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Coupling effect between magnetic wires and its influence on high gradient magnetic separation performance

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Abstract: High gradient magnetic separation (HGMS) is effective for the separation of weakly magnetic minerals, and this method is achieved through the use of matrix, which is made of huge numbers of rod wires. So that the coupling effect of magnetic field and flow field between wires has a marked effect on the HGMS performance. In the investigation, the coupling effect between magnetic wires and its influence on high gradient magnetic separation performance were theoretically described and simulated using COMSOL Multiphysics. It is found that the magnetic field round a wire would be affected by the neighboring wires, and then a coupling effect of magnetic field between wires was produced, increasing the magnetic induction intensity on the upstream and downstream of wire surface. And the coupling effect of flow field could increase the slurry velocity at the regions of the wire surface with azimuth angles of 0° and 90°, which is beneficial for the selective capture of wire. These simulated results were basically validated with the experimental separation, using an innovative Magnetic Capture Analysis Method. It is found that the wire spacing has significant effect on the coupling effect of magnetic wires, and a critical spacing for wires could achieve an excellent coupling effect, which is beneficial for the improvement of HGMS performance. This investigation contributes to improve HGMS performance in concentrating fine weakly magnetic ores.

***Keywords*:** high gradient magnetic separation, matrix, coupling effect, weakly magnetic particles

1. Introduction

High gradient magnetic separation (HGMS) is effective for the concentration or separation of weakly magnetic minerals, such as hematite, limonite, wolframite and ilmenite, and for the purification of non-metallic ores such as quartz, feldspar, and kaolin (Padmanabhan and Sreenivas, 2011; Hu et al, 2023). This method is achieved through the use of cylindrical magnetic matrix (rod matrix) (Xiong, 2011), and the configuration of rod matrix presents a decisive role on the dynamics of particles and on the separation performance of HGMS, due to the fact that it has an inherent determination on the distribution of magnetic field and flow field (Bedescu et al, 1996; Li et al, 2018).

Actually, the matrix is made of huge numbers of rod wires, forming a high gradient magnetic field at the vicinity of the wires in background magnetic field and serving as a carrier for capturing weakly magnetic particles (Zheng et al, 2015; Chen et al, 2017). Therefore, for a matrix, the spacing between magnetic wires has significant effect on the HGMS performance, as it would significantly influence the magnetic field and flow field distribution around the magnetic wire (Zeng et al, 2019a). In particular, when the spacing between magnetic wires is adequately large, the distribution of both the magnetic and flow fields in the vicinity of these wires closely resemble those found around a single magnetic wire. Notably, there is no observable coupling effect between the wires in this situation. However, as the spacing between magnetic wires decreases, the interactions of magnetic field and flow field between the adjacent magnetic wires would become increasingly evident (Zeng et al, 2019b).

In the practical high gradient magnetic separation, it is essential to maintain an appropriate wire spacing to prevent magnetic particles from passing through the center of adjacent wires and ensure the HGMS performance. Typically, the spacing between wires is either equal to or even less than the diameter of the wire itself (Chen et al, 2014). Therefore, there have coupling effects of magnetic field

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and flow field between the adjacent magnetic wires in the practical HGMS process, and these coupling effects have significant influence on HGMS performance (Chen et al, 2016). Although the vital significance of the coupling effects between the wires in the HGMS process, deep understandings on the effect of the coupling effects between the wires on the HGMS performance are disappointedly scarce. This is primarily resulted from the fact that, there is no effective methods available for the measurement or detection of the coupling effects on the HGMS performance. For instance, Chen Luzheng (Chen et al, 2014) has provided an effective way for the optimization of rod matrix and may be used to improve the PHGMS performance, but these studies were only demonstrated through experiments and could not explain the coupling effect between magnetic wires.

In this investigation, the coupling effect between magnetic wires and its influence on high gradient magnetic separation performance were theoretically described and simulated using COMSOL Multiphysics. These theoretical and simulated results were then basically validated with the experimental magnetic capture to hematite ore, using an experimental magnetic capture method.

2. Theoretical description

As shown in Fig. 1 (left), suppose a cylindrical magnetic wire of radius a is placed in the separation zone of the pilot-scale PHGMS separator and a uniform magnetic field (B_0) is applied in the separating zone. A paramagnetic magnetic particle of volume (V) and magnetic susceptibility (K) is carried through the wire by a feed velocity of (v_0). And, the capture of real matrix for magnetic particles is shown in Fig. 1 (right).

In the capture process of single wire or real matrix, the particles are mainly subjected of magnetic force F_m, hydrodynamic drag F_d and gravity force F_g.

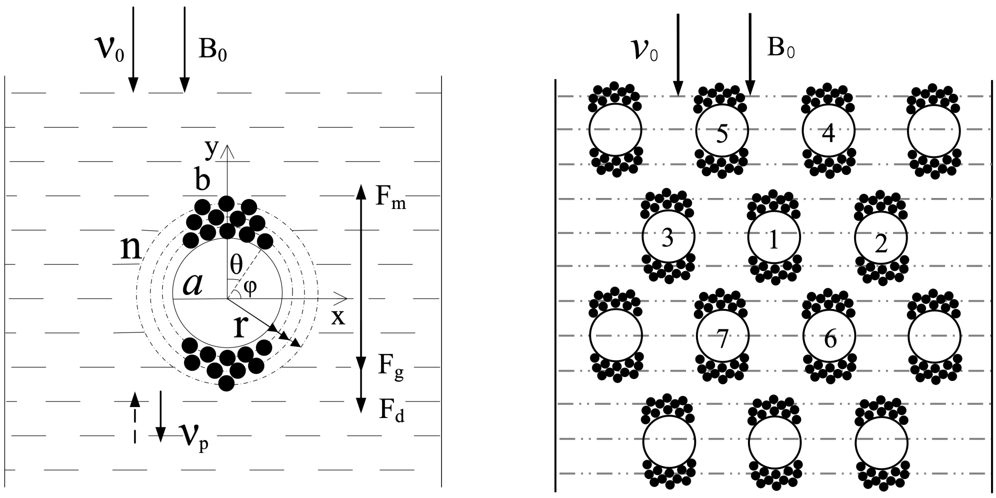


Fig. 1. Magnetic capture of single wire (left) and real matrix (right) to magnetic particles

2.1. Magnetic force F_m

In the capture process of single wire, the magnetic induction component around magnetic wire is written as:

$$\begin{cases} B_r = \left(B_0 + \frac{1}{8}\mu_0 M \frac{a^2}{r^2}\right) cos\theta \\ B_\theta = -\left(B_0 - \frac{1}{8}\mu_0 M \frac{a^2}{r^2}\right) sin\theta \end{cases} \tag{1}$$

where, μ_0 is the permeability of free space, M is the induced magnetization of the wire, r is the capture radius of magnetic force from the center of wire to that of the particle.

The magnetic field gradient of this magnetic induction component is derived from Eq. (1):

$$gradB = -\mu_0 M \frac{a^2}{r^3} \tag{2}$$

From Eq. (2), the magnetic field gradient increases with increase in the induced magnetization and decrease in the radius of wire; for a give wire, the field gradient reaches the maximum while the wire is totally magnetized. Thus, in the magnetic field direction, the magnetic capture force F_m acted upon the particle would be written as:

$$\begin{cases} F_{mr} = \frac{\pi}{12\mu_0} K b^3 {B_0}^2 \frac{a^2}{r^3}\left(\frac{a^2}{4r^2} + cos2\theta\right) \\ F_{m\theta} = \frac{\pi}{12\mu_0} K b^3 {B_0}^2 \frac{a^2}{r^3} sin2\theta \end{cases} \quad (3)$$

where, b is the radius of particle.

While in the capture of real matrix, the magnetic force acting onto the particles is the same as the capture of single wire. But, the magnetic field around the wire would be affected by adjacent magnetic wire, so the magnetic induction around the wire in the real matrix should be written as:

$$B = B_1 + B_2 + B_3 + B_4 + B_5 + B_6 + B_7 \quad (4)$$

where, the B_1, B_2, B_3, B_4, B_5, B_6 and B_7 are the magnetic induction around the wire 1, wire 2, wire 3, wire 4, wire 5, wire 6 and wire 7, respectively.

2.2. Hydrodynamic drag F_d

In the capture process of single wire, the slurry would flow through the wire, and the slurry velocity in the separating area was calculated through the continuity equation of fluid flow:

$$\begin{cases} \nu_r = \nu_0\left(1 - \frac{a^2}{4r^2}\right) cos\theta \\ \nu_\theta = -\nu_0\left(1 + \frac{a^2}{4r^2}\right) \sin\theta \end{cases} \quad (5)$$

where, ν_l and ν_p are the velocity of slurry and particles, respectively.

The hydrodynamic drag F_d is the main force against the magnetic capture, and it could be calculated using the above equation:

$$F_d = 3\pi\eta b(\nu_l - \nu_p) \quad (6)$$

Combing the equations (5) and (6), the hydrodynamic drag was calculated as:

$$\begin{cases} F_{dr} = 3\pi\eta b\left[\nu_0\left(1 - \frac{a^2}{4r^2}\right)\cos\theta - \frac{d_r}{d_t}\right] \\ F_{d\theta} = 3\pi\eta b\left[-\nu_0\left(1 + \frac{a^2}{4r^2}\right)\sin\theta - r\frac{d_r}{d_\theta}\right] \end{cases} \quad (7)$$

where, $\frac{d_r}{d_t}$ and $r\frac{d_r}{d_\theta}$ are the radial component and tangential components of particle velocity.

While in the capture of real matrix, the hydrodynamic drag acting onto the particles is the same as the capture of single wire. But, the slurry flow around the wire would be affected by the adjacent wire, so the slurry velocity could be written as:

$$\nu = \nu_1 + \nu_2 + \nu_3 + \nu_4 + \nu_5 + \nu_6 + \nu_7 \quad (8)$$

where, the ν_1, ν_2, ν_3, ν_4, ν_5, ν_6 and ν_7 are the slurry velocity around the wire 1, wire 2, wire 3, wire 4, wire 5, wire 6 and wire 7, respectively.

2.3. Gravity force F_g

In the HGMS process with single wire or real matrix, the gravity acting on the mineral particles could be represented as:

$$\begin{cases} F_{gr} = (\rho_p - \rho_f) \cdot g \cdot V \cdot \cos\theta \\ F_{gr} = (\rho_p - \rho_f) \cdot g \cdot V \cdot \sin\theta \end{cases} \quad (9)$$

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

3. Simulation and experiments

3.1 Cyclic pilot-scale pulsating HGMS separator

A SLon-100 cyclic pilot-scale pulsating HGMS separator was used for the present investigation. This separator is fed periodically. When the separator was operated, via feed box the slurry was fed through the magnetic wire located in the separating zone of the separator, with magnetic particles captured onto the wires and non-magnetic particles flowing out of the zone. When a batch of feed was finished, the energizing current was switched off and the magnetic particles captured onto the wires were washed out to get a magnetic product.

3.2. Model description

In this work, the flow field characteristics and magnetic field characteristics were simulated via COMSOL Multiphysics simulation software, which was based on finite element method. In the simulation, the model was built up for the two-dimensional section of the single wire and matrix, as illustrated in Fig. 2. In the simulation, the initial velocity of the slurry is fixed at 3.0 cm/s, and the background magnetic induction in the separation zone is 0.8 T.
In the capture model of single wire, a wire of 2.0 mm diameter was displaced in the separation area. While in the capture model of real matrix, eighteen wires of 2.0 mm diameter were used in the matrix to facilitate the calculation process and simply the simulation process. It should be noted that in the simulation of different real matrix, the spacing(d_L) between the magnetic wires is set as 3.00 mm, 2.00 mm, 1.50 mm and 1.20 mm, respectively.

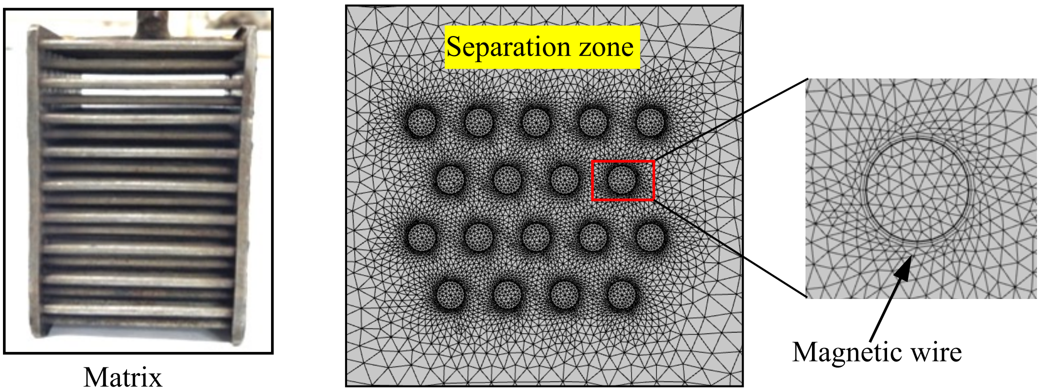


Fig. 2. Real matrix (left) and its physical model (right) for simulation

In this two-dimensional physical model, free triangle mesh was adopted for mesh generation, with the maximum and minimum mesh sizes set at 3.7000 mm and 0.0125 mm, respectively. The maximum mesh growth rate was set at 1.25, with the curvature factor and narrow area resolution set at 0.25 and 1.00, respectively; and, other related boundary conditions for the simulation specifically were listed in Table 1. In this simulation process, the slurry was fed into the separating area from the inlet, and flown out from the outlet; and, a vertical magnetic field is placed in the separating zone.

Table 1. Boundary conditions for COMSOL Multiphysics simulation

Boundary conditions	Values set for simulation
Relative magnetic permeability of wire (K)	7000
Background magnetic induction (B_0)	0.8 T
Viscosity of slurry (η)	1.2×10^{-3} Pa·s
Density of slurry	1.3×10^{3} kg/m^3
Diameter of wire (a)	2 mm
Velocity of feed (v_f)	0.03 m/s
Spacing (d_L) between the wires	3, 2, 1.5, 1.2 mm

3.3. Description of material

In this investigation, a typical hematite ore assaying 36.75% Fe, was used for the single wire and real matrix capture experiments. The material is less than 0.15 mm and 90.24% of the material is smaller than 0.074 mm. The main non-magnetic components in the material are SiO_2, Al_2O_3 and CaO.

3.4. Method

The Magnetic Capture Analysis (MCA) method (Chen et al, 2017) was used in the capture experiment, to measure the capture performance and evaluate the coupling effect between magnetic wires. As shown in Fig. 3, in the method, the circular holes were regularly drilled in two non-magnetic plates, which were used for inserting magnetic wires. In this method, the spacing between the magnetic wires could be adjusted according to research needs. In the investigations, the wires were inserted in the plates at different spacing, and the spacing was set as 3.00 mm, 2.00 mm, 1.50 mm and 1.20 mm, respectively.

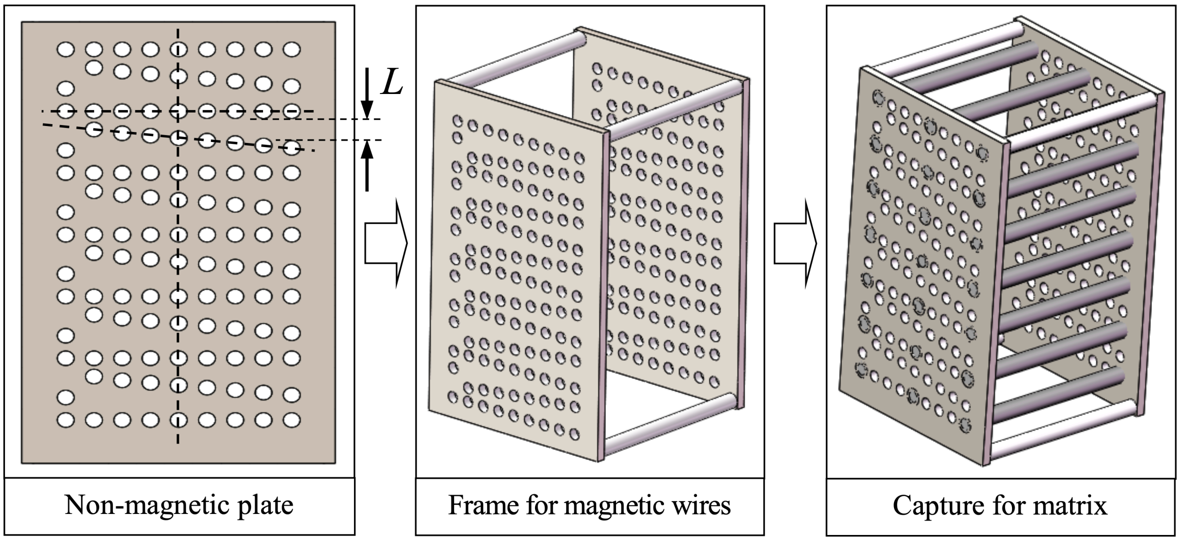


Fig. 3. Schematic diagram on operational principle of MCA method

All the investigations for the magnetic capture of magnetic wires are achieved with the pilot-scale pulsating HGMS separator. When a separation process is finished, the frame inserted with magnetic wires is taken out of the separator, and the magnetic particles captured onto the wires are washed out with clean water and dried for weighing and analysis. In each experimental, 60 magnetic wires were used and 100 g material was fed into the separating zone.

4. Results and discussion

4.1. Effect of wire spacing on magnetic field distribution

In HGMS process, the magnetic particles are mainly captured onto the matrix according to the magnetic force. Therefore, the magnetic field distribution has significant effect on the HGMS performance. In practice, the matrix is made of numerous magnetic wires, and the wires could be arranged in different spacing. In order to reveal the influence of the wire spacing on the magnetic field distribution, the magnetic field in the separation zone was simulated using the capture moder mentioned previously, as shown in Fig. 4 and Fig. 5. In this simulation, the spacing between magnetic wires were respectively set at 1.0 mm, 1.2 mm, 1.5 mm, 2.0 mm and 3.0 mm, with other simulation parameters listed in Table 1. Furthermore, the magnetic field around a single wire was also simulated, to compare the magnetic field around single-wire and real matrix.

From Fig. 4 and Fig. 5, when a single-wire was displaced in the magnetic field, the magnetic lines magnetic lines accumulate around the wire in the direction of magnetic induction, forming two attractive regions on the upstream and downstream surfaces of the wire, where the magnetic induction is significantly increased. It is important to note that when the wire spacing is 3 mm, the magnetic field distribution around the wire closely resembles that of a single-wire, indicating that there is no coupling effect between the magnetic media at this time. However, when the wire spacing is reduced to 2 mm, the magnetic field around the wire is influenced by the neighboring wires, leading to the emergence of a coupling effect between magnetic fields. This coupling effect results in an increase in magnetic induction intensity on the upstream and downstream surfaces of the wire, enhancing the magnetic capture force for magnetic particles. Nevertheless, at this spacing, the effective magnetic capture surface of the magnetic wire is reduced.

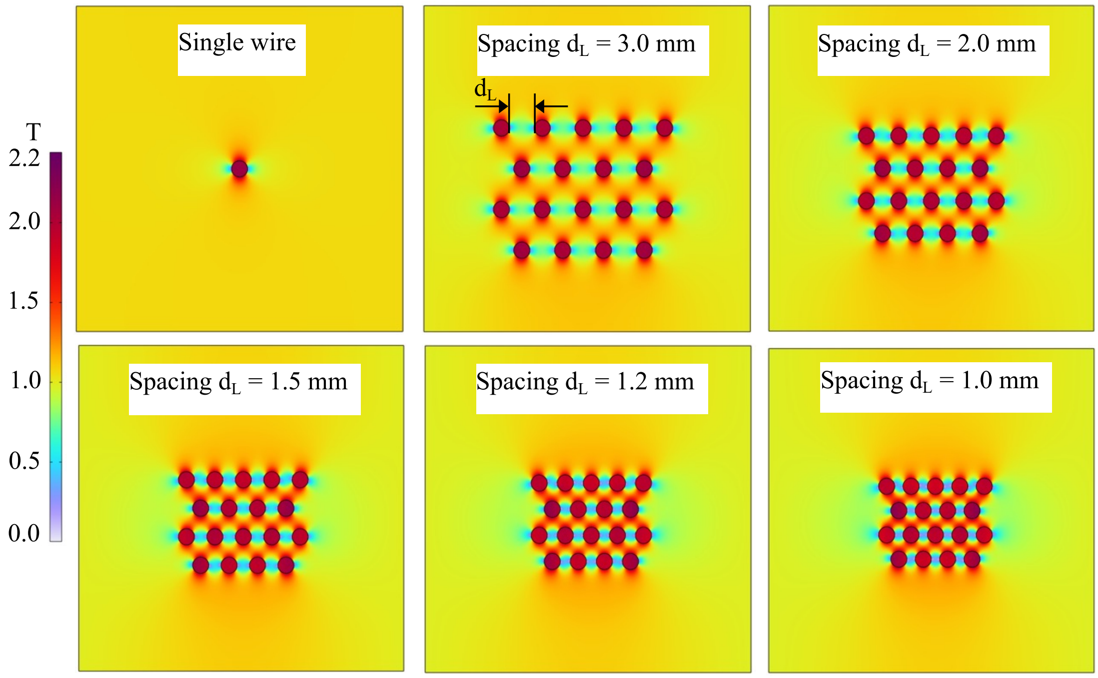


Fig. 4. Magnetic field characteristics in separation zone with different wire spacing

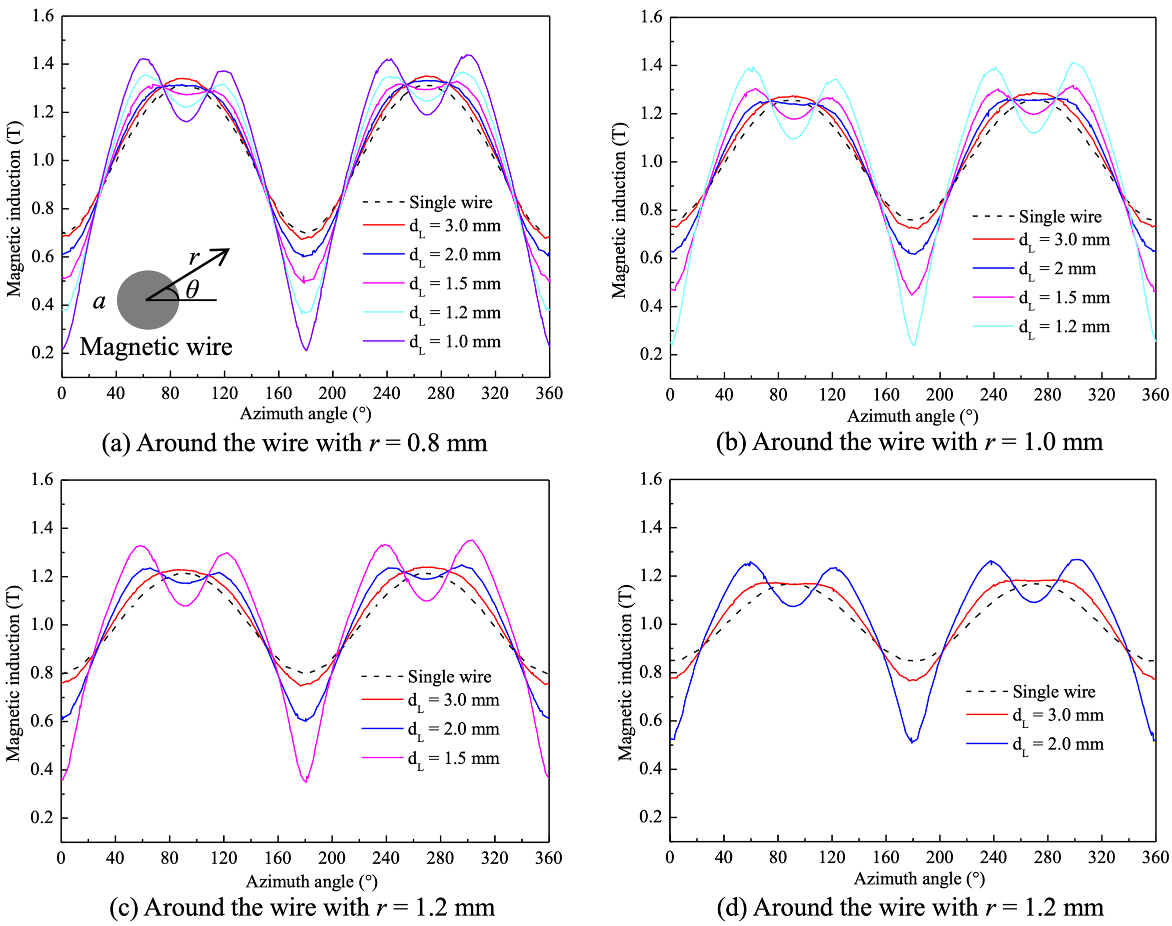


Fig. 5. Magnetic induction around wire with different wire spacing

The decrease in the spacing would strengthen the coupling effect of magnetic field between wires, and then strengthen the magnetic capture force of wire. But, when the spacing between magnetic wires is only 1.0 mm, this magnetic field effect would significantly reduce the capture area and capture ability of the wire, as shown in Fig. 5. The research results indicate that appropriately reducing the distance between magnetic media is beneficial for improving and optimizing the magnetic field coupling effect between the wires.

The reduction in wire spacing enhances the coupling effect of the magnetic field between wires, thereby increasing the magnetic capture force of the wire. However, when the spacing between magnetic wires is reduced to 1.0 mm, as shown in Figure 5, this magnetic field effect significantly reduces the capture area and capacity of the wire. The findings of this study indicate that appropriately reducing the distance between magnetic media can be beneficial for improving and optimizing the magnetic field coupling effect between the wire.

4.2 Effect of wire spacing on flow field distribution

Using the same boundary conditions as the magnetic field characteristics simulation above, the effect of spacing between magnetic wires on the flow field distribution was investigation, as shown in Fig. 6 and Fig. 7.

As shown in Fig. 6, it is evident that for the single wire, there is a circular flow around the wire, leading to the formation of fluid void areas on the upstream and downstream surfaces. This results in a decrease in fluid density within these regions, subsequently reducing the amount of fluid present within those areas. Specifically, as shown in Fig. 7, in the regions of the magnetic wire surface with azimuth angles of 0° and 90°, the slurry fluid velocity is almost zero, and these two regions are the primary areas for capturing particles, which is extremely detrimental to the selective capture of the wire.

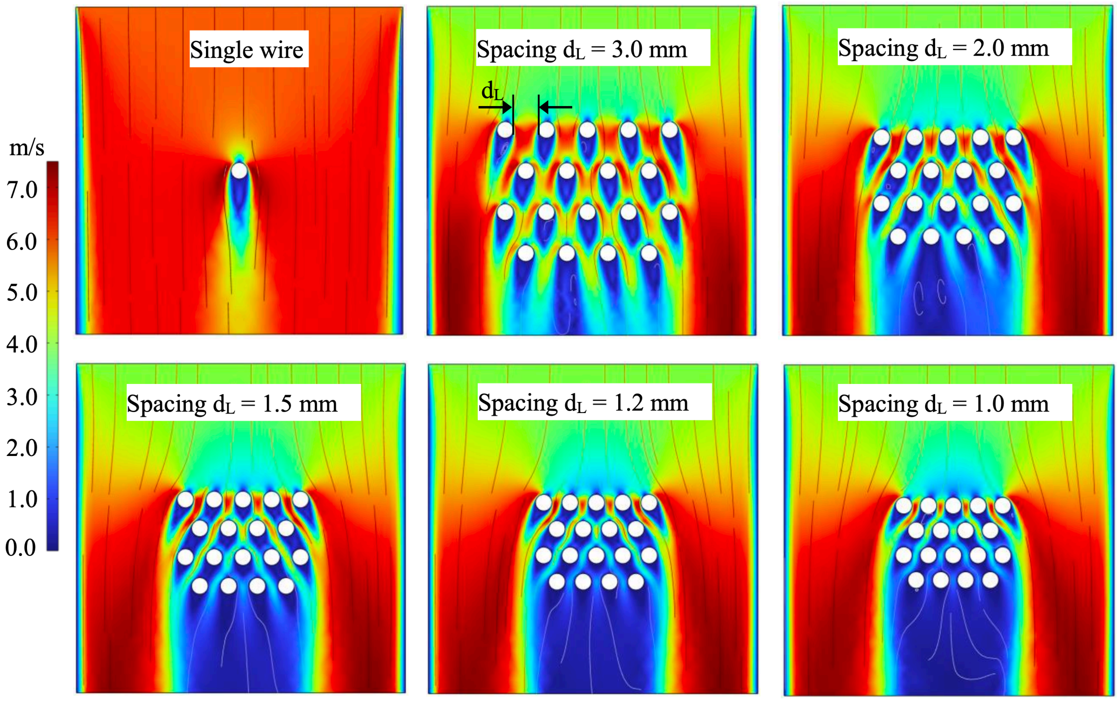
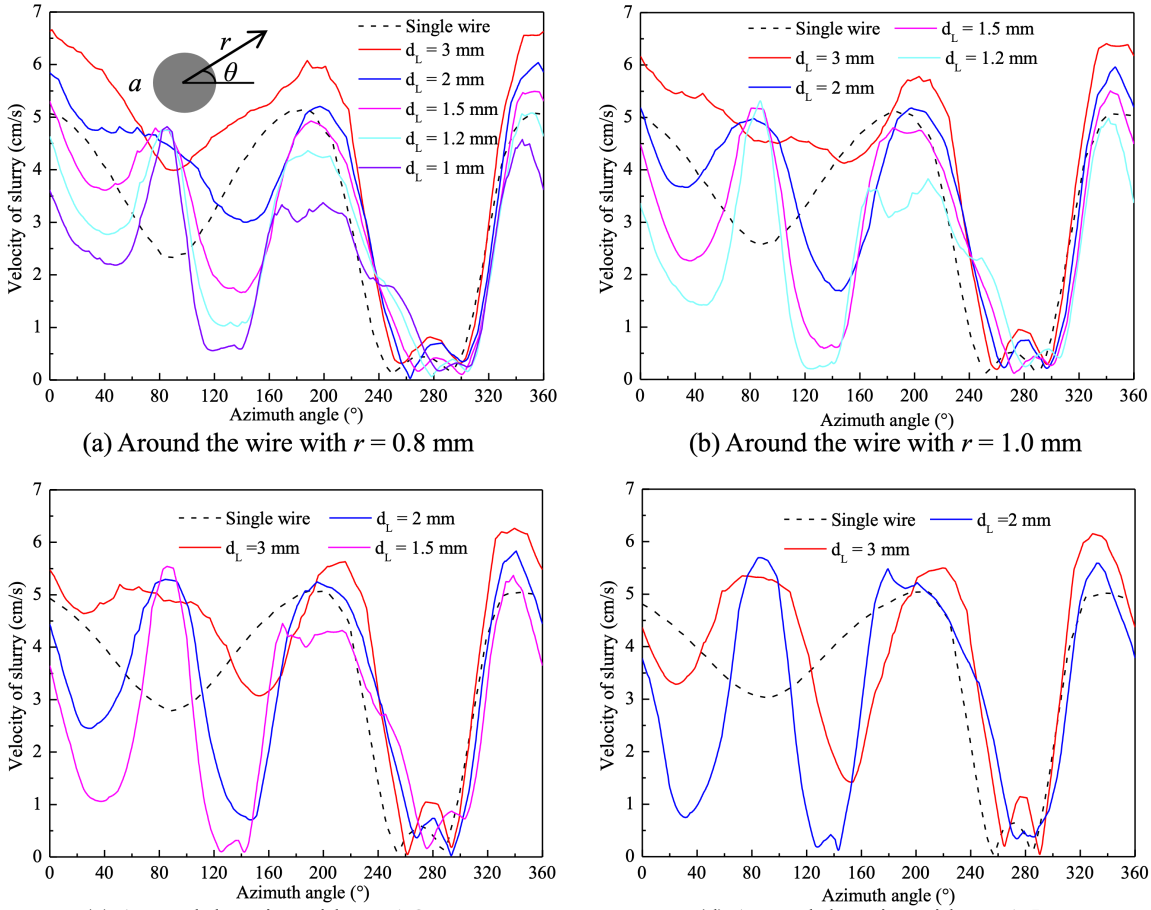


Fig. 6. Flow field characteristics in separation zone with different wire spacing

In the real matrix, the flow field around wire would be affected by the by the neighboring wires. As shown in Fig. 7, when the spacing between wires is smaller than 2.0 mm, there is a coupling effect in the flow field between wires, causing a significant increase in the slurry fluid velocity at the regions of the wire surface with azimuth angles of 0° and 90°, which is beneficial for the selective capture of magnetic particles by magnetic wire. It also should be noted that the decrease in the spacing would strengthen the coupling effect of flow field between wires. However, when the wire spacing is smaller than 1.0 mm, the slurry cannot flow through the wires freely.

4.3. Effect of wire spacing on HGMS performance

In this work, in order to reveal the influence of the coupling effect between magnetic wires on the HGMS performance, the high gradient magnetic separation experiments with wire spacing of 0.5 mm, 0.8 mm, 1.0 mm, 1.2 mm, 1.5 mm, 2.0 mm and 3.0 were firstly carried out. From Fig. 8, the spacing has a very significant effect on the HGMS performance. The recovery was initially increased with increase in the spacing, reached high levels in the range from 1.5 to 2.0 mm, and then rapidly decreased as the spacing is further increased. The grade of concentrate was initially increased with increase in the spacing, reached high levels in the range from 1.2 to 2.0 mm, and then slowly decreased as the spacing is further increased.



(a) Around the wire with $r = 0.8$ mm (b) Around the wire with $r = 1.0$ mm

(c) Around the wire with $r = 1.2$ mm (d) Around the wire with $r = 1.5$ mm

Fig. 7. Slurry velocity around wire with different wire spacing

The spacing between magnetic wires has an inherent determination on the magnetic flied distribution and the flow flied distribution, and produces a significant effect on the separation performance. While the spacing is controlled in the range of 1.2-2.0 mm in the present investigation, there have well coupling effect of magnetic field and flow field between magnetic wire. This excellent coupling effect could generate a larger magnetic field strength and fluid velocity on the upper and lower surfaces of the wire, thereby ensuring a higher concentrate grade and recovery. However, when the spacing is further decreased, the slurry and particles would not pass through the matrix freely, which would significantly deteriorate the HGMS performance.

4.4 Effect of slurry velocity on HGMS performance

The effect of slurry velocity on the HGMS performance was investigated with the wire spacing of 1.0 mm, 1.2 mm, 1.5 mm and 2.0 mm, as shown in Fig. 9. The spacing has a very significant effect on the recovery. Although the two magnetic inductions produced different sets of indicators, they follow the same trend. The recovery of concentrate drastically decreased with increase in the slurry velocity from 2 cm/s to 8 cm/s. Meanwhile, in the case of a small wire spacing, such as the 1 mm or 1.2 mm spacing shown in the Fig. 9, the recovery of concentrate obtained by HGMS is relatively low, regardless of whether the slurry flow rate is high or low. This is primarily resulted from the fact that, the coupling effect between small-spaced wires would significantly reduce the effective capture area of the magnetic wire.

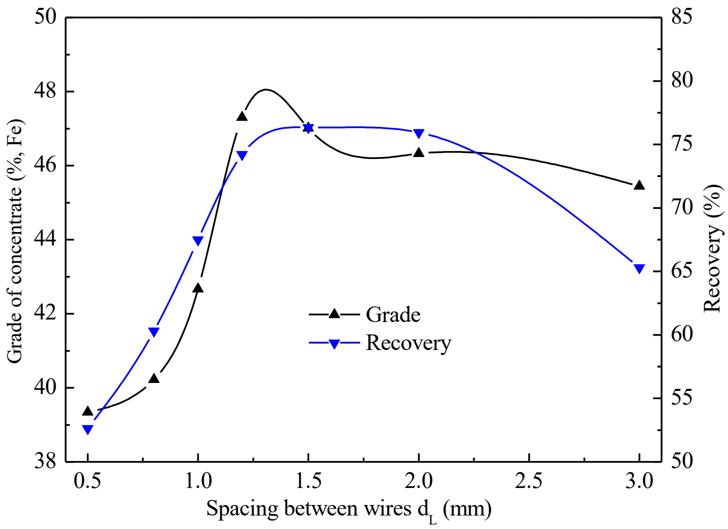


Fig. 8 Effect of wire spacing on HGMS separation

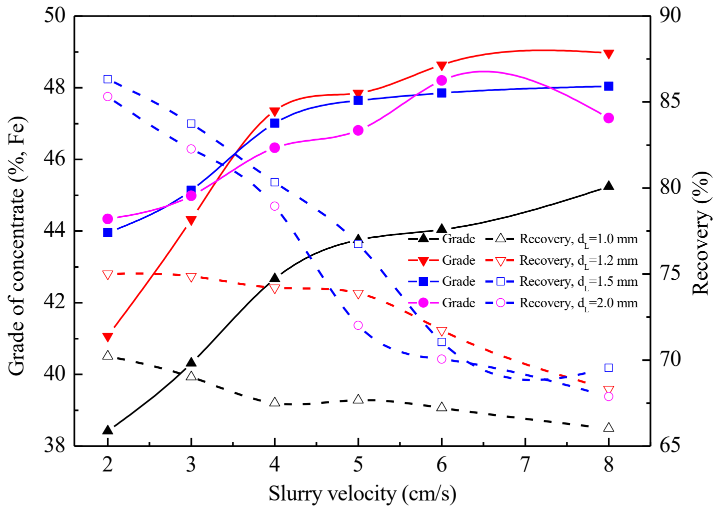


Fig. 9. Effect of slurry velocity on HGMS separation

It is noted that the grade of concentrate increased with increase in the slurry velocity from 2 cm/s to 8 cm/s. The most important discovery of this investigation lies in the fact that in the case of a small wire spacing, the increase in slurry velocity has a more significant effect on improving the concentrate grade, comparing to a larger wire spacing. This is primarily resulted from the fact that, the high slurry velocity could improve the fluidity of slurry in the matrix. Therefore, under the conditions of small wire spacing and high slurry velocity, the flow field coupling effect between wires has a positive promoting effect on improving the HGMS performance.

4. Conclusions

(1) In the capture of matrix, the magnetic field round a wire was affected by the neighboring wires, and then a coupling effect of magnetic field between wires would be produced, increasing the magnetic induction intensity on the upstream and downstream of wire surface, but reducing the effective magnetic capture surface of magnetic wire.

(2) The coupling effect of flow field could increase the slurry velocity at the regions of the wire surface with azimuth angles of 0° and 90°, which is beneficial for the selective capture of magnetic wire.

(3) The simulated results were basically validated with the experimental separation, and it is found that the wire spacing has significant effect on the coupling effect of magnetic wires. A critical spacing for wires could achieve an excellent coupling effect, which is beneficial for the improvement of HGMS performance.

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