiments was performed to determine the capture cross section as a function of the independent variables. Table I lists the variables investigated and their range. For convenience the list has been divided into material characteristics and separator parameters. A total of 120 experiments were conducted; 76 involved water/contaminant mixtures and 44 involved water/soil/contaminant mixtures. The experimental parameters were selected to give a useful range for each parameter.

Table I. Independent Variables Investigated

Material Characteristics	Separator Parameters
Particle Size: 0.5 - 50 μm	Matrix Element Size: 5 - 100 μm
Impurity Concentration: 0.4 - 400 ppm	Matrix Element Spacing: 80 - 1200 μm
Solids Concentration: 5 - 30 wt %	Magnetic Field Strength: 0.5 - 7.5 T
Magnetic Susceptibility* ($\times 10^6$): 129 - 1478	Matrix Material: 430 Stainless Steel & Ni
Surfactant Concentration.: 0.05 - 0.2 wt %	Residence Time: 1.0 - 8.0 s
Slurry pH: 7 - 10	Superficial Velocity: 0.25 - 4.0 cm/s

* SI units

The experiments were conducted using both conventional and superconducting magnets with magnetic field orientations both parallel and perpendicular to the slurry velocity. In all cases the flow velocity through the matrix was oriented with the gravity vector (vertical flow downward). Back-flushing of the matrix was done at zero magnetic field and with the flow direction reversed. The slurry was pumped through the matrix using a peristaltic pump at constant flowrate in aliquots of 250 ml. Feed slurry homogeneity was maintained using a fluid mixer at the pump inlet. Feed and multipass effluent samples (25 mL) were analyzed for contaminant concentration using both inductively coupled plasma - atomic emission spectrophotometry and optical absorption spectrophotometry. In most cases redundant samples were analyzed.

DATA CORRELATION

The capture cross section, λ for each test was determined experimentally based on the measured feed and effluent concentrations, the particle force balance, the matrix geometry and the contaminant particle size. To correlate λ we introduce a modified Hartmann number which is a ratio of magnetic to viscous forces. We neglect the effect of gravity because the orientation of the matrices was not changed in the tests. The modified Hartmann number is given by

$$H_m = \frac{(\chi_p - \chi_f) B_o H_s D_p^2}{\mu U_o D_p} \quad (11)$$

This dimensionless number alone is insufficient for data correlation because it contains insufficient geometric information about the separator matrix. Only the contaminant particle diameter is included in the modified Hartmann number. At least two other lengths associated with the process are important to the problem, the matrix filament diameter, D_m

and the matrix filament spacing, S . These lengths are nondimensionalized using D_p giving the length ratios D_m/D_p and S/D_p . The general form of λ is given by

$$\lambda = C H_m^m (D_p/D_m)^n (D_p/S)^p \quad (12)$$

where the reciprocals of the dimensionless lengths have been used for convenience to make exponents n and p positive and C is a constant.

The data with $\pm 100\%$ error bars are shown in Fig. 3 where λ is plotted as a function of H_m , D_p/D_m and D_p/S with $m=0.2$, $n=0.5$ and $p=0.5$. Data for both water and soil slurries are shown. The constant, C is obtained from a power fit of the data as 0.025. The correlation for capture cross section is then

$$\lambda = 0.025 H_m^{0.2} (D_p/D_m)^{0.5} (D_p/S)^{0.5} \quad (13)$$

Figure 3. HGMS capture cross section for water and soil slurries correlated with modified Hartmann number and matrix geometry.

DISCUSSION

The capture cross section is significantly less than 1.0, which implies that particles are swept around the matrix elements by the fluid flow even if the particles enter the region defined by the projected frontal area of the matrix element. Also the CCS is proportional to the magnetic force and the contaminant particle diameter and inversely proportional to the matrix element diameter and the matrix element spacing. These results are consistent with our experiment observations.

Watson⁷ suggested using the ratio of magnetic velocity to superficial velocity as a measure of magnetic capture where

$$\frac{U_m}{U_o} = \frac{(\chi_p - \chi_f) B_o H_s D_p^2}{9\mu U_o D_m} \quad (14)$$

and if $U_m/U_o > 2$ separation would occur. Our modified Hartmann number is related to the velocity ratio as follows:

$$H_m = 9 \frac{U_m}{U_o} \frac{D_m}{D_p} \quad (15)$$

In addition, our proposed correlation includes the length ratio D_p/S where S accounts for the filament spacing within the matrix.

The capture cross section, λ is inversely proportional to U_o , the superficial velocity, which is the ratio of the separator length and the slurry residence time in the matrix. Intuitively, one expects to have to maximize both the separator length and the matrix residence time for optimum performance, however, only their ratio need be considered making U_o the more fundamental parameter.

CONCLUSIONS

1. We propose a rate model based on a contaminant particle force balance and an empirically determined capture cross section as the basis for analyzing the performance of high gradient magnetic separators.
2. The correlation for the capture cross section is based on experiment results from water and soil slurries with well characterized magnetic surrogates. A wide range of variables suggested by previous studies was investigated.
3. Results for the capture cross section were correlated with a modified Hartmann number and the length ratios D_p/D_m and D_p/S which describe the matrix geometry (filament size and spacing) and the contaminant particle size.
4. The correlation is similar to the magnetic velocity ratio suggested by others but includes a matrix spacing parameter, S to account for filament density.
5. Use of the empirically determined capture cross section in the proposed rate model enables the prediction of high gradient magnetic separator performance for a variety of materials and applications.

ACKNOWLEDGMENT

The authors wish to acknowledge the Department of Energy, Office of Technology Development for partial financial support for this project.

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