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Numerical simulation of agglomeration process dynamics of ferromagnetic mineral particles in a weak magnetic field

Jiangang Ku [a,*], Huihuang Chen [b], Kui He [a], Lu Xu [a], Quanxiang Yan [a]

[a] College of Zijin Mining, Fuzhou University, Fuzhou 350116, Fujian, China

[b] College of Chemistry and Chemical Engineering, Central South University, Changsha 410083, Hunan, China

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ABSTRACT

Based on the magnetic dipole theory of magnetic-field distribution, the forces acting on ferromagnetic mineral particles (FMMPs) in the magnetic separation process were calculated in detail and a macro-scale dynamic model of magnetic agglomeration (MA) of particle swarms was established. A calculation method toward the dynamic model was proposed, and the two-dimensional dynamic process of the interaction between FMMPs was simulated. Furthermore, the energy conversion of single mineral particles to magnetic chains (MCs) was also analyzed. The results show that magnetic dipole–dipole attraction (MDDA) acting on FMMPs was the primary force in the magnetic separation process, and the dynamic process of MC formation from single mineral particles was closely related to time, distance between particles, and the external magnetic-field orientation. For FMMPs arranged in chain structures oriented along the external magnetic field, the time required for FMMPs to form MCs was less than 50 ms. In addition, the optimum time for MC destruction was in the initial stages (less than 5 ms) of the MC-formation process; either removal of the permanent magnet or discontinuation of the excitation current was the most direct and efficient way to fragment MCs once formed.

1. Introduction

Magnetic separation is a physical separation of discrete particles based on the three-way competition between magnetic force, gravity, frictional resistance, and magnetic dipole–dipole attraction (MDDA) (Oberteuffer, 1974). The principle of magnetic separation can be illustrated in Eq. (1).

$$F_{\mathrm{m}}^{\mathrm{mag}} > \sum F_{\mathrm{c}}^{\mathrm{mag}} \quad \text{and} \quad F_{\mathrm{m}}^{\text{non-mag}} < \sum F_{\mathrm{c}}^{\text{non-mag}} \tag{1}$$

where F_{c} is a competing force, F^{mag} and $F^{\text{non-mag}}$ are forces acting on magnetic and "non-magnetic" particles, respectively.

In general, in order to achieve high recovery of magnetic particles, the magnetic force must be greater than the sum of the other competing forces. Meanwhile, in order to achieve high grade of magnetic particles, magnetic force acting on "non-magnetic" particles must be less than the sum of the other competing forces. The selectivity of the process will be determined by the relative values of the magnetic and competing forces. Therefore, the analysis and fundamental understanding of forces acting on ferromagnetic mineral particles (FMMPs) are crucial for the application of magnetic separation. Among various forces acting on FMMPs during magnetic separation, the MDDA is the interacting force generated by magnetic induction between FMMPs and plays a dominating role in determining the structure of magnetic chains (MCs) created by MA (Ku, 2007). Yet, unfortunately, most people—including many professionals—intentionally or unintentionally ignore MDDA in calculation (Stradling, 1993; Svoboda and Fujitab, 2003) and analysis (Arol and Aydogan, 2004; Yavuz et al., 2009).

Study on the dynamic process of FMMPs in the slurry system will deepen the understanding of MA process, and help us to improve the recovery of magnetic separation by using MA or enhance the selectivity of magnetic separation by preventing MA. The MA behavior of FMMPs has been extensively studied. Adhesion forces including van der Waals, liquid bridge, and electrostatic forces between particles in high-gradient magnetic fields have been calculated (Senkawa et al., 2011). Different equations for calculating the magnetic force acting on a single magnetic particle in a non-uniform magnetic field have been derived by means of computer analysis (Bagster, 1987; Smolkin and Smolkin, 2006). A general formula for the calculation of magnetic force between magnetic mineral particles was previously derived using Coulomb's law (Chu and Jiang, 1990). The intensity of MCs formed by FMMPs was also calculated (Xie, 2000). A MA force formula applicable to the MA process of two ferromagnetic particles in (or out of) a magnetic field has been derived on the basis of the surface current of a magnetic material and electromagnetic theory (Lin et al., 2000). As previously stated, the interacting forces between magnetic mineral particles have been extensively studied. However, research on the dynamic process of FMMPs in

* Corresponding author. Tel.: +86 0591 22865210; fax: +86 0591 22865211.
E-mail addresses: kcc22@163.com.cn (J. Ku), 452894552@qq.com (H. Chen), 243280330@qq.com (K. He), 445884001@qq.com (L. Xu), 282455589@qq.com (Q. Yan).

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the slurry system is rarely reported due to the difficulty in calculating the accurate values of various forces.

In this study, the forces acting on FMMPs, such as frictional resistance and MDDA, were calculated and analyzed. On this basis, a dynamic model of FMMPs was established and simulated to illustrate the dynamic formation of MCs from the single-particle state. Energy conversion during MC formation was calculated in detail. The present study focuses on a discussion of the dynamic processes involved in MC formation from FMMPs in a magnetic field and the energy conversions taking place during MC formation.

2. Dynamic modeling

2.1. Force analysis of FMMPs in a magnetic separation process

FMMPs are not only subject to gravity (F_g), magnetic force (F_m), and frictional resistance (F_D) in the separating space of a magnetic separator, but also magnetic interactions and collisions (Tembely et al., 2012). The molecular thermal motion of mineral particles can be ignored in a magnetic field as the diameters of particles are from dozens of microns to millimeters in size (Li et al., 2010).

2.1.1. Gravity F_g

The force of gravity F_g acting on a magnetic particle in water includes the effect of gravity and buoyancy as expressed in Eq. (1):

$$F_g = \frac{\pi d^3}{6}(\rho_k - \rho)g \tag{1}$$

where d is the particle diameter, ρ_k and ρ are densities of the mineral particle and water, respectively, and g is the gravitational acceleration.

2.1.2. Magnetic force F_m

The magnetic force F_m acting on FMMPs is calculated by using Eq. (2):

$$F_m = \mu_0 \chi m H(\text{grad}H) \tag{2}$$

where μ_0 is the permeability of the medium, χ is the magnetic susceptibility of the particle, m is the mass of the particle, and H and grad$H$ correspond to the intensity of the magnetic field and the magnetic field gradient, respectively. The H value of a wet drum-type weak magnet separator (Φ 1050 × 3000) can be expressed using the distance from the particle position to the drum surface h:

$$H = 1.32 \times 10^5 e^{-17.312h}. \tag{3}$$

Substituting Eq. (3) into Eq. (2), the magnetic force F_m becomes:

$$F_m = \mu_0 \chi \frac{\pi d^3}{6} c H^2 \tag{4}$$

where c is the non-uniform distribution factor of the magnetic field ($c = 17.312$).

2.1.3. Frictional resistance F_D

The flow pattern of mineral particles in the separation space of the magnetic separator is under turbulence conditions, and the Reynolds number (Re) range is widely distributed. Thus, the frictional resistance F_D is calculated using Eq. (5) developed by Abraham (1970):

$$F_D = \psi_t \left(1 + \frac{2k}{\sqrt{R_e}}\right) \rho d^2 v^2 \tag{5}$$

where ψ_t and k are the resistance coefficients related to the Reynolds number, R_e is the Reynolds number, ρ is the density of the medium, d is the diameter of the mineral particle, and v is the velocity of the mineral particle relative to the medium. Some modifications to Eq. (5) have been made by Concha and Almendra (1979) combining boundary-layer theory and experimental data, where $\psi_t = 0.11$ and $k = 4.53$; Eq. (5) was developed in order to correlate the particle diameter at any value to Re.

2.1.4. MDDA F_{mm}

The distance between FMMPs under the initial slurry condition is relatively large. Therefore, the traditional magnetic-field distribution model of the magnetic dipole can be applied to calculate the interaction between magnetic particles (Jolly et al., 1996). The diagram of interactions between two magnetic dipole models is shown in Fig. 1.

The interaction energy of two magnetic dipoles U_{mm} is calculated using Eq. (6); here, m, μ_r, θ, and l are the magnetic dipole moment of the particle, differential permeability of the particle, angle between the magnetic field orientation and the direction of two particles, and distance between two FMMPs, respectively (Ku, 2007).

$$U_{mm} = \frac{|m|^2\left(1 - 3\cos^2\theta\right)}{4\pi\mu_0\mu_r l^3} \tag{6}$$

The MDDA F_{mm} is calculated using Eq. (7) (Tian et al., 2011):

$$F_{mm} = \frac{3|m|^2\left(1 - 2\cos^2\theta + 5\cos^4\theta\right)^{1/2}}{4\pi\mu_0\mu_r l^3}. \tag{7}$$

The magnitude of the magnetic moment m of FMMPs is affected by other FMMPs after being magnetized (Zhang et al., 2010). The actual magnitude of the magnetic moment of a particle in the magnetic field is achieved only when it is fully magnetized (Li et al., 2008), which can be calculated by the following equation:

$$m = 4\pi\mu_0\mu_r\beta r^3\left[1 + \frac{2\chi r^3}{(\chi+3)\left(r^2+l^2\right)^{3/2}}\right]H \tag{8}$$

where H is the intensity of the magnetic field.

2.2. Numerical comparison between MDDA and other forces

Permanent magnetic wet drum separators (Φ 1050 × 3000, produced by Sinosteel Maanshan Mining Research Institute Co., Ltd., Maanshan, China) and titanomagnetite ($\rho = 5.08$ g · cm^{-3}, magnetic susceptibility $\chi = 2.44$, obtained from Panzhihua Mine, China) are

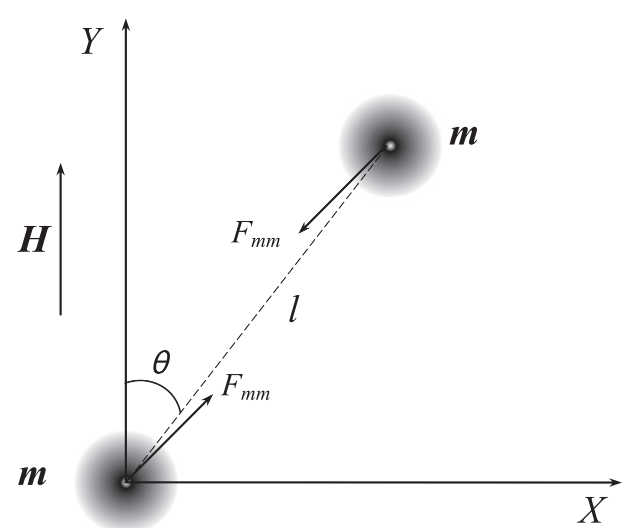

Fig. 1. Diagram of interaction between two magnetic dipole models.