MAGNETIC FLOCCULATION AND FILTRATION

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INTRODUCTION

In terms of their magnetic properties, materials may be divided in various groups: ferromagnetic materials have magnetic susceptibility (i.e., the ratio of magnetization to the magnetic field strength) of order 1, paramagnetic materials have positive magnetic susceptibility in the range of $10^{-3}$-10$^{-5}$, and diamagnetic materials have negative magnetic susceptibility in the proximity of -10$^{-5}$. Also, some materials having magnetic susceptibility between ferromagnetic and paramagnetic are called super-paramagnetic. Based on differences of the magnetic susceptibility of materials, magnetic separation has been introduced as a recovery and pollution control process for many environmental and industrial problems. The idea of using strong and high-gradient magnetic fields (HGMFs) to separate weakly magnetic particles has recently been introduced (1). Phenomena of interest in magnetic separations are: (a) particle flocculation due to induced dipole-dipole interactions and (b) particle filtration by HGMFs.

In this study, experiments were conducted to investigate the efficiency of high-gradient magnetic filtration (HGMF) of colloidal particles. This process can be analyzed by studying particle-collector and particle-particle interactions. The development of a modeling approach to describe particle-particle interactions and understand the mechanism of particle flocculation in homogeneous and high-gradient magnetic fields is discussed. Studies of particle-particle interactions have led to the introduction of magnetic-seeding flocculation as a process to separate nonmagnetic particles by flocculation with small amounts of injected magnetic particles. The flocs consisting of low and high magnetic-susceptibility particles can respond and thus be separated in a high-gradient magnetic filter. Preliminary results of magnetic-seeding flocculation and filtration are presented here.

EXPERIMENTAL

The experimental system for HGMF experiments is shown in Figure 1. A stirred tank was used for magnetic seeding with the objective to increase the collision frequency of the particles. Experiments were conducted using a 2-Tesla water-cooled electro-magnet. A magnetic filter packed with a ferromagnetic wire of 76-micrometer diameter was used for magnetic filtration of a suspension containing sorbent sodium titanate particles, magnetically seeded with polystyrene/magnetite particles. The result was up to 99.4% removal of colloidal sodium titanate particles at a concentration ratio of sodium titanate to polystyrene/magnetite particles 20:1. This result shows that HGMF, in combination with magnetic seeding, is an effective separation method for colloidal particles.

Fundamental particle phenomena occurring in the magnetic bed during the HGMF experiment are particle-particle and particle-collector collisions. A mathematical description of these phenomena is needed to elucidate the mechanisms of flocculation and filtration by HGMF and eventually yield a predictive tool that can be used for the design of efficient magnetic filters.
THEORETICAL

A mathematical analysis is introduced in this work to model particle-particle interactions and magnetic flocculation kinetics of magnetically seeded and non-seeded particle suspensions. This analysis is aiming at providing a basic understanding of particle dynamics in suspensions as well as in HGMF beds. The developed model will be extended to describe experimental data of particle flocculation and filtration and predict the performance of high-gradient magnetic filters.

The forces considered in this work include external forces, such as gravity and magnetism, acting on individual particles and interparticle forces, such as van der Waals, electrostatic, hydrodynamic, and magnetic dipole forces. Brownian relative diffusivity is also considered.

External Forces

External forces due to gravity and magnetism act on particles suspended in a liquid medium. The magnitude of these forces depends on a number of parameters, such as particle size, density, magnetic susceptibility, and magnetic field. The result of these forces is translation of particles in the suspension. Different particles travel at different velocities. The difference of the velocities of two particles is called the relative velocity, which is the velocity of one particle with respect to a reference frame based on the center of the other particle.

Gravity: The far-field relative gravitational velocity for two particles is the difference of their respective individual velocities. Individual particle velocities are obtained from a force balance of gravity, buoyancy, and drag forces for each particle.

Magnetic Attraction: The magnetic force on a small particle can be given in terms of the magnetic field (1). A force balance of magnetic, buoyancy, and drag forces for each particle gives the relative velocity due to magnetic forces.

Interparticle Forces

In dilute suspensions, the forces acting between two particles change in strength as one particle approaches the other. The interparticle forces to be considered in this work are discussed below.

van der Waals Forces: Hamaker (2) calculated the van der Waals interparticle force potential for unequal sized spheres as a function of separation and the Hamaker constant. Later, another expression was derived by Schenkel and Kitchener (3), which incorporates electromagnetic retardation effects in Hamaker's formula.

Electrostatic Forces: Electrostatic repulsion arises when two particles of the same charge sign approach each other and their diffuse layers of ions overlap. There is no general analytical solution providing the electrostatic potential between spherical particles. For particle size radii much larger than the thickness of the electric double layer and small surface potential, the interaction energy can be calculated from the corresponding flat-plate interactions. Assuming that the interaction energy of two particles is given by the contribution of infinitesimal parallel rings on the surface of the particles, Verwey and Overbeek obtained an approximate analytical expression by integrating the contributions over the entire surface. Improvements to this approximation were made by McCartney and Levine (4), who expressed the potential in terms of a distribution of electric dipoles on the surface of the particles and developed an integral equation, for which a better approximation was derived. Other analytical expressions applicable under various conditions are given in the literature (5,6). Bell et al. (6) derived a formula to be applicable for larger potential values, while Hogg et al. (5) gave an expression for particles of different surface potential which is useful for heterogeneous particle interactions.

Hydrodynamic Forces: Haber et al. (7) and Zinchenko (8) developed exact solutions for the hydrodynamic resistance to particle collision using the method of bispherical coordinates. Haber et al.'s solution was applied to axisymmetric motion of two drops, and Zinchenko's was applied to the asymmetric motion of drops. Although these solutions were originally calculated for drop motion, they can easily be applied to particle motion by assigning a large value to the ratio of drop viscosity to fluid viscosity (9). Zhang and Davis (9) derived the axisymmetric relative mobility functions from resistance
functions obtained by Zinchenko. Similar expressions for the asymmetric relative mobility functions were also found. These hydrodynamic functions were incorporated in this work.

**Magnetic Dipole Attraction:** The magnetic dipole moment between two particles is expressed with the magnetic interparticle force, which depends on the orientation of the particle pair in the magnetic field. An orientation-averaged magnetic dipole interaction has been derived by Chan et al. (10). When orientation-averaging is not included in the analysis, it is expected that the direction of the magnetic field will play a significant role on the flocculation frequency.

**Flocculation Frequency**

The far-field relative velocity between two particles is the vector addition of the gravitational relative velocity and the magnetic relative velocity in the absence of interparticle forces. Thus, the relative velocity depends on the orientation of the magnetic field and the magnetic field gradient as compared to the gravitational field. The relative velocity can be found based on a force balance (11,12). Solving this force balance will yield the flocculation frequency between two particles under the influence of a magnetic field.

When Brownian diffusion dominates over external forces, the contribution of external forces is negligible and only interparticle forces and Brownian diffusion are considered. In the absence of the magnetic field, the flocculation frequency has been determined by Zhang and Davis (9). In the presence of a magnetic field, an integration of the magnetic force is required over all orientations of the particles in the magnetic field. Such an integration has been carried out by Chan et al. (10), and their results have been incorporated in a Brownian diffusion model by Tsouris and Scott (13).

When external forces dominate over Brownian diffusion, the Brownian diffusion term can be eliminated. Solution of this case will provide the trajectory of a particle from an arbitrary starting position relative to a stationary particle. The limiting or critical trajectory for a collision to occur can then be found. From this critical radius parameter, the flocculation frequency can be obtained (14).

In this way, the particle flocculation frequency can be calculated as a function of all parameters of the system. This flocculation frequency can then be used in a bivariate population balance model to estimate the effect of flocculation on the particle population as a function of time (15).

Finally, the modeling approach described here permits studies of magnetic seeding flocculation in which magnetic particles are added to a suspension of nonmagnetic particles. Initially, flocculation of nonmagnetic with magnetic particles will occur due to both external forces and interparticle forces, but no contribution will be provided by magnetic dipoles. The resulting flocs, however, have higher magnetic susceptibility than the original nonmagnetic particles, therefore in this case, magnetic dipoles will contribute to particle flocculation. This mechanism suggests that magnetic seeding can mathematically be described as a heterogeneous flocculation process, which can sufficiently be handled by the bivariate population balance approach (15).

**SUMMARY**

A model is available in predicting flocculation frequencies between particles of various properties under the influence of a magnetic field. This model provides a basic understanding of fundamental phenomena, such as particle-particle and particle-collector interactions, occurring in HGMF, and will be extended to describe experimental data of particle flocculation and filtration and predict the performance of high-gradient magnetic filters. It is also expected that this model will eventually lead to a tool for the design and optimization of magnetic filters for environmental, metallurgical, biochemical, and other applications.

**REFERENCES**


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