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Classification techniques and parameter optimization of Cyclone Continuous Centrifugal Separator for hematite ore

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Abstract: The Cyclonic Continuous Centrifugal Separator (CCCS) is a new type of separation equipment developed based on cyclonic continuous centrifugal separation technology and combined with the separation principle of the fluidized bed. Taking hematite as the research object, the main parameters and conditions of the best hematite classification were determined through the classification test by using CCCS. Based on the classification test, the significance order of each process parameter and their interaction with hematite classification efficiency of the underflow products was analyzed with the Response Surface Methodology, the optimal process parameter of hematite classification was obtained and a multiple regression equation was established. The optimized process conditions were as follows, feeding pressure 55.48 kPa, backwash pressure 9.79 kPa, and underflow pressure 31.94 kPa. Under these conditions, the average hematite ore classification efficiency of coarse fraction (-2~+0.15mm), medium fraction (-0.15~+0.074mm) and fine fraction (-0.074mm) were 85.08%, 65.10% and 51.41%, respectively, and the relative errors with the predicted values were 1.6%, 4.0% and 2.5%, respectively. The results showed that the analytical model has good predictive performance. This research provides a certain prospect for the application of Cyclonic Continuous Centrifugal Separation to hematite ore classification. it provides a reference for the application of the Response Surface Methodology in the classification of hematite by Cyclonic Continuous Centrifugal Separation.

Keywords: hematite, Cyclonic Continuous Centrifugal Separator (CCCS), classification, Response Surface Methodology

1. Introduction

Iron is important to the national economy and people's livelihood. It was widely used in electrical, chemical, electronic, military and transportation fields. Hematite is a kind of iron mineral widely distributed in nature. China is rich in hematite resources, mainly distributed in Liaoning, Hebei, Gansu, Anhui, Shanxi, etc. Hematite is a weak magnetic oxide mineral, which is usually enriched by high-intensity magnetic or roasting-magnetic or flotation separation. Generally, hematite ore is successively broken, ground, classified, and separated, usually enriched by high-intensity magnetic or roasting-magnetic separation or flotation.

Gravity separation is a clean and effective method of beneficiation in which centrifugal classification is a method that converts the density difference of ore particles into the sedimentation velocity difference by using a centrifugal force field to achieve the classification of heavy and light minerals (Xie et al., 2018; Ding et al., 2016; You et al., 2017). At present, horizontal centrifuges are widely used in China, while Knelson (Chen et al., 2020) and Falcon (Marion et al., 2017) centrifuges were mainly used abroad. Knelson centrifugal separator has high centrifugal strength, but because of its high price, it is mainly used for the separation of rare and precious metal minerals (Wen 2016), Falcon centrifuge has high enrichment ratio, small water and power consumption, and can effectively deal with micro-fine particles. It is mainly used for preselection and scavenging (Liu et al., 2015). Compared with gravity separation, flotation, and magnetic separation equipment, centrifugal separation equipment has the

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advantage of simple operation, low operating cost, environmental friendliness, and high enrichment ratio. But on the whole, the centrifugal separator still has the disadvantage of small processing capacity, and it is mostly used for the separation of precious metals or tin ore with a small precision mineral rate, and it was rarely used for the treatment of ores with a high yield of heavy minerals, such as hematite ore. Therefore, the development of new classification or separation equipment and technology has become increasingly important.

The Cyclonic Continuous Centrifugal Separator (CCCS) developed by Kunming University of Science and Technology was based on the comprehensive action of the centrifugal force field formed by the spin of pulp and backwash resistance, which can discharge the light minerals and heavy minerals from the overflow pipe and sedimentation cone respectively, thus realizing continuous separation or classification of materials (Xie et al., 2018). The new equipment overcomes the disadvantages of intermittent operation and small processing capacity of the horizontal centrifuge and realizes continuous operation with large processing capacity and convenient operation and maintenance.

The effects of multiple factors on the classification efficiency of hematite ore were studied in the experiment, so an appropriate tool should be applied to analyze this process. Response Surface Methodology (RSM) is a statistics-based approach to calculate the best results within a possible application area or to better understand any response controlled by a multivariable. The RSM has the advantage of being able to assess the likelihood of interaction between factors in the experimental region, determine the best response based on different priorities, and ultimately develop an available data model with minimal experimental labor.

In this paper, CCCS was used to study the influencing factors of hematite classification, and the test results were analyzed by the RSM to optimize the process parameters (Xie and Zhou, 2012; Wang et al., 2014). Finally, the classification test of hematite with different size fractions was carried out and a better index was obtained according to the optimized process parameters. This study provides a research basis for Response Surface Method to guide the CCCS for efficient separation of hematite.

2. Materials and methods

2.1. Experimental materials

The hematite sample was taken from Dahongshan Mining Company of Kunming Iron and Steel Group concentrator. The raw ore was analyzed by chemical multielement and X-ray diffraction, and the analysis results are shown in Table 1 and Table 2.

Table 1. Major element analysis of hematite ore sample

Ingredient	Fe	SiO_2	Al_2O_3	CaO	MgO	P	S
Content / %	64.12	3.28	1.04	1.53	1.14	0.13	0.09

Table 2. The phase analysis results of hematite ore

Minerals	Hematite	Martite	Magnetite	Siderite	Iron silicate	Pyrite
Content / %	54.40	7.56	4.15	1.46	0.81	0.12
Distribution / %	79.42	11.03	6.06	2.13	1.18	0.18

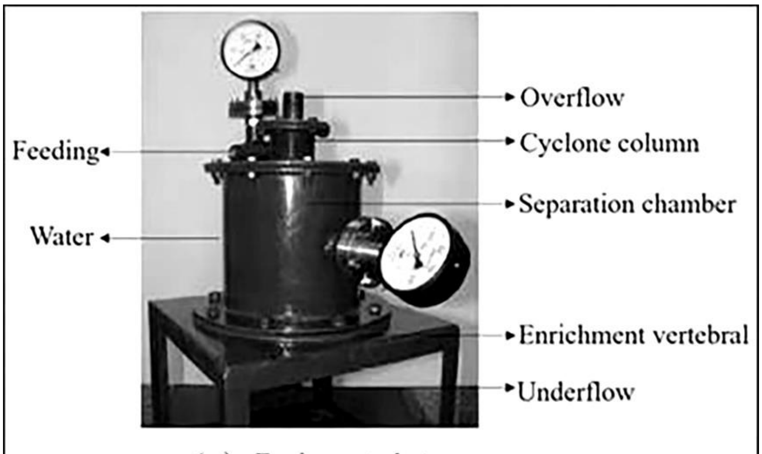
It can be seen from Table 1 that the Fe grade of hematite ore is 64.12%, other gangue components are mainly SiO_2, Al_2O_3, CaO, and MgO. From Table 2, the iron minerals in the raw ore are mainly hematite (54.40%), and gangue minerals are mainly martite, magnetite, and siderite.

In this study, hematite ore below 2 mm was obtained from the raw ore after crushing, grinding, and screening, then a series of specific classification tests were carried out.

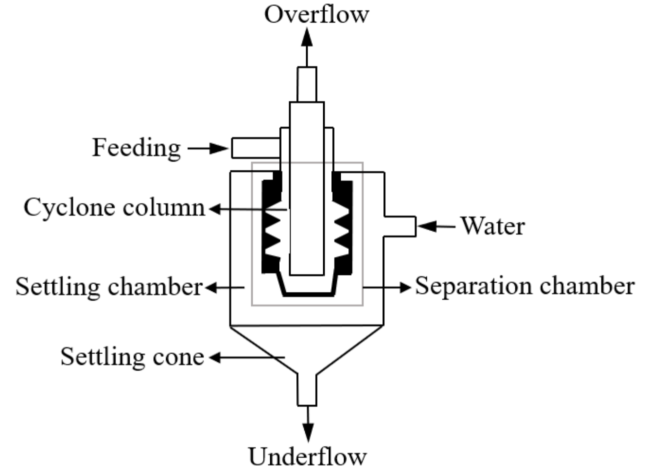
2.2. Test equipment

The main equipment of the test is the Cyclonic Continuous Centrifugal Separator (CCCS) including a tangential feeding pipe, overflow pipe, settlement pipe, cyclone column, sorting chamber, settlement cone, settlement chamber, and other major components (Fig.1). A vertical feeding pump and stirring tank were included in the supporting test equipment. The working principle of the separator is that the slurry is tangentially pumped into the CCCS under a certain pressure. At the same time, by regulating the pressure of the settlement chamber, the ore particles are first settled and separated in the cyclone column, and then they continue to be separated in the separation chamber.

The denser and coarser particles move downward in the axial direction and outward in the radial direction under the action of the cyclone field, and then move down along the conical wall and flow out from the bottom. The particles with less dense and finer grain move to the axis direction and form an upward movement in the inner vortex. With the action of backwash water, the lighter mineral with finer grain is discharged from the overflow port.



（a） Equipment photo



（b） Equipment schematic diagram

Fig. 1. Equipment photo and schematic diagram of Cyclone Continuous Centrifugal Separator

2.3. Experimental methods

2.3.1. Classification experimental

The process diagram of the classification test is shown in Fig.2. The slurry with a concentration of 10% is stirred for 3 minutes in the barrel, and then the slurry is pumped into the CCCS at a certain pressure by the feed pump for classification. The pressures of feeding, overflow, underflow, and backwash are all regulated by the valve. The classification of products is obtained from the overflow port and the underflow port respectively. At the end of each classification test, the overflow and underflow products were filtered, dried, and weighed, and the classification efficiency of hematite ore was calculated. In this study, the underflow products are taken as the object to analyze and calculate the classification efficiency. The mathematical expression of the classification efficiency formula is shown in Equation (1).

$$E = \frac{(\alpha-\theta)(\beta-\alpha)}{\alpha(\beta-\theta)(1-\alpha)} \times 100\% \tag{1}$$

In the formula Equation (1), E is the classification efficiency (%); α is the percentage of the feeding less than a certain grain size (%); β is the percentage of overflow less than a certain particle size (%); θ is the percentage of underflow less than a certain grain size (%).

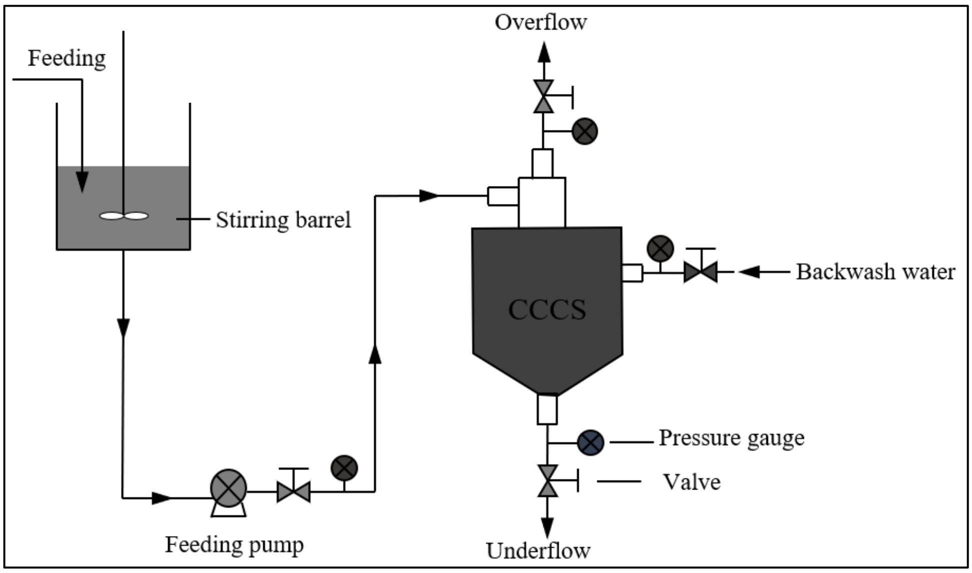


Fig 2. Schematic diagram of classification test process

2.3.2. Analysis of the forces on the ore particles during the classification process

The main forces received by the ore particles at the fluidization holes of the separation chamber of the CCCS are gravity F_g, centrifugal force F_a, centrifugal buoyancy F_b, resistance F_c, backwash resistance F_d, fluid friction resistance F_e, and feeding pressure F_f, etc. The force analysis is shown in Fig.3. The formula of force is shown in Equation (2) to Equation (10).

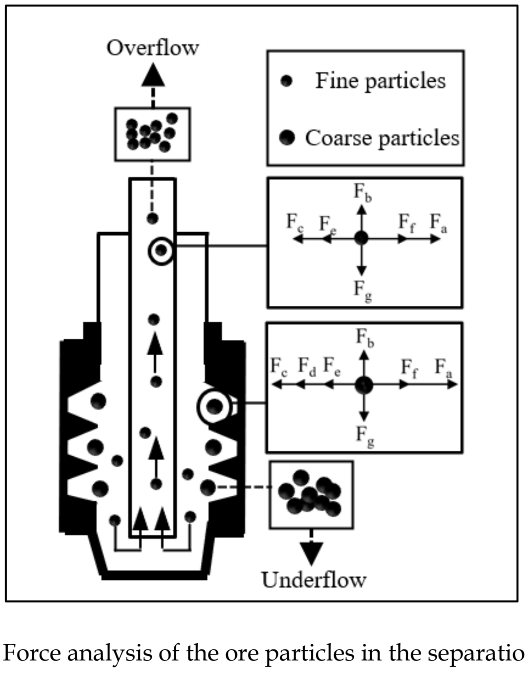


Fig. 3. Force analysis of the ore particles in the separation chamber

- Gravity(Ku et al., 2015):

$$F_g = mg = d_p^3 \rho_s g \tag{2}$$

where m is the mass of mineral grains, kg; g is the gravitational acceleration, m^2/s; d_p is the diameter of mineral grains, m; ρ_s is the density of mineral grains, kg/m^3; g is the weight acceleration, m/s^2.

- Centrifugal force:

Centrifugal force (Zhang et al., 2017) is the main force that mineral particles were subjected to enter the separator. Sufficient centrifugal strength which was used to magnify differences in sedimentation rates of minerals of different densities is the basis of the selective classification of hematite particles. The centrifugal force of the mineral particles moving to the vicinity of the fluidization is:

$$F_a = \frac{\pi}{6} d_p^3 \rho_s \vec{r} \omega^2 \tag{3}$$

where d_p is the diameter of mineral grains, m; ρ_s is the density of mineral grains, kg/m^3;
r is the radius of ore grain, m; ω is the angular velocity of the ore grain when it rotates, rad/s;

- Centrifugal buoyancy(Juan and Francisco. 2020):

$$F_b = \frac{\pi}{6} d_p^3 \rho \vec{r} \omega^2 \tag{4}$$

where d_p is the diameter of mineral grains, m; ρ is the density of the fluid, kg/m^3.

- Resistance(Wen et al. 2006):

$$F_c = \frac{\pi d_p^2}{4} \times \frac{C_d}{2} \rho |\mu_r| \overrightarrow{\mu_r}$$
$$\overrightarrow{\mu_r} = \overrightarrow{\mu_f} - \overrightarrow{\mu_\rho}$$
$$C_d = 24\mu / \left(\rho d_\rho |\mu_r|\right) \tag{5}$$

where d_p is the diameter of mineral grains, m; μ_r is the relative velocity of fluid and mineral particles, m/s; $\mu_f$is the fluid's velocity m/s; $\mu_p$is the mineral particles' velocity m/s; $C_d$is the resistance coefficient; μ is the dynamic viscosity coefficient; ρ is the density of the fluid kg/m^3.

- Backwash resistance:

$$F_d = \rho A v^2 \tag{6}$$

where ρ is the density of the fluid, kg/m^3; A is the positive projection area of mineral particles m^2; v is the backwash velocity m/s.

- The frictional resistance F_e of fluid to ore particles can be obtained by Stokes formula as follows:

$$F_e = 3\pi\mu d v_1 \tag{7}$$

where μ is the dynamic viscosity coefficient; d is the diameter of the ore grain, m; v_1 is the radial relative fluid velocity of the ore grain, m/s.

- Feeding pressure:

$$F_f = \rho A v_2^2 \tag{8}$$

where ρ is the density of the fluid; A is the positive projection area of mineral particles, m^2; v_2 is the feeding velocity, m/s.

According to the force analysis of ore particles in the separation chamber of the separator, the force formula of the X-axis direction can be obtained, as shown below.

Force analysis of particles at fluidization hole： $F = F_a + F_f - F_c - F_d - F_e$ (9)

Force analysis of particles at non-fluidized holes: $F = F_c + F_e - F_a - F_f$ (10)

When $F > 0$, the ore particles can pass through the fluidization hole, then enter the settling chamber and discharge from the underflow port; when $F < 0$, the ore particles cannot pass through the fluidization hole and can be discharged through the overflow.

2.3.3. Response surface Method

RSM is a statistical test method for optimizing stochastic processes (Yong et al. 2020). The objective is to find out the quantitative relationship between experimental indicators and influencing factors, and find the best combination of the levels of each factor to guide experimental research. The design-Expert12 software was used in the test. Through the analysis of feeding pressure, backwash water pressure and underflow pressure in the CCCS, the main factors and horizontal ranges affecting the classification efficiency of hematite beneficiation were determined, and the test results were analyzed for variance. The influence of various factors on the classification of hematite was discussed, and multiple regression fitting and regression models were established. The result is an optimal process parameter that is used to guide experimental studies.

3. Results and discussion

3.1. Single-factor analysis

The preliminary study shows that pressures of feeding, backwash, and underflow are the main factors affecting the classification efficiency of the separator (Li 2017). In this section, the above three influencing factors are discussed in the classification of -2mm hematite ore by the CCCS, and the classification efficiency of -2~+0.15 mm(coarse fraction), -0.15~+0.074 mm(medium fraction), and -0.074 mm(fine fraction) in underflow products is analyzed.

3.1.1. Effect of feeding pressure

The centrifugal strength of the CCCS is determined by the feeding pressure, and a higher feeding pressure can produce a larger centrifugal force so that the ore particles can achieve a better classification effect, while a smaller feeding pressure will form a worse effect relatively (Zong et al. 2018). The experiment was carried out under feeding pressures of 30 kPa, 35 kPa, 40 kPa, 45 kPa, 50 kPa, and 55 kPa respectively with the backwash water pressure being fixed at 15 kPa and the underflow pressure at 30 kPa. The test results are shown in Fig. 4.

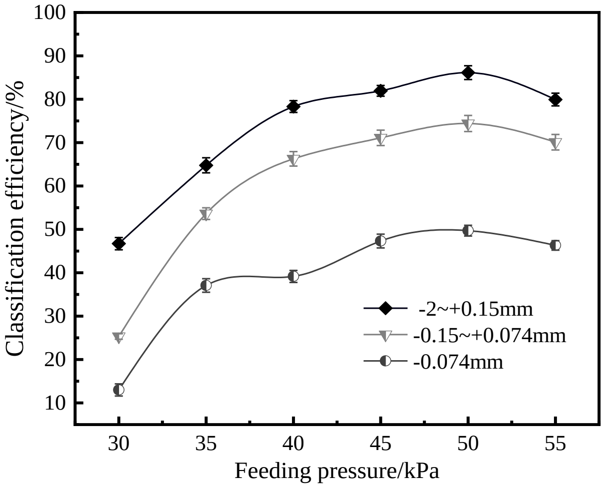


Fig. 4. The influence of feeding pressure on the classification efficiency

As seen in Fig.4, when the feeding pressure increases from 30 kPa to 50 kPa, the classification efficiency of different size fractions is improved. However the feeding pressure continues to increase to 55 kPa, and the classification efficiency of hematite ore in each size fraction gradually decreases, which indicates that higher feeding pressure in a certain range could significantly improve the classification efficiency of hematite. Therefore, the optimum feeding pressure for this test was 50 kPa.

3.1.2. Effect of backwash water pressure

Different size fractions of material are selectively passed through the fluidization hole by backwash water pressure. When the backwash water pressure is large enough, the coarse fraction materials are prevented from passing through the fluidization hole, resulting in a lower yield of coarse fraction materials; on the contrary, if the pressure is too small, part of the fine particles will form underflow. So the backwash water pressure affects its classification effect. The test was carried out with backwash water pressure being at 0 kPa，10 kPa，20 kPa，30 kPa, and 40 kPa, meanwhile, the feeding pressure was 50 kPa and the underflow pressure was 30 kPa. The results are shown in Fig. 5.

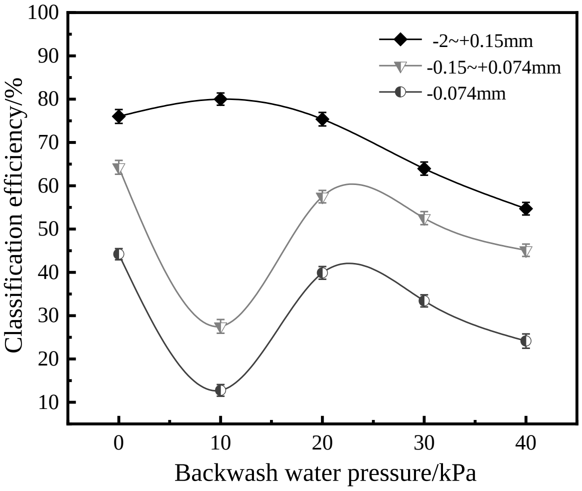


Fig. 5. The influence of backwash water pressure on the classification efficiency

It can be seen from Fig.5, that when the backwash water pressure increases from 0 kPa to 10 kPa, the hematite classification efficiency of coarse fraction (-2~+0.15mm) appears to be an upward trend, while that of medium fraction (-0.15~+0.074mm) and fine fraction (-0.074mm) gradually decreases. When the backwash water pressure continues to rise to 40 kPa, the classification efficiency of each fraction gradually reduces. The results show that the low backwash water pressure is beneficial to the separation between coarse and fine fractions. Therefore, the appropriate backwash water pressure was determined to be 10 kPa.

3.1.3. Effect of underflow pressure

The inner pressure of the CCCS is affected by the underflow pressure. In this part, the effect of underflow pressure on the hematite classification is discussed. The underflow pressure of 23 kPa, 25 kPa, 27 kPa, 29 kPa, 31 kPa, and 33 kPa was conducted respectively with the feeding pressure of 50 kPa and backwash water pressure of 10 kPa. The test results are shown in Fig. 6.

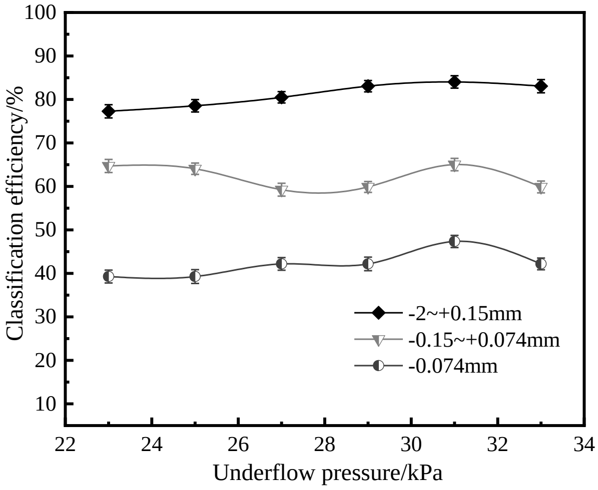


Fig. 6. The influence of underflow pressure on the classification efficiency

As can be seen from Fig. 6, when the underflow pressure was increased from 23 kPa to 31 kPa, the hematite classification efficiency of coarse fraction (-2~+0.15mm) and fine fraction (-0.074mm) were both improved. However, when the underflow pressure continues to increase to 33 kPa, the hematite classification efficiency of three-size fractions was gradually reduced. Therefore, the underflow pressure was chosen to be 31 kPa.

According to the above test results, the optimal classification efficiency of hematite with the parameter being feeding pressure 50 kPa, backwash water pressure 10 kPa, and underflow pressure 31 kPa can be obtained. Under the circumstances, the classification efficiency of coarse fraction, medium fraction, and fine fraction is 84.04%, 65.02%, and 49.35%, respectively.

3.2. Optimization experiment by Box-Behnken response surface method

3.2.1. Model Design

First or second-order polynomial fitting complex nonlinear functional relations are analyzed by RSM, and the nonlinear effects of various factors are expressed through images to explore the optimal design values. The response surface model was usually expressed by a second-order polynomial in engineering applications, and its mathematical expression is shown in Equation (11).

$$\mathrm{Y} = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i\neq j=1}^{n} \beta_{ij} X_i Y_j \tag{11}$$

In the formula, X is the influencing factor variable, i, j are the types of influencing factors, n is the number of influencing factors, and Y is the predicted response value, β_0, β_i, β_{ii}, and β_{ij} represent the offset term, linear offset, second-order offset coefficient, and interaction coefficient, respectively.

Based on the results of the single factor experiments, the feeding pressure(X_1), backwash water pressure(X_2), and underflow pressure(X_3) were selected as independent variables for the Box-Behnken module in Design Expert12. Taking the classification efficiency of hematite in underflow as the response value. The proposed design factors and central combination levels are shown in Table 3.

Table 3. The proposed design factors and central combination levels

Factors	Codes	Unit	Coding Levels		
			-1 (low)	0	1 (high)
Feeding pressure	X_1	kPa	40.0	50.0	60.0
Backwash water pressure	X_2	kPa	5.0	10.0	15.0
Underflow pressure	X_3	kPa	20.0	30.0	40.0

3.2.2. Regression equations and analysis of variance

The test scheme was generated by Design-Expert 12 software, and the hematite ore classification efficiency values under various test conditions are shown in Table 4.

It can be seen from Table 4 that the classification efficiency ranges of hematite with different particle sizes, such as coarse, medium, and fine fractions, are 78.27%-85.14%, 59.56%-65.01%, and 45.26%-52.36%, respectively. The test data in Table 4 was fitted by the method of multivariate quadratic regression response surface fitting.

The quadratic regression equation models (see, E_1, E_2, and E_3) for coarse fraction, medium fraction, and fine fraction are shown in Equations (12), (13), and (14), respectively:

$$\begin{aligned} E_1 = {} & 84.35 + 2.43X_1 + 0.34X_2 + 0.445X_3 - 0.61X_1X_2 - 0.09X_1X_3 \\ & + 0.625X_2X_3 - 2.11X_1^2 - 0.668X_2^2 - 0.853X_3^2 \end{aligned} \tag{12}$$

$$\begin{aligned} E_2 = {} & 64.45 + 1.99X_1 - 0.5263X_2 - 0.0375X_3 - 0.1325X_1X_2 + 0.07X_1X_3 \\ & - 0.8X_2X_3 - 1.48X_1^2 - 0.9527X_2^2 - 0.5753X_3^2 \end{aligned} \tag{13}$$

$$\begin{aligned} E_3 = {} & 51.17 + 1.00X_1 + 0.3238X_2 + 1.23X_3 - 0.12X_1X_2 - 0.6725X_1X_3 \\ & + 0.8125X_2X_3 - 1.29X_1^2 - 1.99X_2^2 - 1.66X_3^2 \end{aligned} \tag{14}$$

Regression analysis of variance was conducted for the hematite classification efficiency model of different size fractions, and the results are shown in Table 5. Where the P-value represents the significance of the fitting model. When $P \leq 0.05$, it is significant, and $P \leq 0.0001$ indicates that the fitting model is highly significant (Yang et al., 2021; Yang et al., 2021). If the regression equation was favorable to the model, there is no defect, so the regression equation can be used to replace the experiment to analyze the experimental results.

Table 4. Factors and level codes and their corresponding test values

No.	Factors			Response values		
	Feeding pressure（kPa）	Backwash water pressure（kPa）	Underflow pressure（kPa）	Classification efficiency/%		
				-2~+0.15（mm）	-0.15~+0.074（mm）	-0.074（mm）
1	40	5	30	78.27	60.57	46.13
2	50	10	30	84.45	64.75	50.79
3	50	5	20	82.58	62.48	46.89
4	60	5	30	84.42	64.73	48.36
5	50	10	30	83.95	63.89	50.16
6	60	15	30	83.65	63.19	49.42
7	40	10	20	78.43	60.56	45.53
8	50	10	30	84.04	65.01	51.97
9	60	10	40	84.16	64.36	49.56
10	40	15	30	79.94	59.56	47.67
11	50	10	30	84.15	63.47	52.36
12	50	15	40	84.32	61.76	49.77
13	40	10	40	79.56	60.16	48.89
14	50	15	20	82.24	63.25	45.26
15	60	10	20	83.39	64.48	48.89
16	50	5	40	82.16	64.19	48.15
17	50	10	30	85.14	65.12	50.56

Table 5. Regression variance analysis of hematite classification efficiency model for each fraction

Products	Coarse fraction（-2~+0.15mm）			Medium fraction (-0.15~+0.074mm）			Fine fraction（-0.074mm）		
Source	Coefficient	F-value	p-value	Coefficient	F-value	p-value	Coefficient	F-value	p-value
Model	84.35	57.76	0.0002	64.45	17.66	0.0005	51.57	10.42	0.0027
X_1	2.43	312.98	<0.0001	1.99	95.98	0.0142	1.00	11.64	0.0113
X_2	0.34	6.14	0.0423	-0.5263	6.72	0.0358	0.3238	1.22	0.3064
X_3	0.445	5.52	0.0642	-0.0375	0.03	0.5587	1.23	17.42	0.0042
X_1X_2	-0.61	9.88	0.0563	-0.1325	0.21	0.0484	-0.12	0.08	0.7809
X_1X_3	-0.09	0.22	0.6569	0.07	0.06	0.8143	-0.6725	4.63	0.0492
X_2X_3	0.625	4.37	0.0746	-0.8	0.05	0.527	0.8125	3.83	0.0911
X_1^2	-2.11	124.22	<0.0001	-1.48	28.08	0.0011	-1.29	10.11	0.0655
X_2^2	-0.668	12.47	0.0096	-0.9527	11.59	0.0614	-1.99	24.12	0.0617
X_3^2	-0.853	20.34	0.0028	-0.5753	4.23	0.0788	-1.66	16.92	0.0045

The data in Table 5 illustrates the P values of regression models for classification efficiency of coarse fraction, medium fraction, and fine fraction hematite are all less than 0.05, indicating that the regression equation is significant and can be used for response prediction and analysis. In terms of a single factor, X_1 and X_2 have a significant influence on the hematite classification efficiency of each fraction, and X_3 has a significant influence on the classification efficiency of fine hematite ($P<0.05$). The interaction term X_1X_2 has a significant effect on the classification efficiency of coarse fraction and medium fraction, and

X_1X_3 has a significant effect on the classification efficiency of fine fraction. The quadratic term X_1^2 has a significant effect on the classification efficiency of coarse and medium fractions, while the other terms are not significant. The larger the F value is, the more significant the influence of each factor is (Yu et al. 2021). The significant effects of various factors and their interaction on the classification efficiency of coarse fraction, medium fraction, and fine-fraction are in the order of $X_1 > X_2 > X_1X_2 > X_3 > X_2X_3 > X_1X_3$, $X_1 > X_2 > X_1X_2 > X_2X_3 > X_1X_3 > X_2X_3 > X_3$ and $X_3 > X_1 > X_1X_3 > X_2X_3 > X_2 > X_1X_2$.

3.2.3. Model reliability analysis

Based on the above analysis, a model plausibility analysis was performed according to the Box-Behnken module in Design Expert12 software to check the accuracy of the model and the feasibility of the optimized test conditions. The results are shown in Table 6 and Fig.7.

Table 6. Correlation coefficient and feasibility analysis of the model

Model	F-value	P-value	R^2	adj. R^2
Coarse fraction(-2~+0.15mm)	57.76	0.0002	0.9867	0.9696
Medium fraction(-0.15~+0.074mm）	17.66	0.0005	0.9578	0.9036
Fine fraction （-0.074mm）	10.42	0.0027	0.9305	0.8412

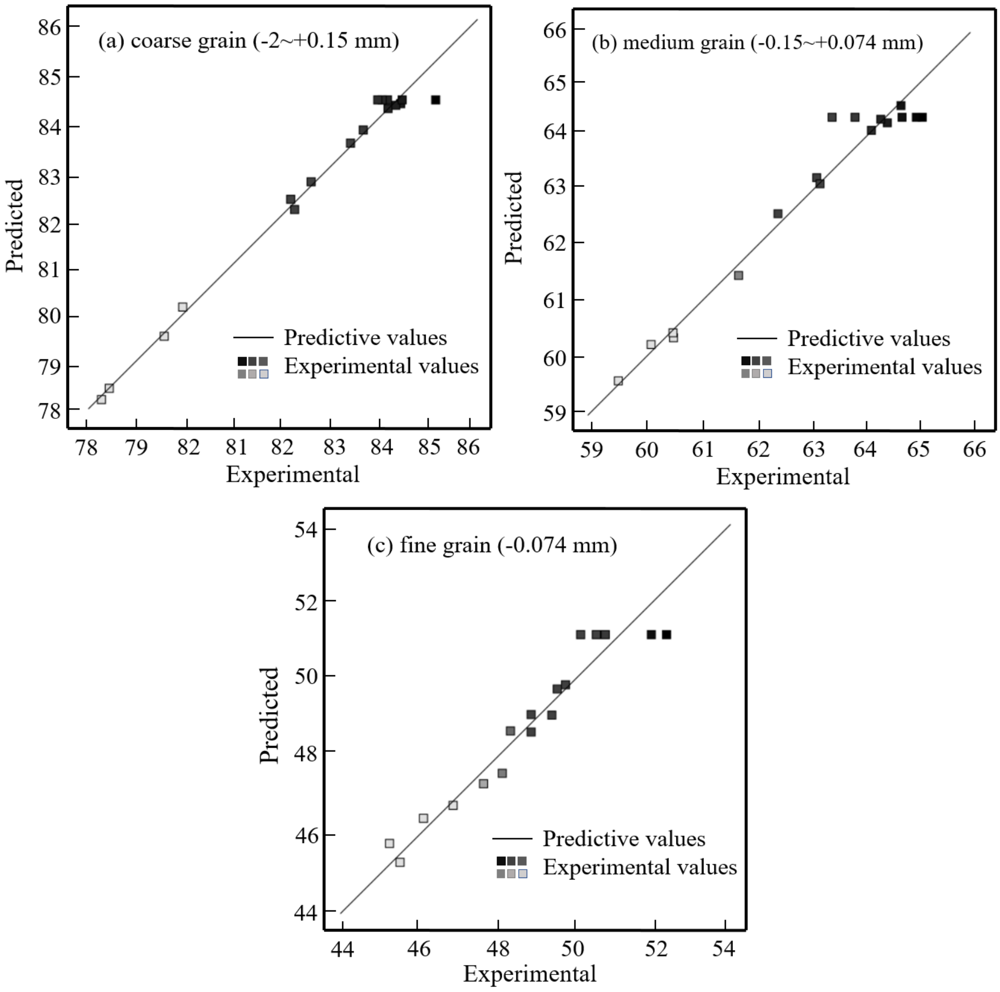


Fig. 7. Comparison of experimental and predicted values of hematite ore classification efficiency of different size fractions

The confidence analysis diagram of the quadratic regression equation for hematite classification efficiency of coarse fraction, medium fraction, and fine fraction is shown in Fig. 7 (a), (b), and (c), respectively.

The straight lines in the figure are fitted predicted values, and the experimental values are evenly distributed near the fitted line, with most points are located on the fitted line. The expected model and experimental fit are shown to be feasible, and the results can be effectively predicted (Liao et al. 2016; Mohammed and Kadhum 2021). Besides, As shown in Table 6, the correlation coefficient value of the regression equation for classification efficiency of the coarse, medium, and fine fractions is R_1^2=0.9867, R_2^2 =0.9578, and R_3^2 =0.9305, and the correction coefficient value is R_{1adj}^2 =0.9696, R_{2adj}^2 =0.9036, R_{3adj}^2=0.8412, respectively. All of them are close to 1, so the accuracy of the model was further verified, and the feasibility of applying the response surface method to optimize hematite classification conditions of various size fractions was also demonstrated.

3.2.4. Evaluation of influencing factors

The graph of the RSM method is a three-dimensional spatial graph and a contour map on a two-dimensional plane composed of factors corresponding to the specific response value (classification efficiency). This typical graph can intuitively reflect the influence of each factor on the response value (Wang et al. 2022). The interaction strength between the two factors is directly reflected by the contour shape, and it is represented as insignificant by a circle and significant by an ellipse. The interaction between the factors is directly reflected in the 3D surface plots, and the steeper the curve indicates the better the interaction between the factors. The model graph function in Design-Expert 12.0 software is used to conduct response surface analysis on the regression model. According to the test results in Table 4, the response surface diagram and contour diagram of the three size fractions of the interaction between feeding pressure, backwash pressure, and underflow pressure on hematite classification efficiency of each fraction was obtained, as shown in Fig 8.

As can be seen from Fig 8 (a), when the underflow pressure was 30 kPa, the curve corresponding to feeding pressure was steeper than that of backwash water pressure, indicating that the influence of feeding pressure on the classification efficiency of coarse hematite is more significant than that of backwash water pressure.

From Fig 8 (b), when the underflow pressure was 30 kPa, the change of the curve corresponding to the feeding pressure is greater than that corresponding to the backwash water pressure, and the feeding pressure has a more significant impact on the classification efficiency of medium fraction hematite than the backwash pressure.

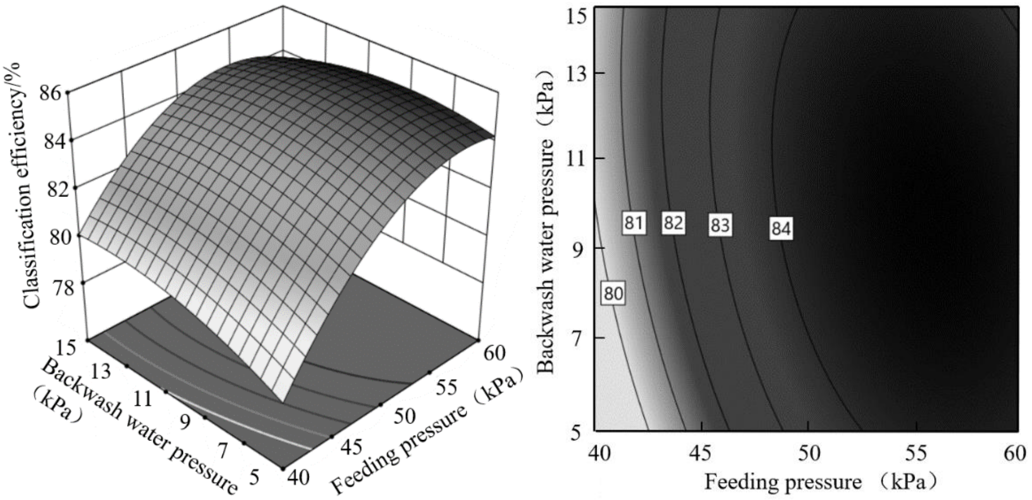
It can be seen from Fig 8 (c) that when the backwash water pressure was 10 kPa, the trend of less change in the rising classification efficiency of fine fraction hematite was presented as the pressure at the underflow was gradually increased, and the rising amplitude was greater than the change in the feeding pressure. The influence of the underflow pressure on the classification efficiency of fine fraction is more significant than that of the feeding pressure.

3.3. Optimal conditions after optimization and actual verification test

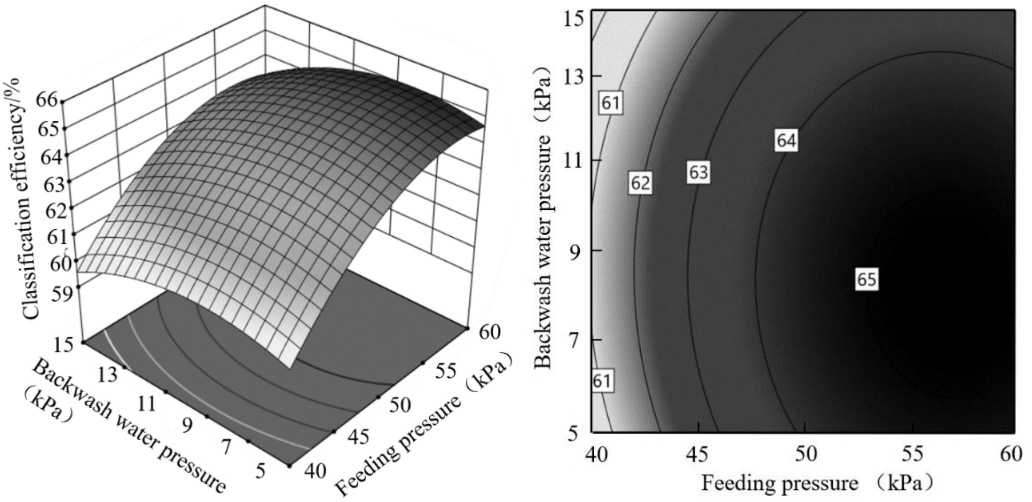
The numerical module in Design-Expert12 software is use d to optimize the test analysis and the optimal conditions for the hematite classification of each fraction are as follows: feeding pressure of 55.48 kPa, backwash water pressure of 9.79 kPa, and underflow pressure of 31.94 kPa. It is predicted that the hematite classification efficiency of coarse fraction, medium fraction and fine fraction is 85.08%, 65.10%, and 51.41%, respectively.

To verify the accuracy of the prediction model, further experiments were carried out under the optimized parameters. The predicted and actual results of hematite classification efficiency for each fraction under the optimized test conditions are shown in Table 6.

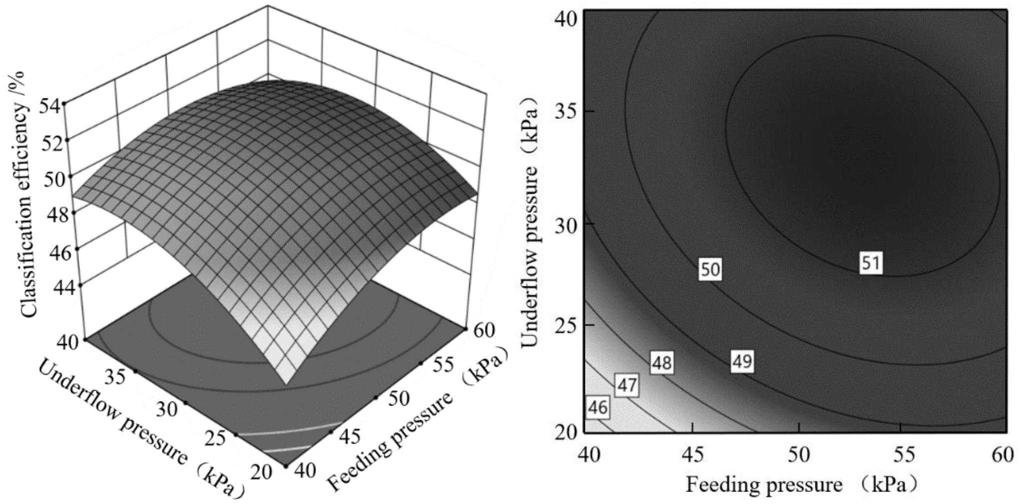
As can be seen from Table 6, the average value with three tests of hematite classification efficiency of the coarse fraction, medium fraction, and fine fraction are 86.46%, 67.79%, and 52.72%, moreover, the relative errors are 1.6%, 4.0%, and 2.5%, respectively. Compared with the predicted value, the actual value indicates that the established model is reliable and can effectively optimize the hematite classification and improve the classification efficiency of hematite ore.



(a) Effect of feeding pressure-backwash water pressure on the classification efficiency of coarse fraction hematite



(b) Effect of feeding pressure-backwash water pressure on the classification efficiency of medium fraction hematite



(c) Effect of feeding pressure-underflow pressure on the classification efficiency of fine fraction hematite

Fig. 8. Effect of significant factors on the classification efficiency of each size fractions hematite

. Table 6. Comparison between the predicted value and actual value of classification efficiency of hematite in each fraction under optimized test conditions

Products	Classification efficiency / %		Relative Error / %
	Predictive value	Actual value	
Coarse fraction（-2~+0.15mm）	85.08	86.46	1.6
Medium fraction（-0.15~+0.074mm）	65.10	67.79	4.0
Fine fraction（-0.074mm）	51.41	52.72	2.5

4. Conclusions

The Cyclonic Continuous Centrifugal Separator (CCCS) is an innovative technology for hematite ore classification. On the basis of single factor tests, the Response Surface Method (RSM) was used to optimize the classification conditions of hematite. The main conclusions of this paper are as follows:

(1) The classification test showed that under the feeding pressure of 50 kPa, backwash pressure of 10 kPa, and underflow pressure of 31 kPa, the classification efficiency of coarse fraction (-2~+0.15mm) is 84.04%, and that of medium fraction(-0.15~+0.074mm) is 65.02%, and that of the fine fraction(-0.074mm) is 49.35%.

(2) The feeding pressure (X_1), backwash pressure (X_2), and underflow pressure (X_3), and their interactions have a significant effect on hematite classification, which was verified by RSM.

(3) The optimal parameters of the hematite ore classification test were obtained by the RSM with the feeding pressure of 55.48 kPa, backwash pressure of 9.79 kPa, and underflow pressure of 31.94 kPa. The results of verification test under the above conditions showed that the average fraction classification efficiency of coarse, medium, and fine hematite ore is 86.46%, 67.79%, and 52.72%, respectively. The mathematical model established for hematite ore classification is significant and reliable with precise regression.

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