Physicochem. Probl. Miner. Process. 53(1), 2017, 94−109

www.minproc.pwr.wroc.pl/journal/

Physicochemical Problems of Mineral Processing

ISSN 1643-1049 (print)
ISSN 2084-4735 (online)

Received February 29, 2016; reviewed; accepted April 22, 2016

STUDY ON BUILDUP OF FINE WEAKLY MAGNETIC MINERALS ON MATRICES IN HIGH GRADIENT MAGNETIC SEPARATION

Xiayu ZHENG, Yuhua WANG, Dongfang LU

School of Minerals Processing & Bioengineering, Central South University, Changsha 410083,China,
19601229xiayu@163.com (X. Zheng), wangyh@csu.edu.cn (Y. Wang)

Abstract: Buildup of magnetic mineral particles on matrices determines the saturated deposit volume of minerals, which is of great importance in the high gradient magnetic separation (HGMS) systems. In this paper buildup of fine weakly magnetic minerals on the matrix is studied with a force equilibrium model. Elaborate rules of particle buildup on the matrix are presented. An imaginary sector ring is used to approximately quantify the volume of saturated particle buildup. The influence of the particle size, magnetic induction, fluid viscosity and velocity as well as matrix size on saturated particle buildup is investigated and discussed. With the same matrix size, the saturated buildup volume decreases with the decrease of the particle size, applied magnetic induction and increase of the fluid viscosity and velocity. The saturated buildup volume normalized by the matrix volume, and the ratio of particle deposit volume to the matrix volume (V_d/V_m) decreases with the increase of the matrix size. Under the same matrices packing fraction, the total mineral deposit volume, when adopting small size matrices, is larger than that when adopting large size matrices. Only small size matrices can be used for recovery of minerals in size of several micrometers. Based on performed analyses, the ore feeding time in a cycle for a cyclic HGMS system and the rotation speed of the swivel for a continuous HGMS system under different circumstances are also discussed.

***Keywords**: particle buildup, force equilibrium, magnetic matrices, magnetic separation*

Introduction

High gradient magnetic separation (HGMS) is an effective method to recover fine weakly magnetic particles from a slurry. Due to its high efficiency and eco-friendly characteristic, HGMS has been widely used in many industrial and scientific fields such as mineral processing (Zeng and Xiong, 2003; Gao and Chen, 2010; Li et al., 2011), environmental engineering (Wu et al., 2011; Merino-Martos, 2011; Nomura et al., 2012), medical engineering (Chimma et al., 2010; Ueda et al., 2014) and bioengineering (Inglis et al., 2004). The most significant and successful application of

http://dx.doi.org/10.5277/ppmp170108

HGMS is the recovery of fine weakly magnetic minerals. A series of high gradient magnetic separators have been developed (Jones, 1960; Iannicelli et al., 1969; Marston and Nolan, 1975; Cibulka et al., 1985; Xiong, 1997; Ning et al., 2012; Chen et al., 2015; Zeng et al., 2015).

In high gradient magnetic separation, high susceptibility magnetic matrices dehomogenize the uniform magnetic field, inducing high magnetic field gradient. The magnetic particles are captured onto the matrices surface due to large magnetic force, and then they are trapped there. The capture of magnetic particles by the matrices and their buildup on the matrices are the main theoretical mechanisms in high gradient magnetic separation and have been extensively investigated by many researchers (Watson, 1973; Luborsky and Drummond, 1976; Briss et al., 1980; Ciesla, 1996; 2004; 2006; 2007; Badescu et al., 1996; Natenapit and Sanflek, 1999; Chen et al., 2012).

For the fine weakly magnetic minerals, their capture efficiency determines the recovery rate. The capture efficiency of a specific magnetic particle is calculated from the so-called capture radius (Watson, 1973). The capture radius of magnetic particle is influenced by many configuration and operation parameters and it was systematically investigated in our previous study (Zheng et al., 2015). Besides the capture of magnetic particles by the matrix, accumulation of magnetic particles on the matrix is also very important. The particle capture efficiency provides prediction of the recovery rate, but it is based on the assumption that all captured particles can be recovered. However, high gradient magnetic separation is a time-dependent process. When buildup of the particles on the matrix reaches saturation, no particle can be accumulated on the matrix. Under this circumstance, the magnetic particles will not be further recovered if there isn't any operation performed. Therefore, the investigation of saturated buildup of the magnetic particles on the matrix is also important.

There are many configuration and operation parameters which influence the capture efficiency of magnetic particles in HGMS. These factors include the particle radius b and density ρ, applied magnetic field strength H_0, magnetic field gradient $gradH$, velocity of the slurry V_0, dynamic viscosity of the fluid η and size of the magnetic matrix (Zheng et al., 2015). These factors also have significant influence on buildup of the magnetic particles on the matrix. Generally, the high gradient magnetic separators can be categorized into two types: cyclic and continuous types (Svoboda and Fujita, 2003). A continuous HGMS system usually includes a swivel on which the matrices are installed. For the cyclic type, saturated particle buildup determines the ore feeding time in a cycle. For the continuous type, saturated particle buildup determines the rotation speed of swivel. Therefore, it is of great significance to clarify the influence of those factors on saturated particle buildup on the matrix. Moreover, the elaborate rules of particle buildup on the matrix can provide us a better understanding of the basic principles of HGMS, which can be of great importance for either optimization of the HGMS system or development of a novel high gradient magnetic separator. In this paper, buildup of the field-dependent susceptibility magnetic minerals on the matrix is investigated with a force equilibrium model. Saturated buildup of the magnetic particles under different circumstances are depicted and compared quantitatively. The influence of particle size, applied magnetic field strength, viscosity of the fluid and matrix size on particle buildup is investigated, and the effects on the performance of HGMS are discussed.

The force equilibrium model

In high gradient magnetic separation (HGMS), there are three configurations, that is longitudinal, transversal and axial. In the longitudinal configuration, the magnetic field is parallel to the direction of the flow and both are perpendicular to the matrix axis. In the transversal configuration, the magnetic field, direction of the flow and matrix axis are mutually perpendicular. In the axial configuration, the matrix axis is parallel to the direction of the flow and both are perpendicular to the magnetic field. Buildup of magnetic particles on the matrix in the longitudinal (Nesset and Finch, 1981) and axial (Badescu et al., 1996) configurations were analytically derived with a force equilibrium model. For the transversal configuration, a static friction model was also developed to describe particle buildup (Maass et al., 1983). However, a saturated particle buildup curve in the transversal configuration is quite random and non-reproductive, therefore additional studies and modifications are needed to describe particle buildup for this configuration. The longitudinal configuration is the most commonly used in mineral processing, and the axial configuration only shows advantages in separation of special substances such as blood cells (Inglis, 2006). Therefore, in this article the longitudinal configuration is adopted to investigate the influence of different configuration and operation factors on saturated buildup of particles.

The susceptibility of many magnetic minerals is not constant but depends on the applied magnetic field (Svoboda, 1994). The relationship between the magnetic susceptibility κ and applied magnetic field strength can be given by:

$$\kappa = \kappa_\infty + \frac{M_0}{H_0} \tag{1}$$

where κ_∞ is the magnetic susceptibility in infinite magnetic field, M_0 is spontaneous magnetization and H_0 is the applied magnetic field.

In the force equilibrium model (Nesset and Finch, 1984; Zheng et al., 2015) the magnetic, gravity and fluid drag are the main considered forces. Figure 1 shows the components of the forces acting on particles in the longitudinal configuration. The gravity force and magnetic forces (Watson, 1973; Luborsky and Drummond, 1975) act in both radial and tangential directions, while the fluid drag force acts only in the tangential direction. The components of magnetic force acting on a field-dependent susceptibility mineral particle of radius b can be given by equations:

$$F_{mr} = -\frac{8}{3}\pi b^3(\kappa_\infty H_0 + fM_0)H_0\frac{Aa^2}{r^3}\left(\cos 2\theta + \frac{Aa^2}{r^2}\right) \quad (2)$$

$$F_{m\theta} = -\frac{8}{3}b^3(\kappa_\infty H_0 + fM_0)H_0\frac{Aa^2}{r^3}\sin 2\theta \quad (3)$$

where r is the distance between the particle and matrix axes , a is the radius of matrix cross section, θ is the angle from the front stagnant point, and the field factor f is given by equation:

$$f = \frac{1}{2\left(1 + \frac{2Aa^2}{r^2}\cos 2\theta + \frac{A^2a^4}{r^4}\right)^{1/2}} \quad (4)$$

where A is the perturbation term for the cylinder matrix and can be given by equation:

$$A = \frac{2\pi M_w}{H_0} \quad (5)$$

where M_w is the matrix magnetization.

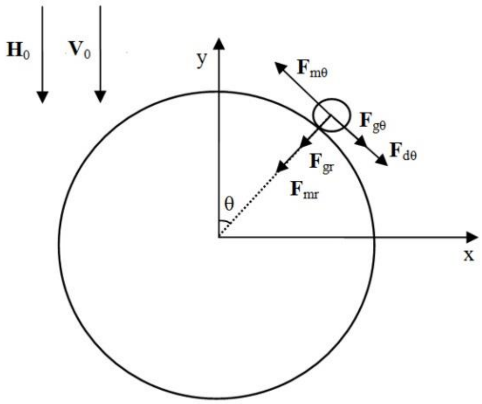

Fig. 1. Components of forces acting on spherical particle

The fluid drag force can be calculated using the shear stress derived from the Blasius solutions to the boundary layer equations and can be given by equation considering the expansion to θ^{11} (Schlichting, 1968):

$$F_{d\theta} = \frac{\pi^2 b^2}{4}\rho_f V_0^{3/2}\left(\frac{v}{r}\right)^{1/2}(6.973\theta - 2.732\theta^3 + 0.292\theta^5 - 0.0183\theta^7 + 0.000043\theta^9 - 0.000115\theta^{11}) \quad (6)$$

where ρ_f, V_0, v are the fluid density, initial velocity and kinematic viscosity ($v = \eta/\rho_f$), respectively.

The radial and tangential components of the gravity force are given by equations:

$$F_{gr} = -\frac{4}{3}\pi b^3(\rho_p - \rho_f)g\cos\theta \quad (7)$$

$$F_{g\theta} = \frac{4}{3}\pi b^3(\rho_p - \rho_f)g\sin\theta \quad (8)$$

where ρ_p and ρ_f are densities of particle and fluid, respectively, g is the gravitational acceleration.

The net forces are the sum of the radial and tangential components of each force:

$$F_{\text{net}r} = F_{mr} + F_{gr} \quad (9)$$

$$F_{\text{net}\theta} = F_{m\theta} + F_{d\theta} + F_{g\theta}\,. \quad (10)$$

The net forces can be calculated layer by layer: 1st layer: $r = a+b$, 2nd layer, $r = a + b + \sqrt{3}b$, 3rd layer, $r = a + b + 2\sqrt{3}b$ and so one. The θ satisfying $F_{\text{net}r} = 0$ and $F_{\text{net}\theta} = 0$ is calculated for each layer and the smaller value of the two angles θ_c is selected. The calculation continues till θ_c <10°,which defines the final layer. Choosing the θ_c <10° can avoid the singularity at the front stagnant point. The plot of θ_c as a function of r is the saturated buildup profile.

Calculations

Since in mineral processing the applied magnetic field in high gradient magnetic separation is seldom above 2.5 T, the magnetic induction range of 0.5~2.5 T will be considered in this work. The matrix is a nickel cylinder with saturation magnetization M_s = 0.6082 T. The matrix perturbation term A, when magnetic induction is 0.5, 1.0, 1.5, 2.0 and 2.5 T, are about 0.98, 0.77, 0.57, 0.44 and 0.35, respectively. The susceptibility of most magnetic minerals in the nature varies with the applied magnetic field. A hematite measured is chosen as the representative field-dependent susceptibility mineral with k_∞ = 0.001433, M_0 = 0.002036T and density ρ_h = 5260 kg/m^3 (Nesset and Finch, 1980). The fluid density and viscosity are similar to pure water: ρ_f = 1000 kg/m^3, η = 1 mPa·s. To investigate the influence of the fluid viscosity on buildup of the magnetic particles, the fluid viscosity η of 0.1, 1.0 and 10 are considered and the density is assumed constant. All the particles are considered to be spherical.

The matrix size is a very important parameter influencing the saturated buildup volume of particles. The ratio of particle deposit volume V_d to the matrix volume V_m can be used to study the effect of the matrix size on particle buildup. For HGMS with the same matrices packing fraction, the total volume of the deposit is only dependent on the value of V_d/V_m as the total volume of the matrices are the same. Therefore, the value V_d/V_m can be used to study the effect of the matrix size on particle buildup and to evaluate the performance of the HGMS system. The particle deposit volume is the product of the cross-sectional area of particle deposit and the matrix length. Assuming that particle buildup occurs throughout the axial direction of the matrix, the V_d/V_m can be calculated by the ratio of the deposit cross-sectional area to the matrix cross-sectional area. The deposit contour is approximately a sector ring as shown of Fig. 2. The normalized deposit value V_d/V_m can be approximately calculated by using equation:

$$\frac{V_d}{V_m}=\frac{\pi(R^2-a^2)\left(\frac{\varphi}{2\pi}\right)}{\pi a^2}=\frac{(R^2-a^2)\varphi}{2\pi a^2} \tag{11}$$

where R is radius of the imaginary sector, φ is the central angle of the sector. The matrices of radii 0.1 mm, 0.2, 0.5 and 1.0 mm are concerned.

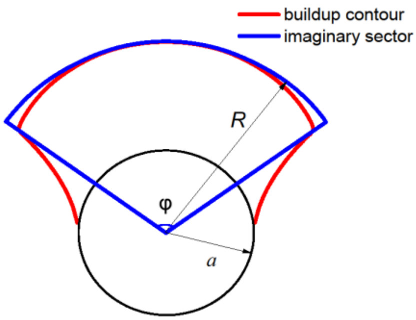

Fig. 2. Schematic diagram of imaginary sector of buildup contour

Results and discussion

Buildup of magnetic particles of different radii

Saturated buildup of the hematite particles of radii from 1 to 50 µm, when the magnetic induction is 0.5 T and fluid velocity is 0.1 m/s, are shown in Fig. 3. Figures 3(a) and (b) show the deposit contour and normalized deposit volume V_d/V_m, respectively. It can be seen that saturated particle buildup decreases significantly with the decrease of the particle size, especially in the size range of 1~20 μm. It is due to the sharp decrease of the magnetic force with the decrease of the particle size as the magnetic force is proportional to the third power of the particle radius. Only one layer of particles radius 1 μm can accumulate on the matrix. The matrix surface area covered with particles is almost the same for all considered particles. The fine particles have very small saturated buildup volume and are difficult to be recovered.

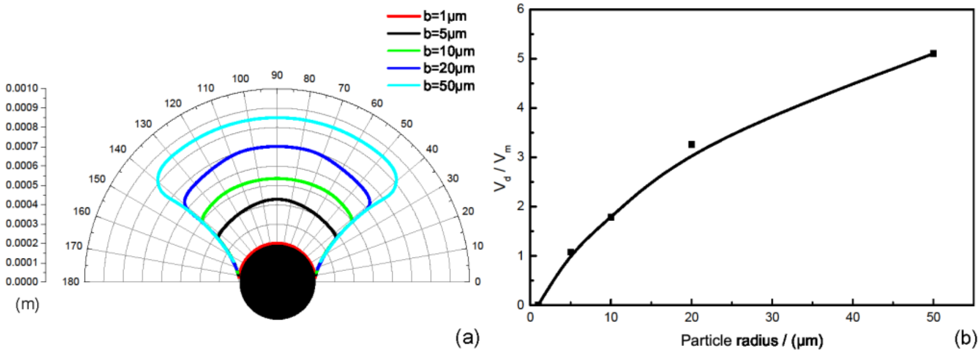

Fig. 3. Saturated buildup of particles of different sizes: magnetic induction $B_0 = 0.5$ T, matrix radius $a = 0.2$ mm, fluid velocity $V_0 = 0.1$ m/s

Effect of magnetic field strength

The magnetic field is an important operation parameter in high gradient magnetic separation. The magnetic field affects both the matrix magnetization state and particle susceptibility, and consequently affects particle buildup. The effect of the magnetic induction on saturated buildup of particles is shown in Fig. 4. Equation (1) shows that the minerals susceptibility decreases with the increase of the magnetic induction. Figure 4(a) shows that the matrix surface area covered with particles in the low magnetic induction is larger than that in the high magnetic induction. However, saturated buildup increases with the increase of the magnetic field within the whole range of 0.5~2.5 T. Figure 4(b) shows that the normalized particle deposit volume V_d /V_m almost linearly increases with the increase of the magnetic field. It can be concluded that, although the minerals susceptibility and the matrix surface area available for the particle buildup decrease with the increase of the magnetic field, saturated particle buildup still increases with the increase of the magnetic field. Therefore, the high magnetic field is conducive for particle buildup on the matrix. However, it doesn't indicate that higher magnetic field is better. Not only high recovery but also concentrate grade should be considered to evaluate the process. As the mineral intergrowths unavoidably exist in the grinding products, the massive low grade intergrowths will accumulate on the matrices in the high magnetic field and subsequently go to the concentrate. It will result in the rapid decrease of the concentrate grade. The influence of the magnetic field on HGMS was discussed in details in our previous paper (Zheng et al., 2015).

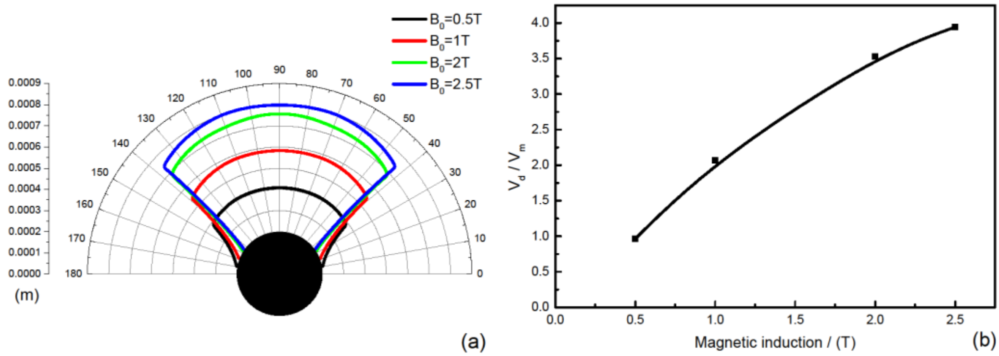

Fig. 4. Influence of the applied magnetic field strength on saturated buildup of particles: particle radius b = 5 μm, matrix radius a = 0.2 mm, fluid velocity V_0 = 0.1 m/s.

Effect of fluid viscosity

High gradient magnetic separation has been widely used in many industrial fields. Under some circumstances, the slurry to be disposed is highly viscous (Katharina et al., 2012; Mishima et al., 2012). The fluid viscosity is also a parameter which influences particle buildup, and consequently the performance of HGMS. Figure 5 shows saturated particle buildup in the fluid of viscosity 0.1, 1.0 and 10 mPa·s. It can be seen that the particle deposit increases with the decrease of the fluid viscosity. As shown in Eq. (6), the fluid drag force is proportional to the fluid viscosity. As the drag force is only in the tangential direction, for the fluid with different viscosity, the matrix surface area covered with particles is the same, as shown in Fig. 5(a). Figure 5(b) shows that the normalized deposit volume decreases nearly by half when the fluid viscosity increases ten-fold. A low fluid viscosity is conducive for buildup of magnetic particles. For a highly viscous fluid, the saturated volume of particle buildup is very small and the matrix is easy to be saturated with particles. Thus, for a cyclic HGMS system, if the slurry to be disposed is highly viscous, the feeding time in a cycle should be limited. For a continuous HGMS system, the rotation speed of the swivel should be increased so that particle-free matrices can be transported to the ore feeding area in time to substitute the proceeding matrices saturated with magnetic particles. When the slurry has low viscosity the ore feeding time in a cycle can be increased for a cyclic HGMS system, and the rotation speed of the swivel can be decreased for a continuous one.

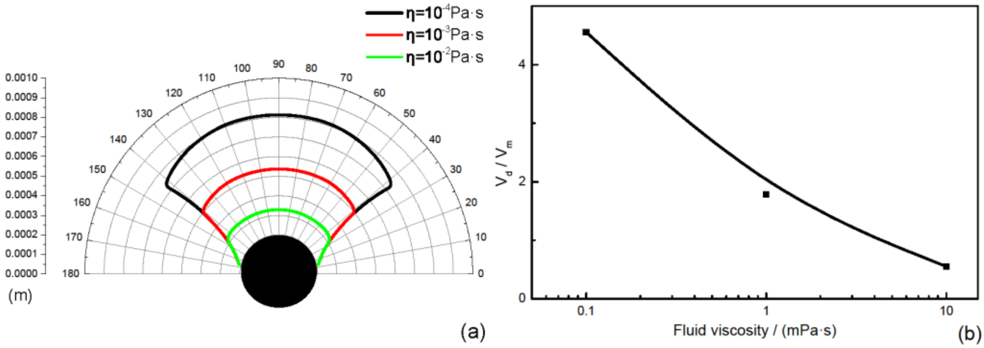

Fig. 5. Effect of the fluid viscosity on the saturated particle buildup: magnetic induction B_0 = 0.5 T, matrix radius a = 0.2 mm, particle radius b = 10 μm

Effect of fluid velocity

Saturated particle buildup for the fluid velocity V_0 equal to 0.05, 0.1, 0.2 and 0.4 m/s is shown in Fig. 6. It can be seen that the fluid velocity significantly affects the process of particle buildup. As the drag force is proportional to the fluid velocity and it only acts in the tangential direction, the fluid velocity affects particle buildup in a way similar to the fluid viscosity, the matrix surface area covered with particles is the same for all considered fluid velocities. Saturated particle buildup decreases sharply with the increase of the fluid velocity. The normalized deposit volumes V_d /V_m, when the fluid velocity is 0.05, 0.1, 0.2 and 0.4m/s, are 4.15, 1.78, 0.63 and 0.04, respectively. Only one layer of particles can accumulate on the matrix when fluid velocity is 0.4 m/s.

With the increase of the fluid velocity, saturated particle buildup decreases. It can be inferred that, for a certain particle size, there is a critical V_0 above which no particles can accumulate on the matrix. The critical values of V_0 as a function of particle size for the magnetic induction of 0.5, 1.0 and 2T are shown in Fig. 7. The critical values V_0 increase with the increase of particle size and the applied magnetic induction. For particles with radius of 10 μm, the critical V_0 for magnetic induction of 0.5, 1.0 and 2 T are 0.44, 0.83 and 1.32, respectively. For particles with radius of 5 μm, the critical values of V_0 are about 0.29, 0.54 and 0.86 m/s, respectively. The mineral particles can hardly accumulate on the matrix for a high fluid velocity, especially for the fine particles, even under the high magnetic induction. When the fluid velocity is low, large saturated particle buildup allows for a long ore feeding time in a cycle for the cyclic HGMS system. If HGMS is operated with the high fluid velocity, the ore feeding time should be limited as particle buildup reaches saturation in a short time. For the continuous HGMS system, the rotation speed of the swivel should increase for the high fluid velocity and can decrease for the low fluid velocity. Although a very low fluid velocity is conducive for particle buildup, the handing capacity of the HGMS system decrease dramatically. Therefore, a moderate fluid velocity, which ensures large particle deposit volume and at the same time appropriate handing capacity, is required for a good performance of the HGMS system.

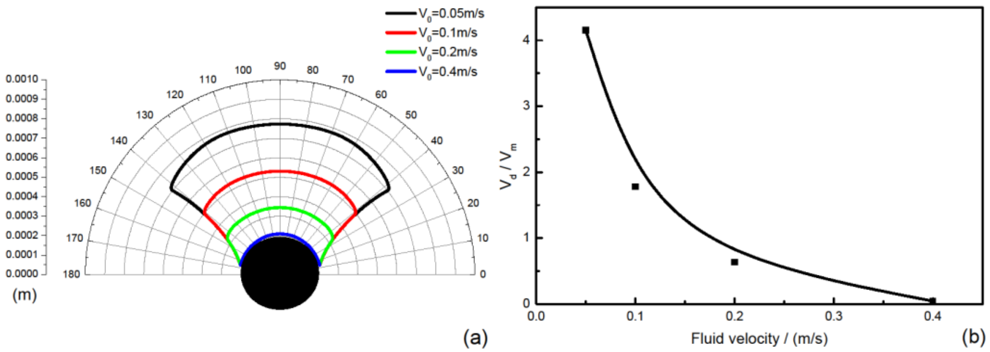

Fig. 6. Effect of fluid velocity on saturated buildup of particles:
magnetic induction B_0 = 0.5 T, matrix radius a = 0.2 mm, particle radius b = 10 μm

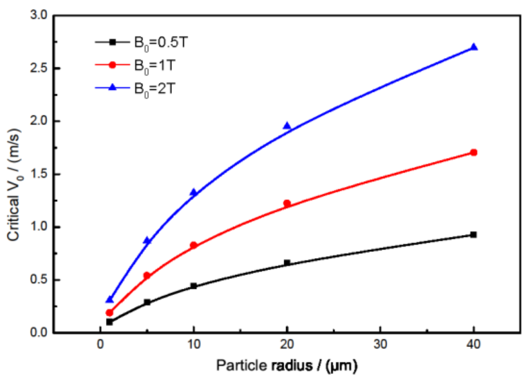

Fig. 7. Critical V_0 as a function of particle radius

Effect of matrix size

The magnetic matrices are the crucial component of the HGMS system. The matrix size has a great influence on the performance of HGMS. The matrix with smaller size can induce larger magnetic field gradient and consequently larger magnetic force acting on the magnetic particles, which is conducive for particle buildup on the matrix. Saturated buildup of mineral particles of radius 15 μm on the matrix of radii 0.1, 0.2, 0.5 and 1.0 mm are shown in Fig. 8. It can be seen that particle buildup increases with the increase of the matrix size, despite that the magnetic gradient induced by the matrix decreases. It is so because, although the small size matrix can induce larger magnetic force, the large magnetic force scope is limited.

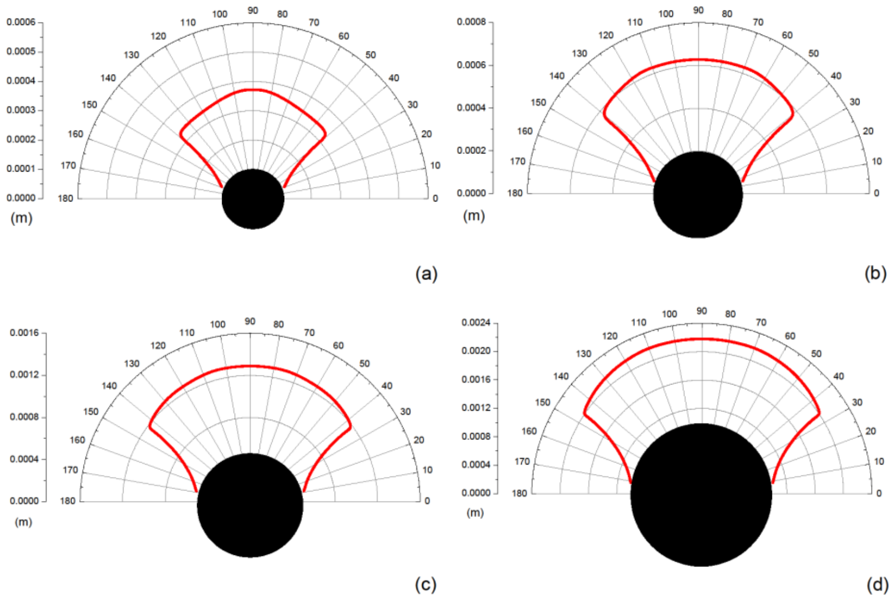

Fig. 8. Saturated buildup of particles of radius 15 μm on the matrices with radii of (a) 0.1 mm, (b) 0.2 mm; (c) 0.5 mm and (d) 1.0 mm

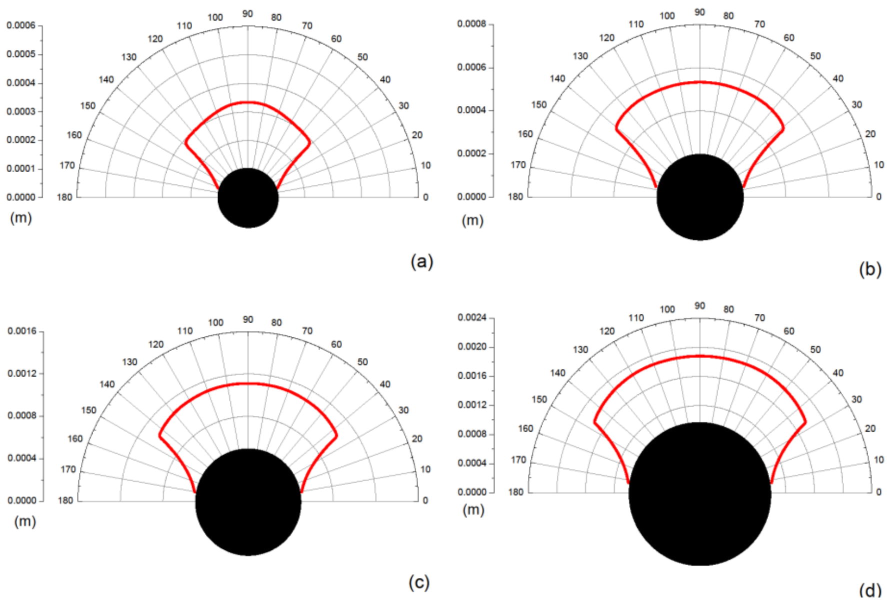

Fig. 9. Saturated buildup of particles of radius 10 μm on the matrices with radii of (a) 0.1 mm, (b) 0.2 mm; (c) 0.5 mm and (d) 1.0 mm

Figures 9 and 10 show saturated buildup of the mineral particles of radii 10 and 5μm, respectively. Saturated particle buildup in Figs. 9 and 10 increases with the increase of the matrix size. It is similar to Fig. 8. Comparing particle buildup in Figs. 8, 9 and 10, for the matrices of the same sizes, it can be said that saturated particle buildup decreases successively. It is due to the magnetic force which decreases with the decrease of the particle size. It can also be seen that saturated particle buildup in Fig. 8(a) is about half of that in Fig. 10(a), while the particle buildup in Fig. 8(d) is about one third of that in Fig. 10(d). It indicates that saturated particle buildup on the large size matrix decreases more significantly than that on the small size matrix with the decrease of the particle size.

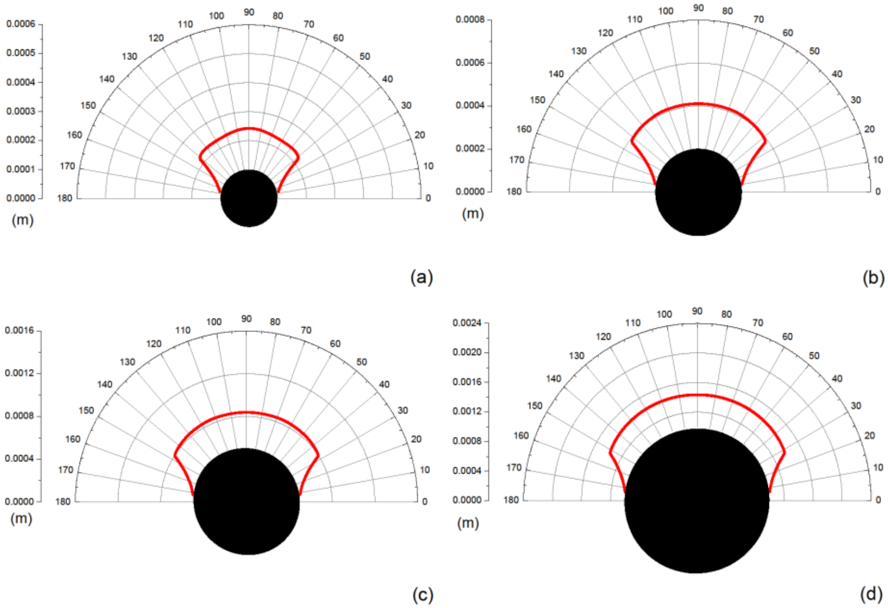

Fig. 10 Saturated buildup of particles of radius 5 μm on the matrices with radii of (a) 0.1 mm, (b) 0.2 mm; (c) 0.5 mm and (d) 1.0 mm

The separation space of the HGMS system is packed with the numbers of matrices. For the mineral particles of radii 5, 10 and 15 μm, although the saturated particle buildup on one matrix increases with the increase of the matrix size, there is not an increase in the total particle buildup on all the matrices packed in the separation space. For the same separation space, more small size matrices can be packed. Figure 11 shows an arrangement of the matrices. Both the longitudinal and transversal spacing between the matrices are $2d$. The ratio of d to a is referred to λ, namely $\lambda = d/a$. The matrices packing fraction is the ratio of the total matrices volume to the volume of the separation space. The red dotted square in Fig. 11 is a representative element of the cross section of the separation space. The matrices packing fraction φ can be calculated by using formula:

$$\varphi=\frac{\pi a^2}{(2a+2d)^2}=\frac{\pi}{4(1+d/a)^2}=\frac{\pi}{4(1+\lambda)^2} \tag{12}$$

Equation (12) shows that the packing fraction is only a function of λ. For matrices of variable radii, the packing fraction is equal to the same λ value.

For the same packing fraction and matrices of variable radii, the total saturated particle buildup has only relationship with the normalized deposit volume V_d/V_m as the total volume of the matrices is the same. The normalized deposit volume of particles of radii 2, 5, 10 and 15 μm as a function of matrix size is shown in Fig. 12. It shows that, although particle buildup on one matrix increases with the increase of the matrix size, the normalized deposit volume V_d/V_m decreases with the increase of the matrix radius for all the particles concerned. Additionally, for the particles of radius 2 μm, no particles can accumulate on the matrix of radius 1 mm. This is different from the particles of radius 5, 10 and 15μm, where saturated particle buildup increases with the increase of the matrix radius. It is because, for very fine mineral particles, there is more significant decrease in the saturated particle buildup on the large size matrix than on the small size matrix, as it was mentioned above.

The obtained results indicate that the small size matrix is conducive for particle buildup, especially for the very fine mineral particles. For the very fine mineral particles no particle buildup occurs on the large size matrix. Under the same matrices packing fraction, the total deposit volume of fine weakly magnetic minerals increases with the decrease of the matrix radius. Thus, for a cyclic HGMS system, the ore feeding time in the cycle should be limited when adopting large size matrices. For a continuous HGMS system configured with the large size matrices, the rotation speed of the swivel should also be increased. For the recovery of very fine magnetic particles, only the small size matrices can be used in HGMS.

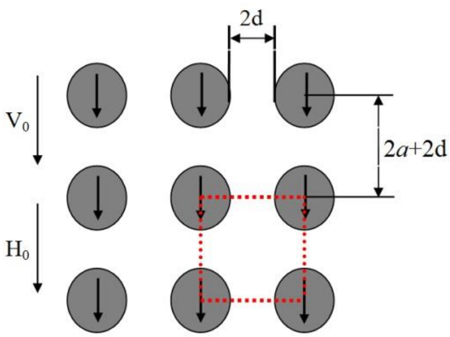

Fig. 11. Arrangement of matrices

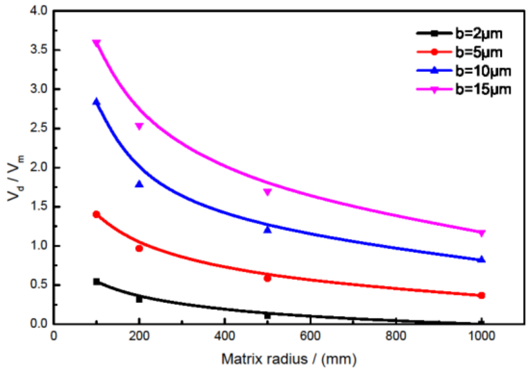

Fig. 12. Normalized deposit volume as a function of matrix radius

Conclusions

Particle buildup of field-dependent susceptibility minerals on the magnetic matrix was investigated. The elaborate particle buildup on matrix under different circumstances was presented. With the same matrix size, saturated particle buildup decreased with the decrease of the particle size, applied magnetic induction and increase of the fluid viscosity and velocity. The saturated buildup volume of particles above 10 μm on a matrix increased with the increase of the matrix radius, but the buildup volume normalized by the matrix volume V_d/V_m decreased with the increase of the matrix radius. Under the condition of the same matrices packing fraction, the total particle buildup volume, when adopting the small size matrices, was much larger than that when adopting the large size matrices. For the very fine particles with size of several micrometers, no buildup occurred on matrices with size of 1 mm and only small size matrices can be used for recovery. Under the condition of low magnetic induction, high fluid viscosity, high fluid velocity, or adopting large size matrices, the matrices were easy to be saturated with magnetic particles. The ore feeding time in a cycle should be limited for a cyclic HGMS system and the rotation speed of the swivel should be increased for a continuous HGMS system and vice versa.

Acknowledgement

This work was financially supported by the National Natural Science Foundation of China (Project No. 51504291) and the Co-Innovation Center for Clean and Efficient Utilization of Strategic Metal Mineral Resources.

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