Aggregation and separation of ultrafine magnetic minerals in microchannels in the presence of a high gradient magnetic field

A thesis

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By

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I hereby certify that the work embodied in the thesis is my own work, conducted under normal supervision.

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Ariful Islam

Dedicated to my parents, wife and children

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Notations

Latin Characters

A	Hamaker constant	J
$\mathbf{B}$	Magnetic field induction	T
D	Particle diameter	m
$\mathbf{m}$	Magnetic dipole moment	$A.m^2$
$\mathbf{m}_i$	Magnetic moment of i-th particle	$A.m^2$
$\mathbf{m}_j$	Magnetic moment of j-th particle	$A.m^2$
r	Centre-to-centre distance between particles	m
d_0	Cut-off distance	m
$\mathbf{M}$	Magnetization	A/m
$\mathbf{H}$	Magnetic intensity	A/m
$\mathbf{J}_M$	Magnetization Current Density	
M_s	Saturation Magnetization	A/m
H_s	Saturation Magnetic Field	A/m
H_c	Coercivity	A/m
H_{ci}	Intrinsic Coercivity	A/m
B_r	Remnant Induction	T
M_r	Remnant Magnetization	A/m
$\vec{\boldsymbol{n}}$	Unit normal vector acting along the centres of two particles	
R	Particle radius	m
R_1	Radius of particle one	m
R_2	Radius of particle two	m
R^*	Reduced particle radius	m
$\hat{R}$	Unit vector along relative positions of two particles	-
E_1	Elastic modulus of particle one	$N.m^{-2}$
E_2	Elastic modulus of particle two	$N.m^{-2}$
E^*	Reduced elastic modulus	$N.m^{-2}$
V	Particle volume	m^3

$\vec{V}$	Relative velocity vector between two particles	m/s
$\overrightarrow{V_1}$	Velocity vector of particle one	m/s
$\overrightarrow{V_2}$	Velocity vector of particle two	m/s
$\overrightarrow{V_n}$	Velocity of particles along normal direction	m/s
m_1	Mass of particle one	kg
m_2	Mass of particle two	kg
m^*	Reduced particle mass	kg
k_B	Boltzmann constant	J/K
U_m	Magnetophoretic mobility	m/s
T	Temperature	K
t	Time	s

Greek Characters

δ	Surface-to-surface distance between particles	m
ν_1	Poisson's ratio of particle one	-
ν_1	Poisson's ratio of particle two	-
β	Damping ratio	-
Δt	Time step	s
ε	dielectric constant	-
ε_0	permittivity of free space	F/m
κ	Debye constant	m^{-1}
ψ_s	Electric potential at the surface	mV
ζ	drag coefficient	$N.s.m^{-1}$
μ	coefficient of the fluid viscosity	$N.s.m^{-2}$
χ_m	Magnetic Susceptibility	m^3/kg
μ_m	Permeability of material	$N.A^{-2}$
μ_0	Permeability of the free space	$N.A^{-2}$
α	Magnetic field gradient	T/m

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Abstract

Aggregation and separation processes of ultrafine magnetic minerals in a microchannel in the presence of fluid flow and external magnetic field gradient (MFG) were studied in this PhD thesis. A computer code based on the Discrete Element Method (DEM) was developed to this aim. The model included the interaction between magnetic dipoles, cohesion as simulated by van der Waals force equation, electric double layer and Brownian forces. The Hertz's non-linear contact model was used to obtain realistic particle deformations. The behaviour of the system was analysed for particle sizes ranged between 0.5 µm and 1.5 µm, in the presence of a magnetic field gradient in the range 0.3-2.0 T/m. The study was carried out in four steps, which are given in the following paragraphs.

In the first step, the aggregation process of different densities and sizes of magnetic particles were analysed in the presence of an external magnetic field induction, in the absence of a magnetic field gradient. Three different types of particles (iron, magnetite and magnetite-polystyrene) and four different particle size distributions (a monomodal, two Gaussians and a trimodal) were considered. It was observed that the total net interparticle force changed from attractive to repulsive when the particle size decreased. Furthermore, the analysis of bulk particle suspension showed that there is a critical value of surface potential above which the particles aggregated in their secondary minimum for all particle size distributions. In addition, the coordination number of the assemblies decreased by following the order monomodal>narrow Gaussian>broader Gaussian>trimodal. This sequence depended on the number of fine particles in the system. More importantly, particle density did not influence the aggregation behaviour, however, the lighter particles developed higher velocities than the heavier particles.

In the second step, the size segregation of fine magnetite particles in the presence of an external magnetic field gradient was investigated. Two opposite phenomena, mutual magnetisation and hydrodynamic resistance due to the presence of an intervening liquid, were incorporated into the computer model. The behaviour of single particles, single chains made of monosized particles and bulk particle suspensions were analysed. For the bulk particle suspensions, two size distributions of particle were considered: a trimodal

and a Gaussian.

For the case of single particles, a threshold value of MFG was observed below which the particles did not move along the direction of MFG. This threshold value of MFG was higher for the smaller (0.5 μm) than for the larger (1.5 μm) particle. The analysis of the motion of single chains made of monosized particles showed that chain velocity increased with increasing number of particles in the chain, due to the effects of mutual magnetisation. For bulk particle suspensions, the value of coordination number and number of particles per cluster decreased and the number of singlets increased with magnetic field gradient for both particle size distributions. This indicated that the level of aggregation decreased significantly with increasing magnetic field gradient. This effect was probably due to the magnetic field gradient force, which is proportional to particle size and make particles of different sizes to move along the direction of magnetic field gradient at different velocities. Therefore, size segregation occurred and less particles aggregated as compared to the case in the absence of MFG. This aggregation was corroborated by the visualisation of the simulations, which demonstrated that small particles did not move in response to the magnetic field gradient while the larger particles aggregated and responded to the external magnetic field gradient.

In the third step, the aggregation and motion of magnetic particles in the presence of fluid flow and a magnetic field gradient were studied. The study was carried out for single particle chains and bulk particle suspensions for two different configurations of magnetic field gradient: co-current and counter-current. The behaviour of the system was analysed for plug and parabolic fluid flows. For the co-current case, it was clear that the velocity of the chains was the result of the addition of the fluid and MFG contributions. However, for a counter-current configuration of MFG, a threshold fluid velocity was observed below which the particles were able to move along the direction of MFG due to the opposite effect of fluid flow and MFG. For the case of parabolic flow, a higher number of particles in the chain was required to move along the direction of MFG in a counter-current configuration of MFG than for the plug flow. In addition, the particle chains were observed to break at the centre of the chain for the case of parabolic flow due to shear effects. For the case of bulk particle suspensions, some of the particles aggregated, while others remained in the form of singlets or doublets. A threshold fluid velocity was observed below which the aggregated particles moved along the direction of MFG while the singlets and doublets moved along the direction of fluid flows in a counter-current configuration. This observation was consistent with the single particle chain study.

The fourth step was the analysis of the aggregation and segregation of magnetic and non-magnetic particles. The aggregation behaviour was analysed by plotting the number of contacts and singlets of these particles. For the case of magnetic particles, the number of contacts per particle increased with particle size due to the dependency of the magnetic force on the particle diameter. However, a few non-magnetic particles aggregated with the magnetic particles. This level of aggregation was probably due to the net force (van der Waals and EDL) between silica and magnetite, which was attractive even at distances of 4 nm. The aggregated magnetic particles separated from the non-magnetic particles for a fluid velocity less than -10 μm/s with a magnetic field gradient of 2.0 T/m. This value of MFG (2.0 T/m) was not sufficient to overcome the fluid drag force when the fluid velocity was higher than -10 μm/s and therefore, all the particles moved in the direction of the fluid flow.

Overall, this thesis has demonstrated that fine magnetic particles can be separated from non-magnetic materials in a microchannel by using a counter-current magnetic field gradient. In addition, the aggregation process was hindered due to the presence of MFG. Nevertheless, an experimental investigation is required, which could aid the simulation results for future applications.