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A simulation on field distribution and particle capture characteristics in a multi-wire PHGMS system

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ABSTRACT

In the development history of high gradient magnetic separation (HGMS), the introduction of pulsating flow was extremely important, it successfully solved the problem of matrix clogging and allowed continuous and stable operation in the industry. However, the current pulsating HGMS (PHGMS) theory remains inadequately understood. In this paper, a 2D simulation model was established in COMSOL Multiphysics to reveal the magnetic field characteristics, flow field distribution, and particle capture dynamics in a PHGMS system. Quantitative comparisons were carried out between single-wire and multi-wire systems in the presence and absence of pulsation flow. The simulation results indicated that due to the coupled effect of neighboring magnetic wires in matrix, the magnetic field strength around an individual magnetic wire would slightly drop while the flow field velocity would increase. The introduction of pulsating flow could increase the peak value of fluid velocity and give particles a chance to move up and down. The analysis of particles travels length and capture probability indicated that the recovery for fine particles might be improved by increasing the strength of pulsating flow. This study provided a novel strategy for the highly efficient recovery of fine, weakly magnetic materials.

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Introduction

High gradient magnetic separation (HGMS) is an important technology for the separation of weakly magnetic minerals. In the development history of HGMS technology, the invention of the first SLon-1000 industrial vertical ring pulsating high-gradient magnetic separator was a milestone.[1–4] In the late 1980s, this machine was developed and showed inspiring results during the industrial tests at Gushan Iron Mine in eastern China.[3] Since then, pulsating high gradient magnetic separation (PHGMS) technology has received extensive attention and has become a key technology worldwide for sorting weakly magnetic ores and purifying nonmetallic ores.[5–9] The SLon series PHGMS separator alone deals with over 1 billion tons of ores annually, generating notable technological and economic gains for human society.

The key reason for the great success of PHGMS was the introduction of pulsating flow into the separation chamber. This solved the problem of matrix clogging and allowed continuous and stable operation in the industry. Meanwhile, the particles were exposed to a faster slurry environment and demonstrated better selectivity during the separation process.[5,10]

However, the current theory of PHGMS remains inadequately understood, even though it has been widely used in many fields for over 30 years. Previous research on the PHGMS process mainly focused on the theoretical equations in idealized conditions, which resulted in a lack of understanding of the complex interaction faced in actual PHGMS setup.[4,11] For example, Xiong Dahe,[3] the inventor of PHGMS technology, studied the behavior of particles in pulsating water without considering the effect of matrix. While in an actual PHGMS system, particles pass through thousands of magnetic wires under the effect of magnetic field force. Ye et al.[12] and Jiang et al.[13] tried to reveal the separation mechanism of PHGMS by building a multi-wire simulation model. However, they did not consider the impact of pulsation flow.

With the continuous depletion of high-quality mineral resources, the recovery of ultra-fine magnetic values from discarded tailings and finely disseminated ores becomes very important. It brings new challenges to the delicate operation of PHGMS and requires an in-depth understanding to its underlying theories. In our recently published work,[14] it was found that ultra-fine ilmenite tailing achieves improved separation

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performance under a relatively strong pulsation flow. These results contradicted the common belief that a strong fluid flow was unfavorable for fine particles, indicating the need to uncover the underlying reasons.

In this study, a 2D simulation model was established in COMSOL Multiphysics to reveal the magnetic field characteristics, flow field distribution, and particle capture dynamics in a PHGMS system. Quantitative comparisons were carried out between single-wire and multi-wire system in the presence and absence of the pulsation effect. The results demonstrated in this study would provide theoretical guidance for the highly efficient recovery of extremely fine particles through PHGMS technology.

Modeling methodology

Simulation model

In the industrial PHGMS system, the direction of background magnetic field is parallel to that of the fluid flow and perpendicular to the axis of magnetic wires.[15] Figure 1 displays the 2D simulation model we established in the COMSOL Multiphysics: magnetic matrix made of magnetic stainless steel is placed in a 29 mm × 70 mm water domain; the horizontal and vertical distance between adjacent wire is 2 mm ($L_h = 2$ R) and $2\sqrt{3}$ mm ($L_v = 2\sqrt{3}$R), respectively, as the radius (R) of the wires is 1 mm; an air domain is added outside the water domain for the specification of the far-field border. When establishing a single-wire system, the matrix is placed at the center of the water domain.

The implemented model included three interfaces, namely "magnetic field, no current" (mfnc) to solve magnetic field distribution, "laminar flow" (spf) to solve flow field distribution, and "particle tracing for fluid flow" (fpt) to solve the particle motion trajectories. The boundary conditions for each interface are set as follows:

(1) **Magnetic field, no current (mfnc)**: A background magnetic field is applied to all the domains in the y-direction, and the outer border of the 2D geometry is defined as having a magnetic scale potential of zero. To solve the conservation equation of magnetic flux, the relative permeability of the water and air domain is set as 1, and that of the matrix domain is derived from the B-H curve of pure iron.

(2) **Laminar flow (spf)**: A water flow normal to the inlet is applied with a velocity of ($v_0+\tilde{v}$), where $v_0$is the feed velocity and $\tilde{v}$ is the pulsating velocity as following[3]:

$$\tilde{v} = \frac{1}{2} S.\,\omega\, sin = (\omega\, t) \tag{1}$$

$$\omega = 2\pi f \tag{2}$$

where S is the pulsating stroke (m), ω is the angular velocity of pulsating wave (rad/s), f is the pulsating frequency (s^{-1}), and t is the time variable in seconds (s).

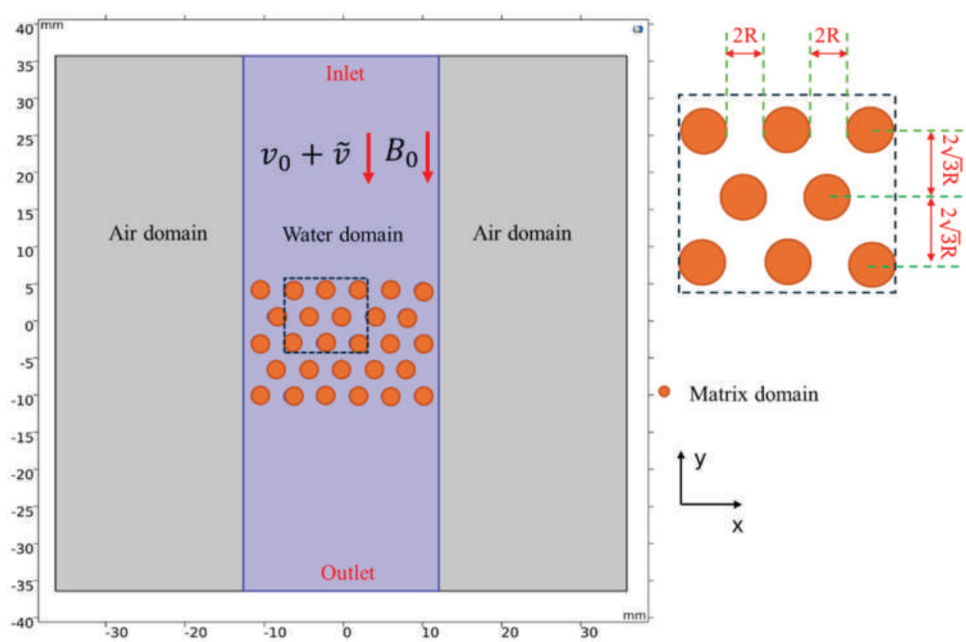

Figure 1. 2D schematic diagram of the simulation model of pulsating HGMS.

At the outlet boundary, the pressure is set as zero, and a no-slip boundary is specified on the interior wall of the fluid channel and surface of the matrix.

(3) Particle tracing for fluid flow (fpt): The particle motion is governed by Newton's second law, and the magnetic particles are subjected to magnetic force F_m, hydrodynamic drag force F_D, and gravitational force F_g.

For detailed information on the expressions of these forces, please refer to our previously published paper.[16] In this model, particles with a diameter of 20 μm, magnetic susceptibility of 0.0005, and density of 5000 kg/m^3 are uniformly released along the x-axis at y = 15 mm. At $t = 0$ s, 14 batches of particles began to be released with a time interval of 1/7 period of the pulsation flow; each batch accounted for 28 particles. The detailed specification of parameters is displayed in Table 1. A time-dependent study is employed to solve the three multi-physics interfaces, with the time step set as 0.005 s and the whole duration set as 3 s.

Results and discussion

Magnetic field characteristic

The magnetic matrix is a key component in the PHGMS system, also its magnetic field characteristic has a decisive effect on its separation performance. Previous studies generally focused on the magnetic field distribution around a single wire,[17] but the actual PHGMS system contains thousands of magnetic wires. Thus, a comparative study between single-wire and multi-wire is necessary to enhance our comprehension for PHGMS process.[18]

The simulation employed a homogeneous background magnetic field of 1.2 T throughout the computational domain. The results could directly demonstrate magnetic flux density B_0 but the magnetic field force $HgradH$ had to be derived from the following equations.[19]

$$HgradH_x = \frac{\partial H^2}{2\partial x} \tag{3}$$

$$HgradH_y = \frac{\partial H^2}{2\partial y} \tag{4}$$

$$HgradH = \sqrt{(HgradH_x)^2 + (HgradH_y)^2} \tag{5}$$

The magnetic field force $HgradH$ describes the force that attracts magnetic particles to the wires, combining the magnetic field strength and its rate of change (gradient). Where ($HgradH_x$) is the x component of $HgradH$, and ($HgradH_y$) is the y component of $HgradH$.

Figure 2 displays the magnetic flux density B_0 and normalized $HgradH$ vector distribution around the single and multi-wire magnetic media. It was clear that the magnetic field distribution around the matrix showed a similar trend: it was high at the top and bottom sides of the matrix but low at the left and right edges. This resulted in similar zones of attraction and repulsion around the matrix. However, the magnetic field distribution around a multi-wire system (Fig. 2b) was apparently more complex due to the coupled effect between matrices. This coupled effect refers to the mutual interaction of magnetic fields of neighboring wires, which changes the magnetic field distribution in the separation zone. Compared to a single wire (Fig. 2a), the magnetic field in the multi-wire system appeared to be squeezed by neighboring matrices.

To gain a clearer vision of this phenomenon, the value of magnetic field H, the magnetic field gradient

Table 1. Specifications of PHGMS simulation model.

Parameters	Specifications
water domain	
Size (mm ×mm)	29×70
Inlet velocity v_0 (m/s)	0.02, 0.04, 0.06, 0.08
Pulsating frequency f (s^{-1})	0, 2, 4, 6, 8, 10, 12
Pulsating stroke S (mm)	0, 2, 4, 6, 8, 10, 12, 14
Matrix domain (pure iron)	
Material	Pure iron
Diameter (mm)	2
Fluid Properties	
density ρ (kg/m^3)	1×10^3
dynamic viscosity η (Pa·s)	1×10^{-3}
relative permeability μ_f(dimensionless)	1
Magnetic field	
Magnetic induction B_0 (T)	0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6
Particles	
diameter D (μm)	20
density ρ_p (kg/m^3)	5×10^3
magnetic susceptibility κ (dimensionless)	5×10^{-4}

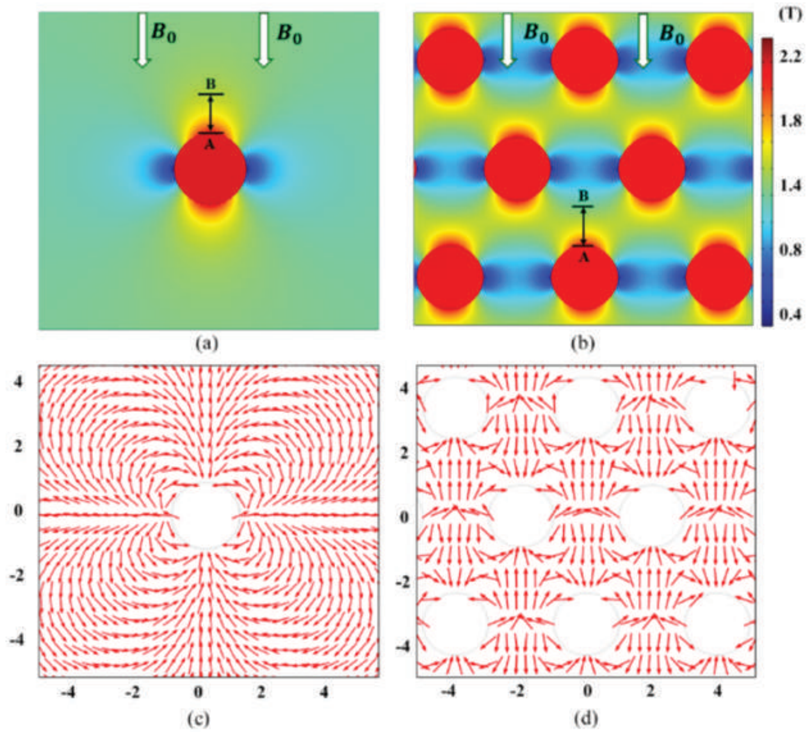

Figure 2. (a) Magnetic field distribution around single, (b) multi-wire, and (c) normalized HgradH vector distribution around single (d) multi-wire at B_0 = 1.2.

gradH, and magnetic field force *HgradH* along Line AB (remarked in Fig. 2) were compared. As shown in Fig. 3, these three parameters all changed rapidly from A to B. While *H* around a single wire was higher than that of a multi-wire media, *gradH* showed the opposite trend, which resulted in a very close value of *HgradH* along AB.

Flow field characters

Flow field characters in the absence of pulsating effects

Before investigating the effect of pulsating flow on particles capture, the flow field distribution characters under v_0 = 0.04 m/s were evaluated for three different

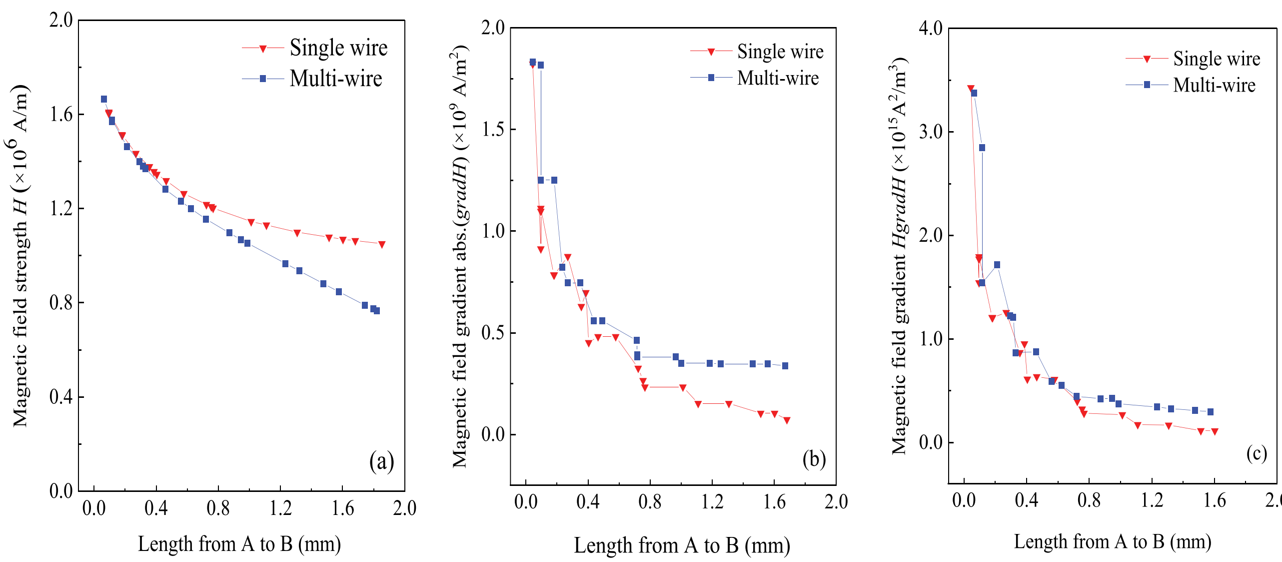

Figure 3. (a) Magnetic field H, (b) magnetic field gradient abs.(gradH), and (c) magnetic field force (HgradH) of distance from matrix surface along the Y-axis for single-wire and multi-wire magnetic media with different distances between magnetic wires at B_0 =1.2 T.

configurations: without wire, single-wire, and multi-wire in the absence of pulsating effect. As shown in Fig. 4, the flow field distribution was uniform when no wires were put in. However, installing a single wire split the water into two parts on the left and right sides, resulting in a stagnant region at the front and a vortex region with a long tail at the rear of the wire. In the case of a multi-wire system, the space between the wires became fluid channels, leaving the water squeezed into these channels with much higher velocities, up to 0.10 m/s. Meanwhile, the stagnant and vortex regions still existed but occupied a much smaller area for each wire.

To sum up, the loading of the wires occupied the space that should have belonged to fluid, squeezing the water to flow in a narrower channel with higher velocity. On the one hand, these narrow channels could provide more chances for particles to pass through attractive regions of the wires, thereby increasing the capturing probability of an individual wire. On the other hand, the increased flow velocity would bring a higher drag force to particles and weaken their capturing probability.

Flow field characters in the presence of pulsating effects

As mentioned before, the key reason for the success of PHGMS was the introduction of pulsating flow into the separation chamber. Therefore, a flow field simulation was carried out under a feed velocity of 0.04 m/s, a pulsating stroke at 10 mm, and a pulsating frequency of 5 r/s. According to equations (1) and (2), the velocity curve in the inlet could now be expressed as equation (6), which shows how the pulsating flow changes velocity over time. The key component of this equation is the oscillating sine function (10πt). Which fluctuates between 1 and −1. The velocity reaches its maximum upward value at 0.197 m/s, and its maximum downward value at 0.117 m/s.

$$v = 0.040 + 0.157\sin(10\pi t) \tag{6}$$

Figure 5 shows the flow field distribution around the matrix within one period of pulsating, and Fig. 6 displays velocity evolution in the y-direction along the line CD (marked in Fig. 5) during $t = 0 \sim 0.4$ s.

It is apparent that the flow pattern changed rapidly when the pulsating flow was applied. The velocity along line CD fluctuated periodically in a wide range from −0.46 m/s to 0.28 m/s. During $t = 0.12 \sim 0.18$ s, the fluid flowed upward, giving the particles a chance to flow back and be captured more easily by the wires. In contrast, the magnitude of the velocity in the y-direction remained stable at about −0.10 m/s in the absence of pulsating flow.

In conclusion, the maximum velocity around the wires could greatly increase when pulsating flow was introduced, subjecting the particles to a larger drag force and making their recovery more difficult. However, at the same time, the pulsating flow also gave the particles a chance to flow back and be captured more easily.

Particle captures characters

With the continuous depletion of high-quality PHGMS feeding resources, the recovery of fine magnetic particles becomes very important. In this section, 20 μm particles were used as feed to study the particle capture characters of the multi-wire PHGMS system. The particles are released as described in section 2.1 unless specially stated, and the properties of the particles are specified in Table 1.

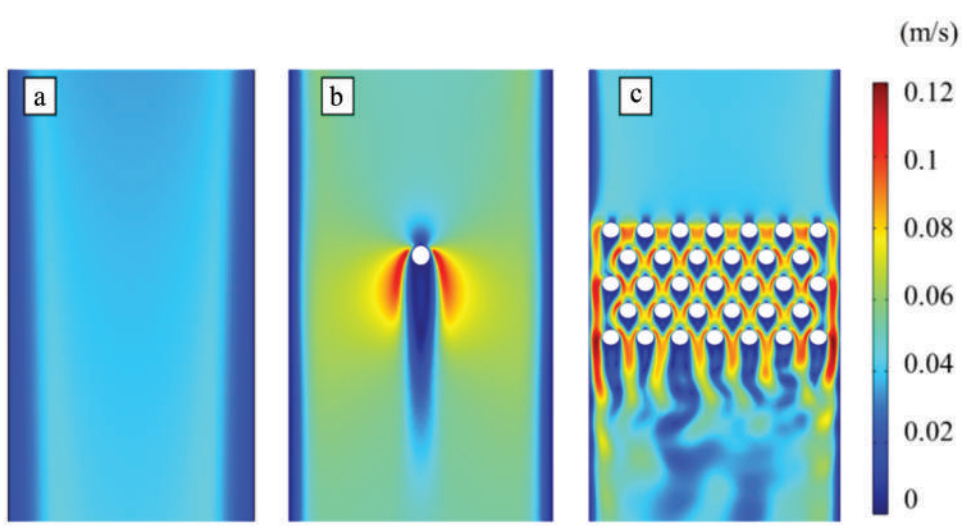

Figure 4. Flow field distribution: (a) without wire, (b) single wire, and (c) multi-wire at v_0 = 0.04 m/s.

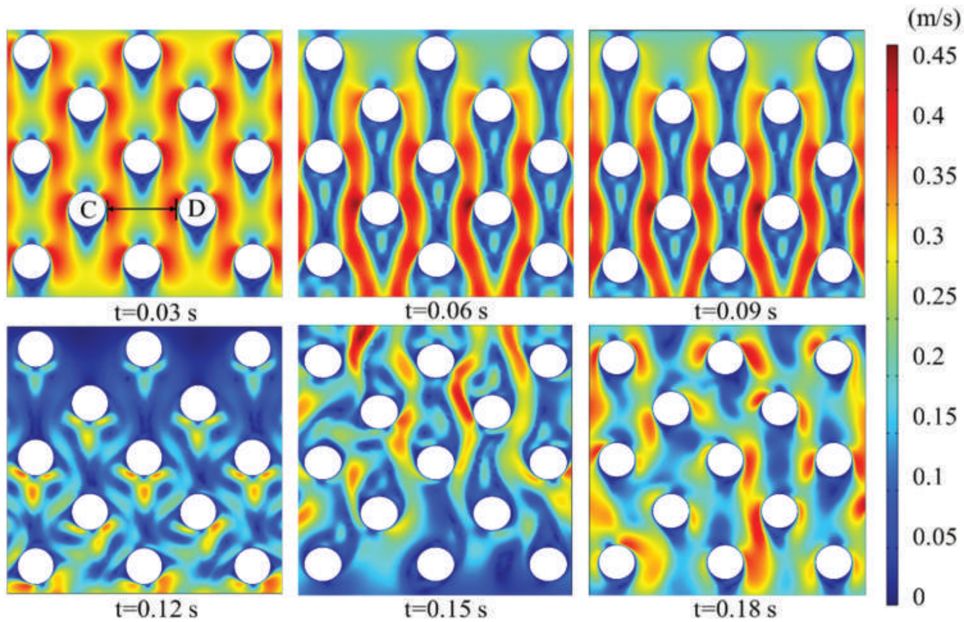

Figure 5. Flow field distribution around multi-wire media over time at $v_0 = 0.04$ m/s; S = 10 mm; f = 5 r/s.

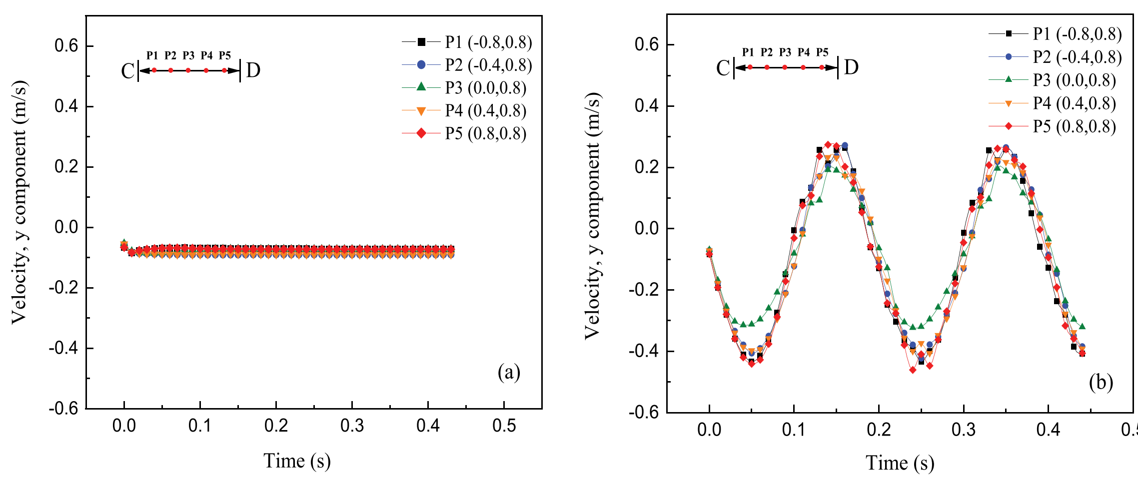

Figure 6. Evolution of vertical fluid flow velocity through horizontal distance between adjacent magnetic wires over time: (a) without pulsating effect and (b) under pulsating effect.

Particle trajectories

The characteristics of the magnetic field and flow field for the multi-wire PHGMS system would finally be reflected in capture performance of the wires. This section discusses the particle motion trajectories under the effect of a pulsating mechanism. The simulation was conducted under a magnetic field of 1.2 T, a feed velocity of 0.02 m/s, a pulsating stroke of 10 mm, and a pulsating frequency of 5 r/s. The evolution of particle motion trajectories around the wires is demonstrated in Fig. 7. It is observed that most particles stopped moving at $t = 1.7$ s; they were then either captured by the wires or swam into tailing. During the entire procedure, the particles found it difficult to be captured the first time they moved around the wires, but the existence of pulsating flow provided them with a chance to move upward. Since the pulsating frequency is 5 times per second, the particles were observed to move up and down 8 times within 1.6 s. In a real PHGMS separator, the number of wires layer is much higher than that in the simulation model, so the particles will have more chances to flow back and forth. This is crucial to PHGMS because the fast-up warding fluid not only helps break the blockage and improve the separation selectivity but also helps create more chances for particles to capture.

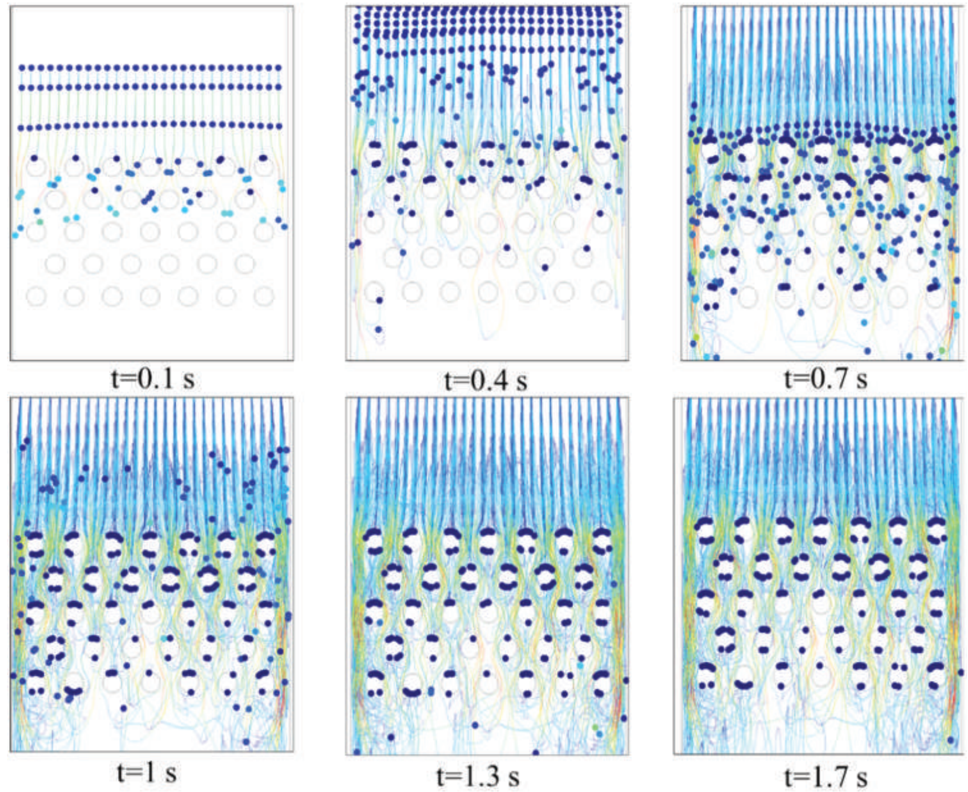

Figure 7. Evolution of particle motion trajectory over time at $B_0 = 1.2$ T, $v_0 = 0.02$ m/s, S = 10 mm, f = 5 r/s.

Effect of pulsation flow on capture probability

Here, the capture probability was defined as the number of particles captured by the matrix divided by the total number of particles released. This section discusses the effect of pulsating frequency and pulsating stroke on travel length and the capture probability.

The effect of pulsating flow on particle travel length in the absence of the magnetic field was first analyzed under a feed velocity of 0.02 m/s. In this simulation, only one batch of particles was released along the x-axis at y = 15 mm. The results in Fig. 8 indicate that for particles released from different position coordinates (x, y), the presence of pulsating flow would increase their travel length in all circumstances. For example, for a particle released from (1.45, 15), the travel length increased from 29 mm to 68 mm when the pulsating stroke increased from 0 to 14 mm, and it increased even larger from 29 mm to 110 mm when the pulsating frequency increased from 0 to 12 r/s. Theoretically, the increment in travel length would increase the

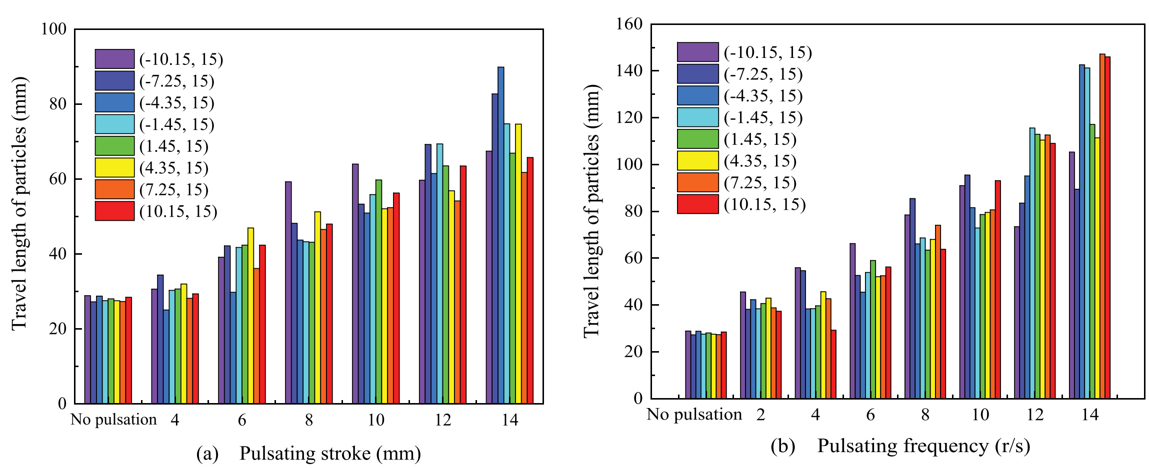

Figure 8. Effect of (a) pulsating stroke and (b) pulsating frequency on travel length of particles in the absence of magnetic field.

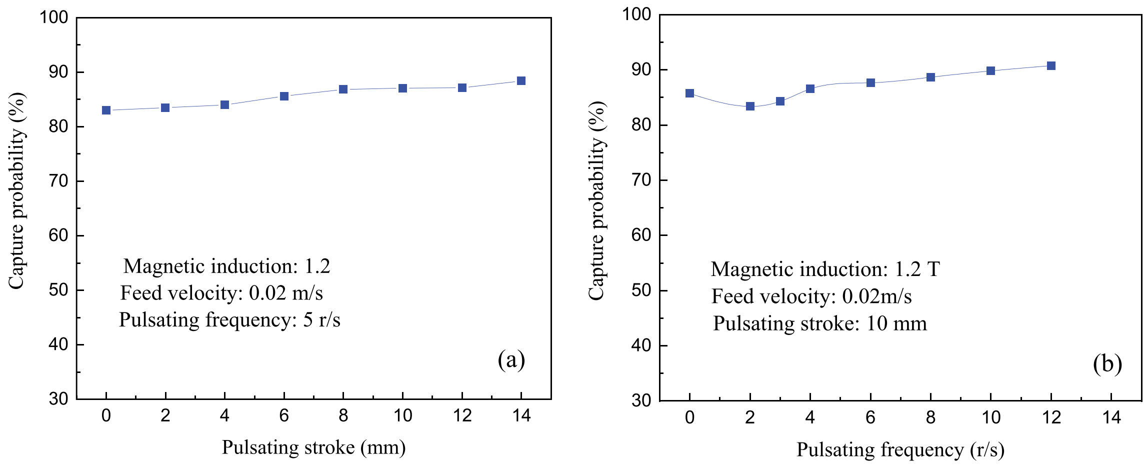

Figure 9. Effect of (a) pulsating stroke and (b) pulsating frequency on capture probability of particles.

probability of particles passing through attractive regions around the matrix, thereby increasing their capture probability.

The effect of pulsating flow on particle capture probability was investigated under a background magnetic field of 1.2 T and a feed velocity of 0.02 m/s. As shown in Fig. 9a, a minor increment in capture probability was observed as the pulsating stroke increased when the pulsating frequency was fixed at 5 r/s. A similar trend was also found for pulsating frequency when the pulsating stroke was fixed at 10 mm, as shown in Fig. 9b.

According to our general understanding, the introduction of a pulsating flow would increase the fluid velocity and bring a larger drag force for particles. As a result, the selectivity would be enhanced while the recovery would drop. However, the findings from Fig. 9 suggest that fine particle recovery could also be improved by increasing the strength of the pulsation flow. As a matter of fact, in our recent research, an ultra-fine ilmenite tailing was found to get a high recovery as well as a high TiO_2 grade under relatively high pulsating stroke and frequency.[14] It is important to note that the results obtained in this study represent idealized conditions and focus only on the initial stage of particle buildup on the magnetic matrix. While the simulation results provide valuable insights, further research is required to determine whether this strategy is suitable for all types of fine ores and under which specific conditions it is most effective.

Conclusions

In this study, a 2D simulation model was established in COMSOL Multiphysics to study the magnetic field characteristics, flow field distribution, and particle capture dynamics in the PHGMS system. Quantitative comparisons were carried out between single-wire and multi-wire system in the presence and absence of the pulsating effect. The main conclusions were as follows:

(1) Compared with the magnetic field distribution in a single-wire PHGMS system, a coupled effect was found in a multi-wire PHGMS system: the magnetic field strength (*H*) around an individual matrix would slightly drop due to the effect of neighboring matrix, but the magnetic gradient (*gradH*) showed the opposite trend, resulting in a very close value of magnetic field force (*HgradH*).
(2) Compared with the flow field distribution in a single-wire PHGMS system, the fluid channel in the multi-wire system was squeezed and became narrower, which resulted in higher fluid velocity around the matrix.
(3) In the multi-wire PHGMS system, the introduction of pulsating flow would bring a higher peak value of fluid velocity and give the particles a chance to move up and down, thereby increasing their travel length and capture probability by wires.

The results of this simulation work were consistent with previous experimental studies. They explained the high recovery for ultra-fine ilmenite tailing under highly pulsating flow and provided a novel strategy for the highly efficient recovery for fine, weakly magnetic materials.

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Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Nourhan Ahmed: Data curation, investigation, writing – original draft preparation
Zixing Xue: Methodology, writing – review and editing
Yaxiong Jiang: Methodology, investigation
Ai Wang: Resources, writing – review and editing
Luzheng Chen: Conceptualization, resources, supervision, funding acquisition

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