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Enhancing PHGMS performance for recovery of ultra-fine ilmenite from tailings

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Abstract: In southwest China, the Panzhihua area annually produces about 80 million tons of tailings with a TiO_2 grade of around 5.0%, which causes serious waste of titanium resources as well as environmental and safety issues. The ilmenite contained in these tailings is ultra-fine in size, so it is difficult to recover under the regular operating conditions of pulsating high gradient magnetic separation (PHGMS). In this study, an SLon-100 PHGMS separator was applied to concentrate an ultra-fine titanium tailing under a wide range of operating conditions. The experimental results indicated that a combination of high pulsating frequency, large pulsating stroke, and low feed velocity was favorable for the highly efficient recovery of ultra-fine ilmenite from the tailings. The TiO_2 grade in the optimal concentrate was enhanced from 4.33% to 13.64%, at a recovery of 66.55% and an enrichment ratio of 3.15 through a one-stage PHGMS process. The size analysis of the optimal concentrate showed that the TiO_2 recovery in -25+18 μm and -18+10 μm fractions exceeded 70%. To further understand this PHGMS performance, the optimal ultra-fine ilmenite and larger-size ilmenite concentration conditions were compared. This study provides a valuable reference in the PHGMS operation for recovering ultra-fine weakly magnetic minerals, including ilmenite.

Keywords: pulsating HGMS operation, Panzhihua titanium tailings, ultra-fine ilmenite, recovery

1. Introduction

Titanium is a critical metal widely used in industries like aerospace, coatings, medical machinery, and outdoor equipment, and it is mainly extracted from ilmenite ($TiFeO_3$) (Pushp et al., 2022). China owns the world's most significant reserves of ilmenite, and nearly 90% are from the Panzhihua region of Sichuan province, an important vanadium-titanium magnetite resource base in southwest China (Zeng et al., 2017). In the process of preparing ilmenite concentrate, about 80 million tons of tailings with a TiO_2 grade of around 5% were produced annually in the Panzhihua region (Huang et al., 2023). The ilmenite mineral in these tailings was in an extremely fine size, making it hard for further utilization. At present, these tailings are being disposed of directly, leading to substantial resource depletion. Furthermore, increasing the quantity of tailings may give rise to environmental worries and provide safety hazards. Therefore, it is essential to investigate ways to enhance the value of these tailings. Many methods have been reported trying to utilize these titanium tailings, including enhanced gravity separation (Zeng et al., 2017), flocculation (Fan et al., 2020), self-carrier flotation (Zhu et al., 2011), and wet high-intensity magnetic separation (Hu et al., 2023). Although specific studies demonstrated potential in recovering the ultrafine ilmenite from these tailings, they face lower throughput difficulties, production cost problems, and environmental issues pending industrial applications (Zhai et al., 2020).

Pulsating high-gradient magnetic separation (PHGMS) is a highly efficient, economical, and environmentally friendly technology for removing weakly magnetic particles from various ores (Padmanabhan and Sreenivas, 2011; Zeng et al., 2019; Zeng et al., 2019; Xue et al., 2020; Dai et al., 2022).

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However, it is not satisfactory when dealing with this kind of ultra-fine ilmenite tailings under regular operating conditions, just as they operate in the Panzhihua region. The core issue lies in the difficulty of finding a balance between the recovery and selectivity of the concentrate. Generally speaking, a strong magnetic force corresponds to a relatively high recovery but low selectivity, while a strong flow field means a low recovery.

Hence, the breakthrough of this study is to upgrade the ultra-fine ilmenite tailing in Panzhihua by applying a one-stage PHGMS process as well as achieving an appropriate balance between the selectivity and recovery of the concentrate, as compared to previous approaches that required multiple roughing and cleaning processes (Huang et al., 2023; Wu et al., 2023). Moreover, it is common that pilot-scale experiments have shown better results than those observed at industrial scales. These findings highlight the necessity of additional research to enhance the PHGMS process in pilot-scale settings and apply these enhancements for widespread application in the industry.

This study aims to enhance the PHGMS performance for the ultra-fine ilmenite tailings in the Panzhihua region. The experiments were conducted in an SLon-100 PHGMS separator, and such operating parameters as magnetic induction, pulsating stroke, pulsating frequency, feed velocity, and rod matrix diameter were optimized to achieve the highest level of performance. Following that, the optimum operating conditions are compared to larger particles. The findings are an essential reference for summarizing the PHGMS theory, identifying its technological characteristics, and dealing with present problems of separating fine and ultra-fine ilmenite particles.

2. Materials and methods

2.1. Materials

The ultra-fine sample was obtained from the typical tailing stream of vanadium-titanium magnetite ore in the Panzhihua region. The chemical analysis of the sample is shown in Table 1. The tailings sample contains 4.33% TiO_2 and 10.08% Fe. According to the previous research on this type of tailings, ilmenite is the main valuable mineral (Huang et al., 2023). Therefore, the nature of concentrating this tailing is to separate ilmenite from other minerals.

Table 1. Main chemical compositions of material

Elements	TiO_2	Fe	CaO	Al_2O_3	SiO_2	S
Content (%)	4.33	10.08	11.98	14.02	39.90	0.28

The sample was also evaluated by standard sieve analysis. Table 2 shows the relationship between the particle size distribution and the TiO_2 concentration obtained in each fraction. The results show that the yield of -44 μm fine particles in the sample reaches 88.68%, and its TiO_2 distribution rate reaches 95.25%. The three fractions of -25+18 μm, -18+10 μm, and -10 μm contain the higher contents of TiO_2 among the other fractions. The yield of -25 μm was 70.13%, and its TiO_2 distribution was 82.23%. The results show that most of the titanium is dispersed as ultra-fine particles, measuring -25 μm in diameter.

Table 2. Particle size analysis of ilmenite tailing sample

Particle size (μm)	**Yield (%)**	**TiO_2 grade (%)**	**TiO_2 distribution (%)**
+149	2.08	2.88	1.38
-149+74	2.10	1.65	0.80
-74+44	7.15	1.55	2.56
-44+25	18.55	3.04	13.02
-25+18	47.83	5.31	58.65
-18+10	4.43	4.46	4.56
-10	17.87	4.61	19.02
Total	100.00	4.33	100.00

2.2. Cyclic pilot-scale PHGMS separator

The experiments were carried out using a SLon-100 cyclic pilot-scale PHGMS separator. The basic structure of the separator is shown in Fig. 1. The pilot-scale separator is supplied periodically. When the electricity is turned on, a direct current passes through the energizing coils, generating a magnetic field in the separating zone. Firstly, the separating zone is filled with flowing water to transmit the pulsating energy to the separating zone. The valve below the pulsating mechanism adjusts the water level and flow rate. Then, the slurry is fed into the matrix in the separating zone through the feed box. Magnetic particles are attracted from the slurry onto the surface of the matrix. Meanwhile, nonmagnetic particles pass through the matrix and go out through the product box as tailings under slurry pulsation, gravity, and hydrodynamic drag combined. The pulsating mechanism drives the slurry in the separating zone to move up and down. As a result, it retains the particles in the matrix in a loose state, allowing magnetic particles to be captured more easily by the matrix and nonmagnetic particles to be dragged out more easily. More detailed information on the operating steps of this separator has been described by (Chen et al., 2017).

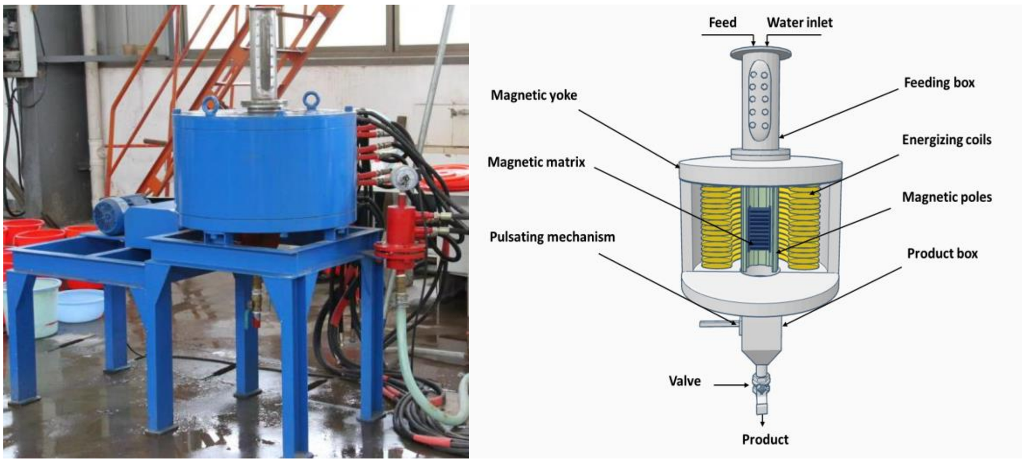

Fig. 1. Structure diagram of SLon-100 cyclic pilot-scale PHGMS separator

2.3. Experimental Approach

In each batch of tests, 200 g of sample was appropriately mixed with 1000 cm^3 of water in a stirrer for 5 min to ensure that mineral particles were uniformly distributed. The slurry was then fed to the SLon-100 separator. Magnetic particles were attracted from the slurry to the rod matrix, while non-magnetic particles left the separate zone to become tailings. The concentrate and tailing were filtered, dried, weighed, and chemically analyzed for TiO_2 grade and recovery. The impacts of major influencing parameters such as background magnetic induction, pulsating stroke, pulsating frequency, feed velocity, and magnetic wire diameter of rod matrix on the TiO_2 grade and recovery were thoroughly investigated. The test data was analyzed to establish the best technical parameters for high-gradient magnetic separation.

3. Results and discussion

3.1. Effect of background magnetic induction

The background magnetic induction significantly affects the PHGMS process by producing the magnetic force required to separate particles. In order to investigate the impact of the background magnetic induction on the selectivity of ultrafine ilmenite from tailing, the PHGMS process was carried out with a pulsating frequency of 300 rpm, a pulsating stroke of 5.0 mm, a feed velocity of 4.0 cm/s, and a rod matrix of 2.0 mm. The choice of the studied operating parameters is based on the previous research, relevant literature, and the actual constraints of the PHGMS unit. The previous investigations generally utilise a background magnetic induction ranging from 0.4 to 1.4 T, pulsating frequencies between 100 and 450 rpm, pulsating strokes of 4.0 to 14 mm, feed velocities of 1.0 to 8.0 cm/s, and rod diameters of 1.0 to 3.0 mm. As shown in Fig. 2, the TiO_2 recovery increased when background magnetic field induction increased from 0.4 T to 1.6 T, whereas the TiO_2 grade showed a slight decrease in the concentrate product under the same conditions. At low background magnetic induction, the PHGMS separator mainly captured larger ilmenite particles, which resulted in a lower recovery; increasing the background magnetic induction leads to additional low-grade intergrowth particles brought into the concentration, which means increasing the concentration's recovery but decreasing the TiO_2 grade. Consequently, the background magnetic induction of 0.8 T was preferred for optimal concentration.

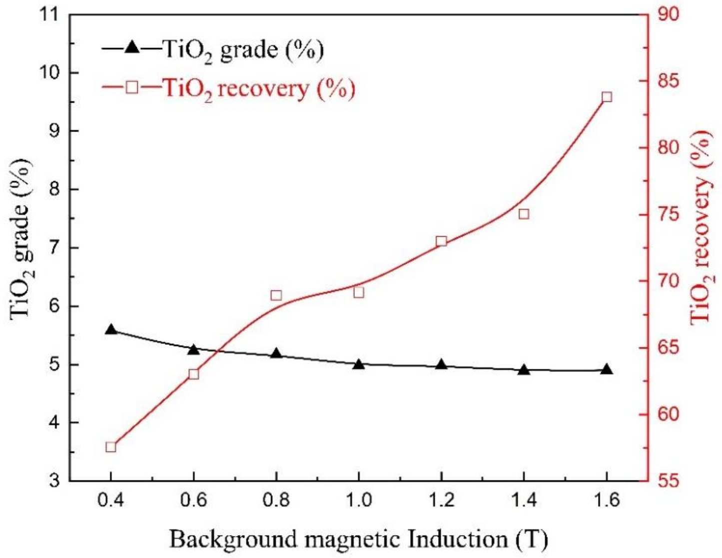

Fig. 2. Effect of background magnetic induction on PHGMS performance

It is well known that, in the PHGMS process, the main forces affecting the particles are the magnetic, gravitational, and drag forces (Yavuz et al., 2006; Zheng et al., 2015). As the particle size decreases, the effect of some forces can be reduced compared to other dominant forces. The magnetic force (Fm) applied on a spherical particle of radius R when subjected to a magnetic field H is given by Eq. (1) (Zheng et al., 2019):

$$Fm = \frac{4}{3}\pi R^3 \mu_0 \kappa H \overrightarrow{\nabla H} \tag{1}$$

where μ_0 is the vacuum permeability, κ is the particle magnetic susceptibility, and ∇H is the magnetic field gradient. According to Eq. (1), the magnetic force is directly proportional to the third power of the particle radius. As a result, the magnetic force exerted on particles decreases significantly as the particle size decreases, making it challenging to recover ultra-fine particles. The drag force and gravitational force are given by Eqs. (2) and (3) (Zheng et al., 2015):

$$F_d = 6\mu\eta R\nu \tag{2}$$

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

where η represents fluid viscosity, ν represents particle-fluid velocity, ρ_p and ρ_l represents the density of the particle and the fluid, and g represents gravitational acceleration. The drag force applied on the particle is directly proportional to the particle radius, as indicated in Eq. (2). Therefore, with the decrease in particle size, the drag force is more dominant than the magnetic force within a specific condition. Considering the gravity force, the drag force acting on ultra-fine particles ranging in size from 1 μm to 30 μm is more significant than the gravitational force, according to (Zheng et al., 2015). According to the theoretical equations and experimental results, increasing the magnetic induction within the studied range has a minimal impact on the grade of the concentrate compared to the effects of other factors linked to the drag force.

3.2. Effect of pulsating stroke

The effect of pulsating stroke of a PHGMS separator on separation performance was studied at a fixed background magnetic induction of 0.8 T, pulsating frequency of 200 rpm, feed velocity of 4.0 cm/s, and rod diameter of 2.0 mm. Figure 3 shows the separation results of the PHGMS separator for recovering ultra-fine ilmenite ore as a function of pulsating stroke.

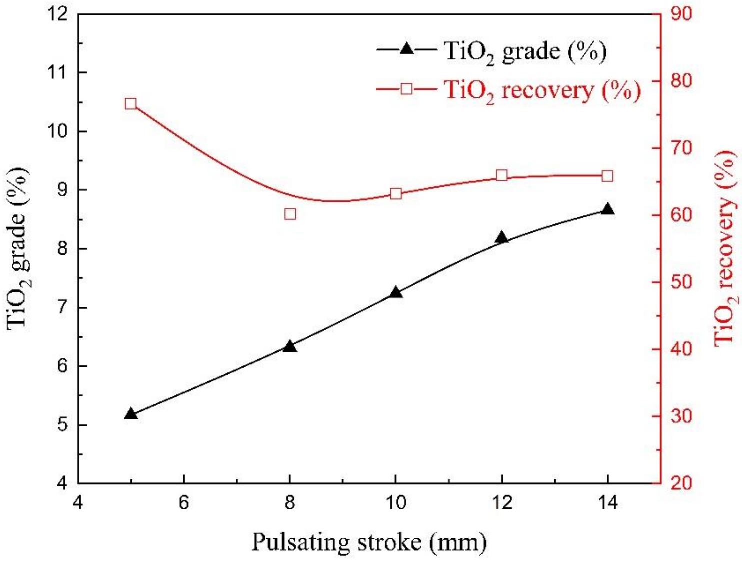

Fig. 3. Effect of pulsating stroke on PHGMS performance

According to Fig. 3, increasing the pulsation stroke had a notable positive impact on the TiO_2 grade, without causing a significant decrease in the TiO_2 recovery in the concentrate. The increase in the TiO_2 grade was easy to understand because increasing the pulsating stroke would cause an increase in the fluid competitiveness to particles, which helps to sweep more gangue minerals into tailings. Generally speaking, increasing the pulsation stroke may result in a decrease in recovery. However, the findings in Fig. 3 indicated that an increase in the pulsating stroke would also support the continuation of a rather high recovery within the range of 14 mm. Increasing the pulsation stroke increased the particle distance traveled within the separation zone (path length) as well as the actual time spent passing through the matrix (residence time), resulting in a higher probability of capturing ilmenite particles into the magnetic matrix (Xiong et al., 1998). Increasing the path length might improve the chance of magnetic particles attaching to the matrix, particularly when dealing with very fine particles that may need more time to be trapped. It is not just based on the distance particles travel but also on how much time they are subjected to the system's competing forces. Increasing the residence time also provides more extensive contact between particles and the magnetic matrix, potentially enhancing the separation efficiency. Therefore, the highest performance of PHGMS for ultrafine particles was achieved at a relatively higher pulsating stroke of 14 mm.

3.3. Effect of pulsating frequency

The influence of pulsating frequency on the performance of the PHGMS separator was also investigated at 0.8 T background magnetic induction, 14 mm pulsating stroke, 4.0 cm/s slurry velocity, and 2.0 mm rod matrix diameter, as seen in Fig. 4.

According to Fig. 4, increasing the pulsating frequency could significantly improve the TiO_2 grade of the concentrate. By increasing the pulsating frequency from 100 rpm to 400 rpm, the TiO_2 grade of the concentrate increased from 5.79% to 10.33%, while the TiO_2 recovery slightly decreased from 67.71% to 58.89%. Increasing the pulsating frequency led to increases in the pulsating energy in the separation zone of the PHGMS process. To improve the separation selectivity and eliminate the mechanical entraining of nonmagnetic particles, the pulsating energy must be sufficiently high to allow the slurry in the separating zone to move up and down and produce a relaxing effect on the particles in the matrix. However, when the pulsating frequency reaches high levels, the recovery is slightly reduced because some particles were swept into tailings by excessive hydrodynamic force (Zheng et al., 2019). Although the general belief is that a moderate pulsating frequency is preferred for achieving the optimal concentration, the results show that a higher pulsating frequency of 400 rpm was recommended to achieve a desirable concentration grade and recovery in the PHGMS process for this ultrafine ilmenite tailings.

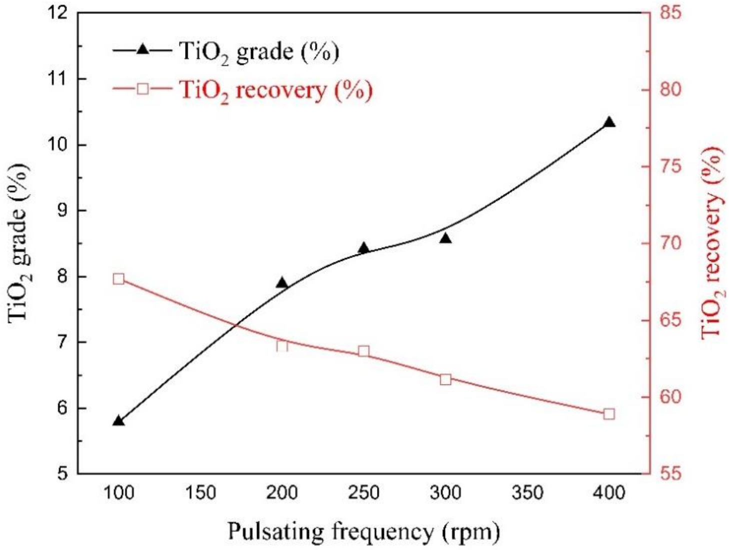

Fig. 4. Effect of pulsating frequency on PHGMS performance

3.4. Effect of feed velocity

In addition to the slurry pulsation, the feed velocity is also a critical factor in the PHGMS separator. It affects the hydrodynamic competitive force acting on particles and reflects the handling capacity of a PHGMS separation system (Chen et al., 2009). Figure 5 illustrates the impact of feed velocity on the separation performance of ultra-fine ilmenite at a fixed background magnetic induction of 0.8 T, a pulsating stroke of 14 mm, a pulsating frequency of 400 rpm, and a rod matrix diameter of 2.0 mm. The results indicated that feed velocity significantly affects the PHGMS performance in recovering the ultra-fine ilmenite. As the feed velocity increases, the grade and recovery of TiO_2 in the concentrate both decrease to varying degrees. This adverse effect of increasing feed velocity on the separation efficiency is due to a shorter period of magnetic particles passing in the separation zone as the feed velocity increases. Consequently, it reduces the number of times particles pass through the separating matrix, which further reduces the probability of capturing particles and affects the recovery. Hence, a feed velocity of 2.0 cm/s was recommended to achieve a desirable concentration grade and recovery in the PHGMS process, for this ultrafine ilmenite tailing.

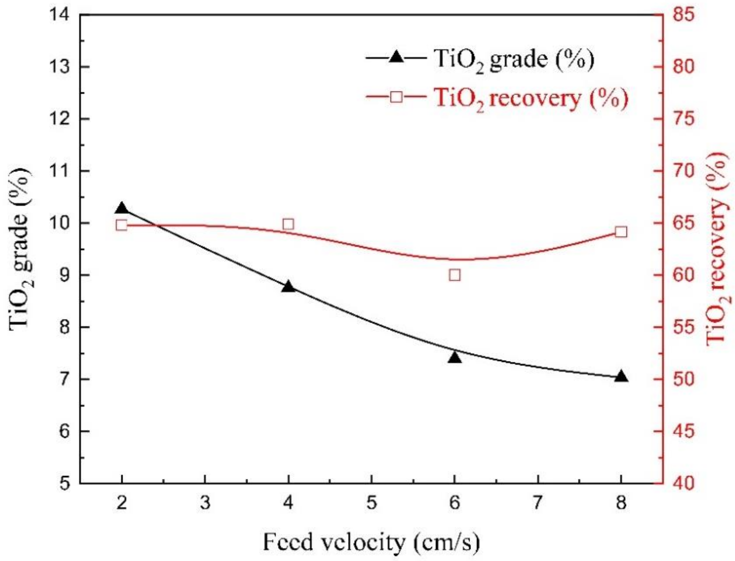

Fig. 5. Effect of feed velocity on PHGMS performance

3.5. Effect of rod diameter

The rod diameter of the matrix determines the magnitude of the magnetic field gradient on the surface of the matrix, which in turn affects the force with which magnetic particles are captured (Zeng et al., 2017). Figure 6 shows the effect of rod diameter on the efficiency of the PHGMS separator for recovering ultra-fine ilmenite at a feed velocity of 2.0 cm/s, a pulsating stroke of 14 mm, and a pulsating frequency of 400 rpm. There was a decrease to varying degrees in the TiO_2 grade and recovery of the concentrate, as the diameter of the rod matrix increased. It is known that there is a correlation between the rod diameter of the matrix and the material's particle size (Liu et al., 2014). A matrix with a smaller rod diameter can provide a significant magnetic field gradient, resulting in a significant magnetic force applied to the particles. Ultra-fine and weak magnetism particles generally experience a lower magnetic force. Hence, employing smaller rod diameters is preferred to enhance the collection efficiency.

Nevertheless, if the wire diameter is excessively small, it can easily distort and block the matrix box. Therefore, the rods employed in industry typically have a diameter of 2.0 mm, whereas a diameter of 1.5 mm is utilized for certain special materials. As illustrated in Fig. 6, ultrafine ilmenite particles could be effectively captured by a matrix with rod diameters of 1.0 mm or 1.5 mm. Considering the slightest difference in TiO_2 grade and recovery of the concentrate, it was more appropriate to choose a rod diameter of 1.5 mm. At this time, the TiO_2 grade of the concentrate could reach 13.64% with a 21.13% yield and 66.55% recovery.

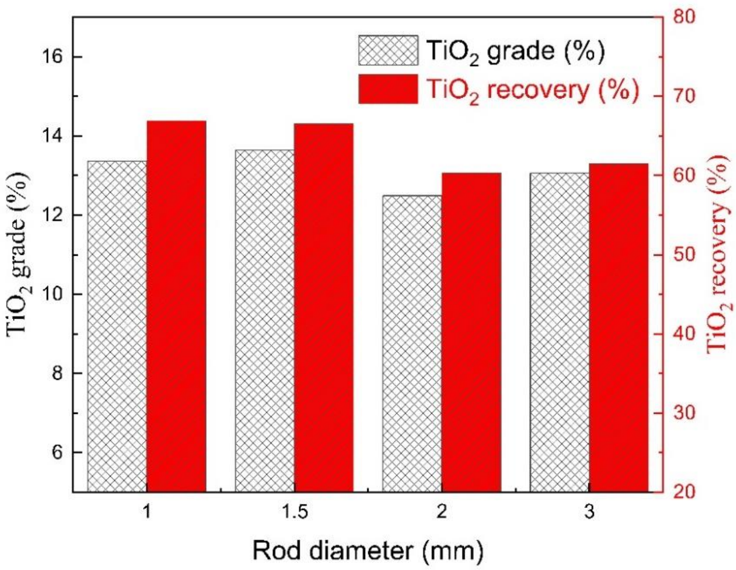

Fig. 6. Effect of rod diameter on PHGMS performance

3.6. Analysis of optimal concentrate product

Based on the results and analysis of the above experiments, it was concluded that a background magnetic induction of 0.8 T, a matrix rod diameter of 1.5 mm, a feed velocity of 2.0 cm/s, a pulsating frequency of 400 rpm, and a pulsating stroke of 14 mm were the optimal separation conditions for recovering the ultra-fine ilmenite tailings from the Panzhihua region. To better understand the separation performance of PHGMS, the chemical analysis and the size analysis of the optimal concentrate product were investigated, and the results are shown in Tables 3 and 4, respectively. The concentration result exhibited an improvement in the TiO_2 and Fe grades, compared to the original feed. The contents of TiO_2 and Fe in the feed were 4.33% and 10.08%, respectively. According to Table 3, the two values have improved to 13.64% and 18.47%, with enrichment ratios of 3.15 and 1.83, respectively.

The particle size analysis of the optimal concentrate product at different size fractions is shown in Table 4. With an overall yield of 21.13% and a TiO_2 grade of 13.64%, PHGMS effectively recovered ultra-fine ilmenite under optimal conditions. Table 4 shows that the yield of particles with a size of -44 μm in the optimal concentrate reached the highest level of 87.37%, while the TiO_2 distribution reached 94.74%. Among them, the yields of the three particle sizes -25+18 μm, -18+10 μm, and -10 μm, -18+10 μm, were respectively 48.97%, 5.78%, and 17.31%, while the corresponding TiO_2 distributions were 63.15%, 6.62%, and 14.02%. The grade of TiO_2 in the concentrate was markedly higher than in the feed, and the recoveries for particle sizes of -25+18 µm and -18+10 µm were above 70%.

Table 3. Chemical analysis of optimal concentrate product

Element	TiO_2	Fe	CaO	Al_2O_3	SiO_2	S
Content (%)	13.64	18.47	8.25	8.20	30.36	0.26

Table 4. Size analysis of optimal concentrate product

Particle size (µm)	**Yield (%)**	**TiO_2 grade (%)**	**TiO_2 distribution (%)**	**TiO_2 recovery (%)**
+149	3.78	4.65	1.29	62.12
-149+74	2.29	5.90	0.99	82.54
-74+44	6.56	6.18	2.97	77.29
-44+25	15.31	9.76	10.95	56.00
-25+18	48.97	17.59	63.15	71.64
-18+10	5.78	15.63	6.62	96.64
-10	17.31	10.45	14.02	49.05
Total (concentrate)	100.00	13.64	100.00	66.55

3.7. Evaluation of PHGMS Separator

To better understand the performance of PHGMS in recovering ultrafine particles, the operating strategy in this work was compared with that in another study dealing with a larger size titanium tailing (Huang et al., 2023). Both samples were subjected to a single rougher stage of the SLon-100 PHGMS separator to recover the ilmenite particles from the Panzhihua tailing product. Table 5 presents a comparison of the detailed operating conditions and indexes of the optimal concentrates between these two studies.

Table 5. Comparison between optimal concentrate of ultrafine ilmenite and larger size ilmenite

Feed		**Optimal concentrate**			**Optimized conditions**
Particle size (µm)	**TiO_2 grade (%)**	**TiO_2 grade (%)**	**TiO_2 recovery (%)**	**Enrichment Ratio***	
–44 µm 88.68%	4.33	13.64	66.55	3.15	Magnetic induction 0.8 T Rod diameter 1.5 mm Feed velocity 2.0 cm/s Pulsating frequency 400 rpm Pulsating stroke 14 mm
–74 µm 35.38%	4.65	8.26	51.37	1.78	Magnetic induction 0.7 T Rod diameter 3.0 mm Feed velocity 5.0 cm/s Pulsating frequency 200 rpm Pulsating stroke 8.0 mm

* *Enrichment Ratio: TiO_2 grade of concentrate / TiO_2 grade of feed.*

According to Table 5, the key points are as follows:

- The PHGMS separator effectively separates ultra-fine and larger-size ilmenite particles from the tailing when certain conditions are met. It improved the TiO_2 grade to 13.64% in the optimal ultra-fine concentrate, at a 3.15 enrichment ratio and 66.55% recovery. Under various PHGMS operating conditions, the TiO_2 grade in the optimal larger size concentrate was enhanced by a 1.78 enrichment ratio and a 51.37% recovery.

- The results highlight the distinct condition requirements for the optimal separation of ultra-fine and larger ilmenite particles from the tailing; for instance, the ultra-fine ilmenite particles require higher magnetic induction than larger ones. A 3.0 mm rod diameter gave the best results for the larger-size ilmenite, while a 1.5 mm rod diameter gave the best results for ultra-fine ilmenite.
- The feed velocity plays a significant role in achieving optimal separation; a lower feed velocity is preferred for the optimal separation of ultra-fine ilmenite, while a higher feed velocity is preferred for the larger-size ilmenite.
- In our conventional recognitions, ultra-fine weak magnetic ore matches a relatively mild pulsating strength to avoid the vast loss of valuable minerals. However, the results from this investigation gave us a new strategy: by combining a low feed velocity with strong pulsating strength, the ultra-fine ilmenite is better recovered.

Overall, ultra-fine ilmenite could be recovered from the Panzhihua tailing under different conditions. Higher pulsating strength and lower feed velocity significantly improved the TiO_2 concentrate grade and recovery. Likewise, adjusting the flow field conditions is necessary to enhance the recovery of ultra-fine ilmenite. Further research is warranted to delve into the underlying mechanism influencing the separation performance and to explore additional avenues for optimizing the process.

4. Conclusions

The current research seeks to enhance the performance of a PHGMS separator employed to beneficiate ultra-fine titanium tailings from the Panzhihua region of China. An optimal concentrated product with a TiO_2 grade of 13.64% and a TiO_2 recovery of 66.55% was obtained during one rougher PHGMS separation process at 0.8 T magnetic field strength, 1.5 mm matrix rod diameter, 2.0 cm/s feed velocity, 400 rpm pulsating frequency, and 14 mm pulsating stroke. Size analyses on the optimal concentrate product indicated that the recoveries for particle sizes ranging from -25+18 μm to -18+10 μm both exceed 70%. A comparison of the operating strategy between this study and another study, which dealt with coarser titanium tailing from the Panzhihua region, indicated that a combination of high pulsating frequency, large pulsating stroke, and low feed velocity was favorable for highly efficient recovery of ultra-fine ilmenite. This study provides a valuable reference in the PHGMS operation for recovering ultra-fine weakly magnetic minerals, including ilmenite.

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References

CHEN, L., LIU, W., ZENG, J., REN, P., 2017. *Quantitative investigation on magnetic capture of single wires in pulsating HGMS*. Powder Technology, 313, 54–59.

CHEN, L., XIONG, D., HUANG, H., 2009. *Pulsating high-gradient magnetic separation of fine hematite from tailings*. Minerals & Metallurgical Processing, 26, 163–168.

DAI, P., YANG, J., WEI, Z., ZENG, J., XUE, Z., CHEN, L., 2022. *Magnetic properties of chalcopyrite and arsenopyrite for high-gradient magnetic separation with Crystal-Field Theory*. Minerals Engineering, 189, 107893.

FAN, G., ZHANG, C., WANG, T., DENG, J., CAO, Y., CHANG, L., ZHOU, G., WU, Y., LI, P., 2020. *New insight into surface adsorption thermodynamic, kinetic properties and adsorption mechanisms of sodium oleate on ilmenite and titanaugite*. Advanced Powder Technology, 31, 3628–3639.

HU, Z., LU, D., ZHENG, X., WANG, Y., XUE, Z., XU, S., 2023. *Development of a high-gradient magnetic separator for enhancing selective separation: A review*. Powder Technology, 118435.

HUANG, H., CHEN, L., XIONG, T., LAI, Q., 2023. *Experimental study on new high gradient magnetic separation process for recovery of ultra-fine ilmenite from titanium tailings in Panxi region*. Metal Mine, 568.

LIU, L., TAN, Q., YUE, T., GUO, Z., LV, L., 2014. *Pre-concentration of ultrafine crushed hematite ores*. Separation of Science and Technology, 49, 1442–1448.

PADMANABHAN, N.P.H., SREENIVAS, T., 2011. *Process parametric study for the recovery of very-fine size uranium values on super-conducting high gradient magnetic separator*. Advanced Powder Technology, 22, 131–137.

PUSHP, P., DASHARATH, S.M., ARATI, C., 2022. *Classification and applications of titanium and its alloys*. Today: Proceedings. 54, 537–542.

WU, L., CHEN, L., WU, N., XIONG, T., ZHANG, B., ZENG, J., LIU, X., 2023. *Experimental comparison between vibrating-pulsating and pulsating high gradient magnetic separators for separating olivine-type low grade ilmenite ore from Panxi area*. The Chinese Journal of Nonferrous Metals, 1–16.

XIONG, D., LIU, S., CHEN, J., 1998. *New technology of pulsating high gradient magnetic separation*. International Journal of Minerals, 54, 111–127.

XUE, Z., WANG, Y., ZHENG, X., LU, D., LI, X., 2020. *Particle capture of special cross-section matrices in axial high gradient magnetic separation: A 3D simulation.* Separation and Purification Technology, 237, 116375.

YAVUZ, C.T., MAYO, J.T., YU, W.W., PRAKASH, A., FALKNER, J.C., YEAN, S., CONG, L., SHIPLEY, H.J., KAN, A., TOMSON, M., NATELSON, D., COLVIN, V.L., 2006. *Low-field magnetic separation of monodisperse* Fe_3O_4 *nanocrystals*. Science, 314, 964–967.

ZENG, J., CHEN, L., YANG, R., TONG, X., REN, P., ZHENG, Y., 2017. *Centrifugal high gradient magnetic separation of fine ilmenite*. International Journal of Minerals, 168, 48–54.

ZENG, J., TONG, X., REN, P., CHEN, L., 2019a. *Theoretical description on size matching for magnetic element to independent particle in high gradient magnetic separation.* Minerals Engineering, 135, 74–82.

ZENG, J., TONG, X., YI, F., CHEN, L., 2019b. *Selective capture of magnetic wires to particles in high gradient magnetic separation.* Minerals, 9, 509.

ZHAI, J., CHEN, P., SUN, W., CHEN, W., WAN, S., 2020. *A review of mineral processing of ilmenite by flotation*. Minerals Engineering, 157, 106558.

ZHENG, X., WANG, Y., LU, D., 2015. *Study on capture radius and efficiency of fine weakly magnetic minerals in high gradient magnetic field*. Minerals Engineering, 74, 79–85.

ZHENG, X., XUE, Z., WANG, Y., ZHU, G., LU, D., LI, X., 2019. *Modeling of particle capture in high gradient magnetic separation: A review.* Powder Technology, 352, 159–169.

ZHU, Y.G., ZHANG, G.F., FENG, Q.M., YAN, D.C., WANG, W.Q., 2011. *Effect of surface dissolution on flotation separation of fine ilmenite from titanaugite*. Transactions of Nonferrous Metals Society of China, 21, 1149–1154.