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Study on capture radius and efficiency of fine weakly magnetic minerals in high gradient magnetic field

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ABSTRACT

The recovery of ultrafine weakly magnetic minerals using HGMS is proved a tough issue in industrial practice. Optimization of HGMS parameters determines the recovery result. The capture limits of weakly magnetic particles of diameter range 1–30 μm in high gradient magnetic field are studied using a numerical computation method. The matrix size and slurry velocity as well as the magnetic induction show great influence on the capture radius. The capture radius decreases rapidly with the decrease of particle size, the increase of matrices diameter and slurry velocity. For generalized condition, the capture radius is largely dependent on the ratio of slurry velocity V_0 to the so called magnetic velocity V_m. The capture efficiency decreases with the increase of the matrices arrangement value of d/a (the ratio of half the spacing between matrices to the matrix radius). The relationship between capture efficiency and V_0/V_m as well as d/a is obtained. This relationship can provide a guidance of choosing matrices of the perfect size and arrangements or configuring the HGMS system to work with high capture efficiency. It is also demonstrated how to regulate the HGMS system from a working point of low capture efficiency to a working point of high capture efficiency.

1. Introduction

Massive ultrafine weakly magnetic particles are produced during the processing of iron ore and these fine minerals generally cannot be recovered and are lost into the tailings because the magnetic force acting on minerals decreases sharply with the decrease of minerals size. As the accessible mineral resources become less and less, more and more attention is paid to the recovery of these fine magnetic minerals. High gradient magnetic separation (HGMS) is a promising method to deal with weakly magnetic minerals (Bochkarew et al., 2004; Chen, 2009). The HGMS system consists of an array of magnetic matrices and a uniform background magnetic field. The matrices are usually stainless steel rods (Zeng and Xiong, 2003), steel mesh (Baik et al., 2012) or steel wools (Wang et al., 2011) of high magnetic susceptibility. The matrices dehomogenize the magnetic field, producing large magnetic field gradient. The paramagnetic particles can be attracted to the matrices' surface and then are trapped there. Besides mineral processing, HGMS has been applied to many industrial and scientific fields such as Environmental Engineering (Miura et al., 2014; Ceff et al., 2012), Bioengineering (Inglis et al., 2006; Inglis, 2004; Jung and Han, 2008) and Pharmaceutical Engineering (Ueda et al., 2014).

For the recovery of the fine weakly magnetic minerals, the characteristics of the matrices such as the cross-section radius a, the magnetization saturation M_s, the arrangement as well as the operating factors such as the magnetic field H_0 and the slurry velocity V_0 have significant influence on the recovery efficiency. Previously, matrices of different size or shapes, different arrangements were manufactured to do experiments to optimize the HGMS system (Too et al., 1986; Badescu et al., 1996; Ebner et al., 2007; Kim et al., 2013; Padmanabhan and Sreenivas, 2011; Chen et al., 2014). However, as there are so many factors influencing the recovery efficiency, the quantitative analyses of these factors were not done systematically. Besides, for the fine weakly magnetic particles of 1–30 μm, there is little literature reporting the capture limit when using matrices of certain size. So up to now, there is no theoretical guidance for us to configure the HGMS for a given fine weakly magnetic mineral, i.e., no theoretical basis can be a guidance to choose the perfect matrices and regulate the operating factors. The objective of this article is to study the magnetic particle capture of the existing matrices in mineral processing and quantify the capture radius and capture efficiency under different combinations of particle size, matrix size and other operating factors.

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Capture radius is a limit where the particle just can be captured by the matrix. Watson calculated capture radius of the magnetic particles in a magnetic filtration for sewage treatment by solving the trajectory equations and put forward a method for the calculation of capture radius (Watson, 1973, 1975). In this paper, we use the model to calculate the capture radius under a number of combinations of the influencing factors and then extend to generalized situation.

2. Force analyses

For fine particles in a fluid in an applied magnetic field, there are several kinds of competitive forces: inertial force, gravitational force, fluid drag force and diffusion force (Lim et al., 2014). As the decrease of the particle size, some forces can be neglected as they are too small compared with other dominant forces (Moeser et al., 2004; Yavuz et al., 2006). For particles in a size range of 1–30 μm, the inertial and diffusion forces can be neglected so the main competitive forces are the gravitational force and drag force. The magnetic force F_m on a paramagnetic particle of radius R (Diameter $D = 2R$) in an applied magnetic field is given by Eq. (1) (Bleaney and Bleaney, 1985).

$$F_m = 4\pi R^3 \mu_0 \kappa H \nabla H / 3 \tag{1}$$

where H and ∇H are the magnetic field strength and gradient of the particle location, μ_0 is the permeability of vacuum, κ is the magnetic susceptibility of the particle. The drag force and gravitational force are given by Eqs. (2) and (3).

$$F_d = 6\pi\eta R v \tag{2}$$

$$F_g = 4\pi R^3 (\rho_p - \rho_l) g / 3 \tag{3}$$

where η is the viscosity of the fluid, v is the relative velocity of the particle and the fluid, ρ_p and ρ_l are the density of the particle and the fluid, g is the gravitational acceleration. Fig. 1 shows the relation of the gravitational force and drag force versus diameter of hematite particle. It can be seen that within the size range of 1–30 μm, the drag force is about 10^4–10^5 times larger than the gravitational force. So for the issue concerned here, the gravitational force can also be neglected and the dominant forces are the magnetic force and the drag force.

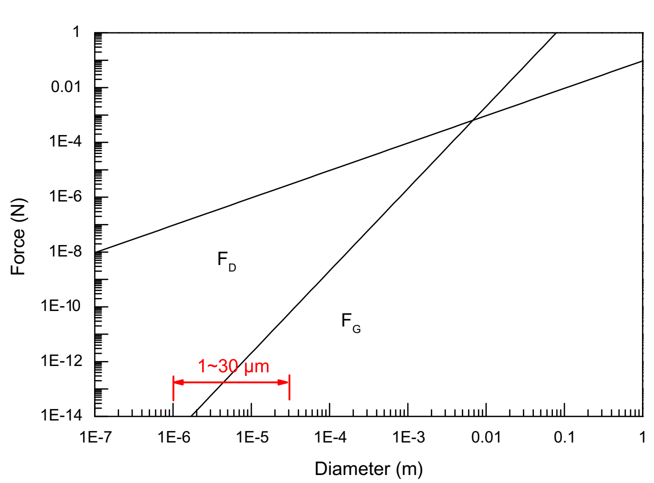

Fig. 1. Relation of gravitational force and drag force vs. diameter of hematite particle. The drag force is calculated with a particle and fluid relative velocity of 0.01 m/s.

3. Capture radius and moving trajectories of magnetic particles

There are three possible configurations in the HGMS: transverse, longitudinal and axial. For the transverse configuration, the magnetic field, the matrices' axis and the direction of the flow are mutually perpendicular; For the longitudinal configuration, the magnetic field is parallel to the direction of flow and both are perpendicular to the matrices' axis; For the axial configuration, the flow direction is parallel to the matrices' axis and both are perpendicular to the magnetic field. As reported (Chen, 2011), the longitudinal configuration has a smaller magnetic leakage factor and has no direct impingement of feed flow on the magnetic deposits, so this configuration presents better performance and is adopted in the study. As shown in Fig. 2, a ferromagnetic matrix of cross section radius a and magnetization saturation Ms is placed in a uniform magnetic field H_0, which is large enough to saturate the matrix, a slurry containing paramagnetic particles passes by with initial velocity V_0. The distance between the particle and the matrix axis is r. The magnetic field distribution around the matrices is shown in Fig. 3. The magnetic field strength is large near the right and left sides of the matrices and high magnetic gradient is induced. What we concern is whether the particle with initial position of y_0 to the x axis and a relatively large value of $-x/a$ will be captured. If particles with initial distance of y_c to the x axis just can be captured and all the particles with initial position of $y_0 > y_c$ cannot be captured, then the value $|y_c/a|$ is defined as the capture radius R_c.

The capture radius can be calculated with a numerical computation method. The motion of particles is determined by Eqs. (4) and (5) (Watson, 1973).

$$\frac{dr_a}{dt} = \left(\frac{V_0}{V_m}\right)\left(1 - \frac{1}{r_a^2}\right)\cos\theta - \left(\frac{V_m}{a}\right)\left(\frac{M_s}{2\mu_0 H_0}\right)\frac{1}{r_a^5} - \left(\frac{V_m}{a}\right)\frac{\cos 2\theta}{r_a^3} \tag{4}$$

$$r_a\frac{d\theta}{dt} = -\left(\frac{V_0}{a}\right)\left(1 + \frac{1}{r_a^2}\right)\sin\theta - \left(\frac{V_m}{a}\right)\frac{\sin 2\theta}{r_a^3} \tag{5}$$

where $r_a = r/a$, μ_0 is the permeability of vacuum, $V_m = \frac{2\kappa M_s H_0 R^2}{9\eta a}$, κ is the magnetic susceptibility of the particle, η is the viscosity of the fluid, V_m is referred to as the magnetic velocity.

In this study, a set of fluid flow V_0 of 0.20 m/s, 0.10 m/s, 0.05 m/s, 0.01 m/s and a set of matrix radius a of 1.0 mm, 0.5 mm, and 0.1 mm were mainly considered. Hematite is chosen as the weakly magnetic mineral, with a density of 5000 Kg/m^3 and magnetic susceptibility of 0.025. The magnetization saturation of the matrix is 2 T, which is close to the saturation of pure iron. Magnetic capture radius can be calculated with Eqs. (4) and (5), the results are shown in Tables 1 and 2.

Results in Tables 1 and 2 show that the magnetic capture radius R_c decreases rapidly with the decrease of the particle size D while increases with the decrease of the matrix radius a and the fluid flow velocity V_0. When the magnetic induction is 1 T and the slurry velocity is 0.1 m/s, for the matrix of radius 1 mm, the capture radiuses of particles of diameter 20 μm, 10 μm, 5 μm and 2 μm

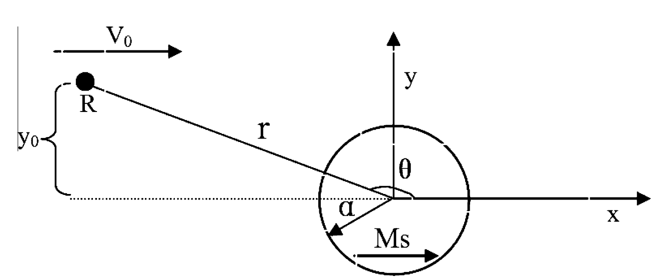

Fig. 2. Schematic diagram of position relationship.