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Modeling and Optimization of Vertical Pulsating High Gradient Magnetic Separator for Iron ore Slime Processing Using Response Surface Methodology

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Abstract: Due to the increasing demand in the high grade ores for the metallurgical operations and the stringent environmental conditions on the mining activity it is essential utilize the waste tailing pond slimes, recovery of iron values form these tailing ponds not only enhance the life of the existingoperating mines also finds the route to achieve the sustainable process. The present study aims to recover iron values from waste tailing ponds of Donimali area of Karnataka using vertical pulsating high gradient magnetic separator, a three-level Box–Behnken factorial design combined with response surface methodology (RSM) for modelling and optimizing of process parameters of Vertical Pulsating High Gradient Magnetic Separator (VPHGMS), namely Magnetic Intensity, matrix Pulsation and revolution of the Ring (RPM) for the separation of Fe (Hematite) from a deslimed iron ore slimy sample was studied. Second-order response functions were utilized for the grade and recovery of the Fe in the concentrate fraction. With the advantage of the optimization function in the statistical software MINTAB 14, optimized levels of the process variables have been determined to achieve the maximum grade of 65.6%, and recovery was 80.64% with combined desirability of 0.8 of Fe in the concentrate fraction was predicted. The influence of the process variables of the VPHGMS on grade and recovery of the Iron bearing minerals in the Magnetic fraction was presented as 3D response surface graphs.

Keywords: Iron Ore, Slimes, VPHGMS, RSM, MINITAB

1. Introduction

Vertical ring and pulsating high gradient magnetic separator (VPHGMS) is designed Magnetic Jigging Principles, where the pulsation mechanisms assist in improving separation efficiency of magnetic minerals from non-magntics. This is achieved by agitating the slurry and keeping the particles free in order to minimise particle entrapment in the matrix thus creating more surfaces for collection of particles within the matrix. Theoretically, this principle allows the separation of mixtures with small difference in density and small difference in magnetic susceptibility. The application of this new technique the extraction of valuable particles from previously discarded fines and slimes dumps which previously were found not to be cost effectively viable for beneficiation, could become a feasible option. In addition, the fines generated during the mining of iron ore could be beneficiated further to generate feed material for direct reduced iron (DRI) [19] whilst coal, manganese and chromite found with gangue minerals containing iron phases could also be separated using this approach. VPHGMS was used to treat titanoferrous magnetite to improve the product quality of the fine magnetite and titanium [19] study reveals that good grade is achieved because of pulsation effect. The success of beneficiation of lean grade ores with VPHGMS separator depends on the selection of suitable process variables at which the response reaches its máximum values. One of the methodologies for obtaining the optimum results is response surface methodology (RSM) [1, 2, 3, 4, 6]. Different experimental designs are used for different objectives, such as randomized block designs that can be used for screening the relevant factors [3, 5]. For evaluation of process variables, the three level factorial designs together with response surface methodology (RSM) Box-Behnken design was used to estímate the coefficientes of thequadratic models. RSM is widely used for modeling and optimization of process parameters in particular chemical and pharmaceutical systems [11, 12]. Some literature reports on modeling using these methods in mineral and coal processing operations are also available. Using central composite design method, models were developed for chromite and celestite concentrates, and clean coal by varying the process variables of multi gravity separator [1, 2]. Further another model was developed for Turkish coals by means of the RSM and Box–Behnken design. In mineral processing grade and recovery are the important parameters which will designate the efficiency of the process/ separation with dissimilar variable conditions, therefore optimization and modeling of process variables are imperative in the concentration process [3].

In the present study, the effect as well as optimization study of three process variables such as Magnetic Intensity (Tesla), Pulsation Frequency (per min) and Ring Rpmof the feed material which have been predicted to play a very significant role in concentrating Iron ore slimes is carried out. The Box–Behnken design with response surface methodology and modeling of Vertical ring Pulsating High Gradient Magnetic Separator (VPHGMS) employing LGS-EX 500 for concentrating the Iron ore slimes has been described with the aim of producing pellet grade concentrates assayingFe 63% Min, SiO_2+$Al_2O_3$7%Max and LOI 4% Max. The optimization studies for maximum grade and recovery of the fine grained hematite could be computed by using MINITAB 14 statistical software.

1.1. Vertical Ring Pulsating High Gradient Magnetic Separator (VPHGMS)

The magnetic separator used in this research study is a newly (2008) designed wet high intensity Magnetic separator called Longi LGS 500 and is shown in Figure 1. The said separator has a capability to attract materials with weakly magnetic attributes [23]. A few studies have been conducted on Chinese iron ores samples have shown tremendous improvement in the beneficiation of minerals such as hematite, martite, vanadic titanomagnetite, manganese and other weakly magnetic minerals at very fine particle sizes [22]. The equipment was designed based on magnetic jigging principles where the pulsation mechanism improves separation efficiency by agitating the slurry and keeping the particles free, Theoretically, this principle allows the separation of mixtures with a small difference in density and in magnetic susceptibility, and also the separation of non-magnetic and magnetic fine mixtures. The ring is arranged in a vertical orientation as opposed to traditional WHIMS which uses a horizontal carousel. The vertical nature of the carousel allows for reverse flushing, i.e. magnetics flushing in the opposite direction of the feed, enabling strongly magnetic and or coarse particles to be removed without having to pass through the full depth of the matrix volume. In addition, the magnetics flushing is accomplished in a location (near the top of rotation) with low stray magnetic field to reduce any residual grip on the magnetic particles. These combined benefits lend to high availability due to minimized matrix plugging. The pulsation in the separation zone showed in Figure 2 explains that the separation performance by agitating the slurry and keeping particles in a loose state, minimizing entrapment. This mechanism also maximizes the particle accumulation (trapping) on all sides of the rod matrix creating more usable surface area for magnetics collection. A further benefit is to reduce particle momentum, which aids in particle capture by the applied magnetic force. This leads to improve fine particle collection and separation.

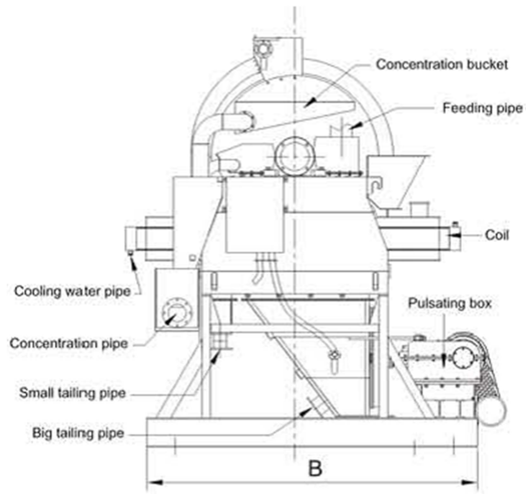


Figure 1. *Vertical Ring Pulsating High Gradient.*

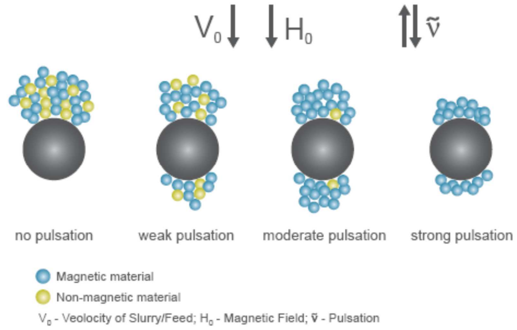


Figure 2. *Pulsating Mechanism in VPHGMS Magnetic Separator.*

1.2. Response Surface Methodology

Response surface methodology (RSM) is a collection of statistical and mathematical methods that are useful for modeling and analyzing problems. In this technique, the main objective is to optimize the response surface that is influenced by various process parameters. The RSM also quantifies the relationship between the controllable input parameters and the response surfaces.

To determine the relationship between the independent variables and the dependent variables, the data collected were subjected to regression analysis using response surface regression procedure of MINITAB 14.12. Regression analysis is used to model a response factor (Yi) as a mathematical function of a few continuous factors. Each response (Yi) was represented by a mathematical equation that correlates the response surfaces.

The response was then expressed as second-order polynomial equation according to equation 1.

$$Yi = f(y) = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=1}^{K-1} \sum_{j=2}^{k} \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

Where Yi is the predicted response used to relate to the independent variable, k is the number of independent variables (factors) shown in Table 1. Xi (i = 1, 2, 3); while β is a constant coefficient and β_i, β_{ij} and β_{ii} the coefficient of linear, interaction and square terms respectively and ε is the random error term.

Table 1. *Variables and levels for the three levels and three factor full factorial design.*

Variables	Symbols	Levels		
		Low(-1)	**Intermediate (0)**	**High(1)**
Intensity(Tesla)	A	10700	12950	15200
Ring Revolution (RPM)	B	2	2.5	3
Pulsation (Per Min)	C	75	150	225

A second order polynomial equation was chosen to fit the experimental results. This model represents the effects of process variables (A, B, C) and their interactions on the response variables (Fe Grade and Fe Recovery). The general form of the model chosen is represented as follows

$$Y = b_0 + b_1 A + b_2 B + b_3 C + b_{12} AB + b_{13} AC + b_{23} BC + b_{11} A^2 + b_{22} B^2 + b_{33} C^2 \quad (2)$$

Where, Y is the predicted response, b_0 is model constant; b_1, b_2 and b_3 are linear coefficients; b_{12}, b_{13}, b_{23} are cross product coefficients and b_{11}, b_{22}, b_{33} are the quadratic coefficients. Statistical software MINITAB 14.12 was used to estimate the coefficients.

2. Experimental

2.1. Materials

The iron ore slime sample from the from tailing dam of DonimalaiIorn Ore Mines, Karnataka, India was collected for the study and sub samples were drawn and was subjected to de-sliming studies in a 50 mm hydro cyclone by varying the spigot and vortex finder at different operating pressure to ascertain best operating conditions for getting better grade and yield of the underflow simultaneously eliminating bulk of the ultra fine impurities in the overflow. The representative deslimed sample was subjected to physic-chemical and mineralogical characterization.

The mineralogical studies revealed that Hematite is the major ore mineral with minor amounts of Geothite occurring in the grain size of 30-100 microns. Fair degree of liberation of ore minerals are noticed at 50 microns size. Quartz [<70 μ] and ferruginous clay [< 10 μ] are the major gangue minerals shown in Figure 3. Amenability of sample indicated that the fine sand -0.15+0.02mm fraction considerably got enriched in Fe values by 4-5% and reduction of silica, alumina and LOI values due to removal of clayey slimes.

After homogenization of deslimed sample, sub sample were drawn followed by coning and quartering method. The sub samples drawn were subjected to magnetic separation in a Vertical ring Pulsating Wet High Gradient Magnetic Separator. The statistically planned experiments were conducted by varying magnetic field intensity, ring revolutions and pulsation for optimizing the VPHGMS parameters to obtain the pellet feed grade concentrates using MINITAB 14 statistical Software.

2.2. Experimental Procedure

The experimental procedures comprises of characterization of feed samples, desliming by hydrocyclone and statistically designed tests with Vertical Pulsating High Gradient Magnetic Separator varying machine parameters.

The particle size distribution along with size fractional chemicalanalysis reveal that the sample analyzes 55.30 % Fe (T), 8.28% SiO_2, 8.1% Al_2O_3, 0.006% P, 0.001% S and 3.73 % LOI. The bulk of the Iron distribution i.e. 77% is in the range of 26 to 150 microns. The amenability of above de-slimed -0.15+0.02 mm fine sand fraction by heavy liquid [TBE~3 specific gravity] centrifuging yielded a sink concentrate assaying 65.1% Fe with 60 wt% yield. Similarly, Frantz Iso-dynamic Magnetic Separation of -0.15+0.02 mm dry fine sand fraction produced a magnetic concentrate assaying 63.15% Fe with 72.1wt% yield. The sample was found to be amenable to both magnetic and enhanced gravity concentration. A slight dilution in the concentrate in magnetic separation was observed and it may be due to the reporting of ferruginous clayey coated grains.

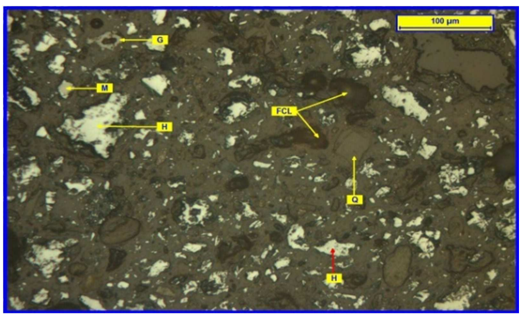


Figure 3. *Photomicrograph displaying distribution of coarse to fine grains of Hematite (H). Few Goethite (G) Quartz (Q) and Ferruginous Clay (FCL) occur as ground mass. Few traces of Magnetite (M) are also seen. (Under Reflected Light----200X).*

De-sliming studies were carried out in a laboratory Mozleycyclone test rig with 50mm hydro cyclone by varying the vortex finder and spigot dia. The tests were carried out at feed consistency of around 12% solids and inlet pressure of around 14psi. Products of each test were collected and analyzed for grade and yield. The results obtained at optimum condition are shown in Table 2. From the results it was observed that about 18% of the slimes report to overflow and only about 10% of the iron units were lost. The underflow has been enriched to 61% Fe with 90% recovery from the feed.

Table 2. *Results of hydrocyclone studies.*

Product	Wt%	Assay %				% DistnFe
		Fe	SiO_2	Al_2O_3	LOI	
Overflow	18.2	31.20	19.64	25.06	9.79	10.2
Underflow	81.8	60.80	6.39	3.71	2.69	89. 8
Head C.	100.0	55.42	8.80	7.59	3.98	100.0

Thus produced deslimed sample was subjected to VPHGMS to enhance the grade and recovery of the iron values. The Box–Behnken factorial design was chosen to find out the relationship between the response functions (Grade and Recovery of the Fe) and three variables namely Intensity, Ring RPM and Pulsation of the VPHGMS. All the experiments were conducted on laboratory model VPHGMS, in which the effects of three important process variables, each at three different levels have been studied. The levels VPHGMS variables are given in Table 1. The process variables such as Intensity, Ring RPM and Pulsation were maintained as per the experimental design. The Magnetic and non-Magnetic fractions were collected, weighed, and then Chemical analysis was carried out for analyzing the grade and recovery of the Fe (Hematite) in the concentrate fraction. All the designed experiments were conducted and the results of these experiments were used for the statistical analysis using MINITAB 14.12.

3. Results and Discussion

A three factor three-level Box–Behnken design was used to determine the responses such as grade and recovery of the Fe. The independent process variables and the results obtained from factorially (Box–Behnken) designed experiments are in Table 3. From the experimental results cited in Table 3 and Eq (2), the second-order response functions representing the Magnetic minerals quality and their recovery could be expressed as functions of the Magnetic Intensity, Ring Revolution and Pulsating frequency. The model equations for grade and recovery of Fe in the Magnetic fraction are given in Eqs. (3) and (4) respectively.

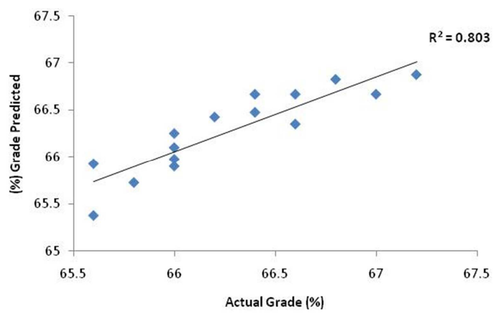
$$Y_{Grade} = 45.62+0.002A+2.84B+0.0095C-9.05E\text{-}08A^2-0.23B^2 -3.7E\text{-}4C^2-1.34E\text{-}4AB+5.6E\text{-}7AC \quad (3)$$

$$Y_{Recovery}=107.2+0.002A-46.61B-0.182C-2.9E\text{-}5A^2+9.58B^2 -3.15E\text{-}5C^2+0.001AB+1.56E\text{-}6AC+0.04BC \quad (4)$$

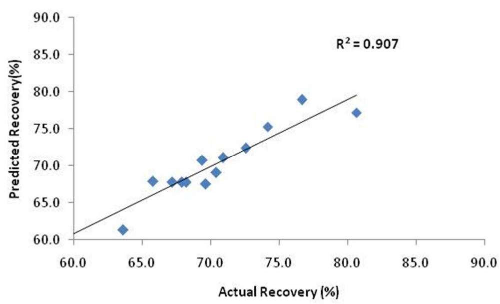
Table 3. *Factorial designed experimental results.*

Run	A	B	C	Observed Results	
				Fe (%) Grade	Fe (%)Recovery
1	+1	0	-1	65.6	74.16
2	0	0	0	66.6	67.90
3	0	0	0	67.0	68.20
4	0	+1	+1	66.8	72.55
5	-1	0	+1	66.2	60.20
6	0	+1	-1	65.6	80.64
7	+1	0	+1	66.4	69.63
8	-1	0	-1	65.8	65.78
9	-1	-1	0	66.0	63.62
10	+1	+1	0	66.0	76.65
11	0	0	0	66.4	67.20
12	-1	+1	0	66.6	69.39
13	0	-1	-1	66.0	70.89
14	0	-1	+1	67.2	55.86
15	+1	-1	0	66.0	70.40

Experimental results and the predicted values obtained using model Eqs. (3) and (4) are tabulated in Table 4. Fig. 2 (a and b) shows the relationship of predicted and the observed data point's indicating that recovery model has made good agreement (R^2 of 0.804 and 0.907 for grade (%) and recovery (%) of Magnetic Fractions respectively) of the response equations than grade model. Any deviation from the operating range of the process variable such as beyond the higher/lower level would affect the performance of the VPHGMS operation. The residual plots versus fitted values for each response are shown in Figure 4 (a) and (b). The residuals are independently distributed with zero mean and a constant variance. The observation of the two plots of responses indicates that Recovery model suggested are adequate than Grade and which is satisfied.



(a)

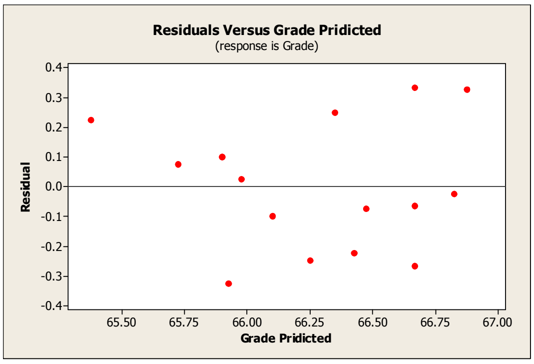


(b)

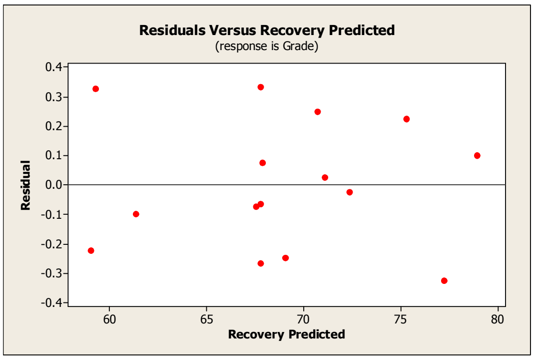
Figure 4. *Relation between predicted and observed values (a) grade (%) of Fe in the Magnetic fraction, (b) recovery (%) of Fe in the Magnetic fraction.*

Table 4. *Observed and predicted values of conducting minerals grade and recovery.*

Run No	Grade		Recovery	
	Observed	**Predicted**	**Observed**	**Predicted**
1.	65.60	65.38	74.16	75.32
2.	66.60	66.67	67.90	67.77
3.	67.00	66.67	68.20	67.77
4.	66.80	66.83	72.55	72.37
5.	66.20	66.43	60.20	59.05
6.	65.60	65.93	80.64	77.21
7.	66.40	66.48	69.63	67.53
8.	65.80	65.73	65.78	67.88
9.	66.00	66.10	63.62	61.35
10.	66.00	65.90	76.65	78.92
11.	66.40	66.67	67.20	67.77
12.	66.60	66.35	69.39	70.72
13.	66.00	65.98	70.89	71.07
14.	67.20	66.88	55.86	59.29
15.	66.00	66.25	70.40	69.07



(a)



(b)

Figure 5. *Residual versus fitted values of the Magnetic Fractions for the corresponding responses of (a) Grade; (b) Recovery.*

Table 5. *Analysis of variance for Response Surface Quadratic model for VPHGMS parameters.*

Analysis of Variance (ANOVA)							
	Grade (%)				**Recovery (%)**		
Source	**DF**				**Adj MS**		
Regression	9	0.29859	F	P	Adj MS	F	P
Linear	3	0.55667	2.27	0.19	53.791	5.44	0.038
A,B,C			4.24	0.077	149.909	15.16	0.006
Square	3	0.29578					
A*A,B*B,C*C			2.25	0.2	7.34	0.74	0.571
Interaction	3	0.04333					
A*B,B*C,A*C			0.33	0.805	4.125	0.42	0.749
Residual Error	5	0.13133					
Lack-of-Fit	3	0.15667		9.891			
Pure Error	2	0.09333	1.68	0.394	16.309	61.93	0.016

The analysis of variance (ANOVA) and estimated regression coefficient of the VPHGMS parameters are tabulated in Table 5. It can be seen that the probability value (P-value) of the independent variables (Magnetic Intensity, Ring RPM, Pulsation) of the processing conditions are less than 0.05 in linear relationships and in square and interaction the P value more than the significant value i.e 0.05. Meanwhile, the P-value for the lacks of fit for Recovery modelis 0.016 which issignificant and theGrade models are greater than 0.05, which is not significant. The model adequacies were justified by the R^2 values, the R^2 values of the Recovery modelmore significant than the Grade model. This suggests that Recovery models was highly significant than the Grade model and indicate that the regression line perfectly fits the data.

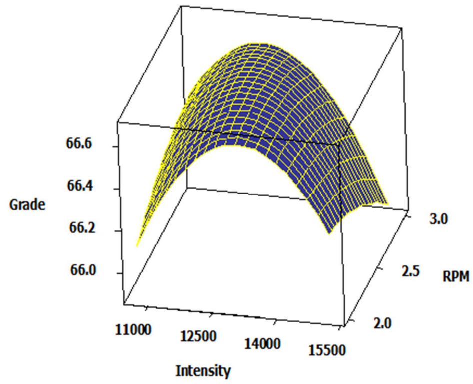
3.1. Effect of Process Variables on (%) of Magnetic Fractions

For better understanding, the predicted models are described in terms of three dimensional (3D) response surface plots which show the effect of process variables of VPHGMS on grade and recovery of Fe% in concentrate Fractions.

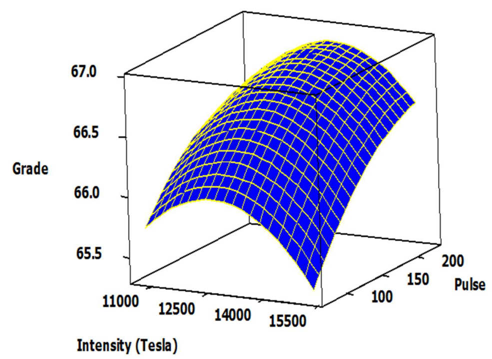
Figure 6(A) shows the effect of Intensity (A) and RPM (B) on the grade of the concentrate fraction at center level of slurry federate. It observed that higher grade is obtained at centre level of intensity (1.29 Tesla) at ring rpm of 2.5, the magnetic intensity of 1.29 T was found to be optimum, wt% yield and % Fe Recovery reaches saturation. At intensities> 1.3T the dilution of grade occurs due to concentration of ferruginous clay.

Figure 6(B) shows the effect of Intensity (A) Pulsation (C) on the grade of the concentrate fraction of the VPHGMS at centre level of ring RPM. The results indicate that an increase in frequency of pulsation decreases the % Fe Recovery and increases the grade of concentrate. Also it was observed that the % Fe grade of tail losses increases significantly if the frequency value increases more than 150.

Figure 6(C) shows the effect of ring RPM (B) and Pulsation (C) on the grade of the concentration fraction of the VPHGMS at centre level of magnetic intensity. The results indicated that an increase in rpm insignificantly Increased the grade of concentrateFurther, it was observed that, the %Fe in tails decreased with increase in the rpm from 2.5 to 3.0.



a



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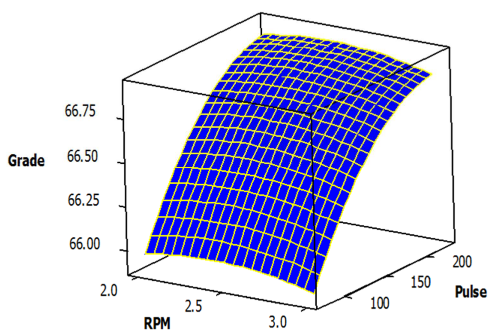


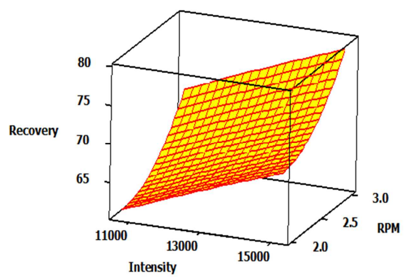
c

Figure 6. *Response surface plots showing the effects on Grade (Fe%) in concentrate fraction(a) between Intensity (A) and RPM (B), (b) between Intensity (A) and Pulse (C), and (c) between RPM (B) and Pulse (C).*

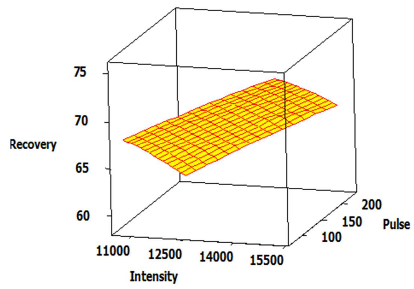
Similarly the effect of process variables on the recovery of the %Fe to the concentrate fraction of the VPHGMS has explained in Figure 7. Figure 7(A) demonstrates the effect of intensity (A) and the RPM (B) on the recovery of %Fe in the concentration fraction at centre level of matrix pulsation. It was observed that, higher the Rpm of the ring at higher intensity recovery has increased and decreased at lower intensity levels.

Figure 7(B) shows the effects of Intensity (A) and Pulsation(C) on the recovery of Fe% in the concentrate fraction of the VPHGMS at centre level of Rpm. The recovery of the concentrate fraction is not deviated largely as the surface shown in the figure it is representing flat plateau depicts the effect of intensity and pulse has minimum effect on the recovery of the Fe % in the concentrate fraction.

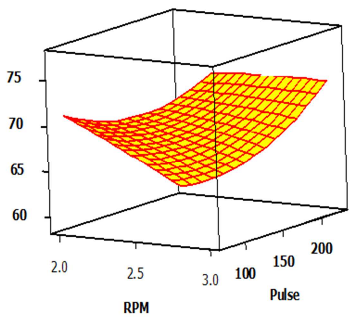
Figure 7(C) shows the effect of ring Rpm (B) and pulsation (C) on the recovery of the concentrate fraction at the central run of the magnetic intensity, the recovery of the concentrate fraction is significantly increased at the higher pulsation effect of the matrix at central level of the Rpm



A



B



C

Figure 7. *Response surface plots showing effects on recovery (%) of Fe% in the concentrate fraction: (a) Between Intensity (A) and ring Rpm (B), (b) Between Intensity (A) and pulsation(C), (c) Between RPM (B) and Pulsation (C).*

Figure 7(c) shows the effect of ring Rpm (B) and pulsation (C) on the recovery of the concentrate fraction at the central run of the magnetic intensity, the recovery of the concentrate fraction is significantly increased at the higher pulsation effect of the matrix at central level of the Rpm

3.2. Optimisation Using Minitab

The key features of using the RSM method is its ability to identify the combination of variable settings so that jointly optimize a single response or a set of responses. In this study, the optimized combination of Intensity, Ring Rpm and Pulsation of matrix variables with the ability to provide targeted Grade is the main objectives. The Intensity was measured by observing the highest response of Fe% Grade and %Fe recovery. By using Minitab software, the optimization process required three factor values i.e. lower, upper and target in order to construct the desirability indices. In the optimization plane, the goals for all the responses are set to maximize and the target values are the highest values of each response obtained from the experimental results. Figure 8 depicts the optimization value of all the responses. Based on the analysis, the predicted optimum Intensity, Rpm and Pulsation are 1.5Tesla, 3.0Rpm and Pulsation is 75 per min, respectively, with desirability equal to 0.6 for Grade and 1.0 for Recovery with composite desirability equals to 0.77 meets the maximum Grade and Recovery of Fe%.

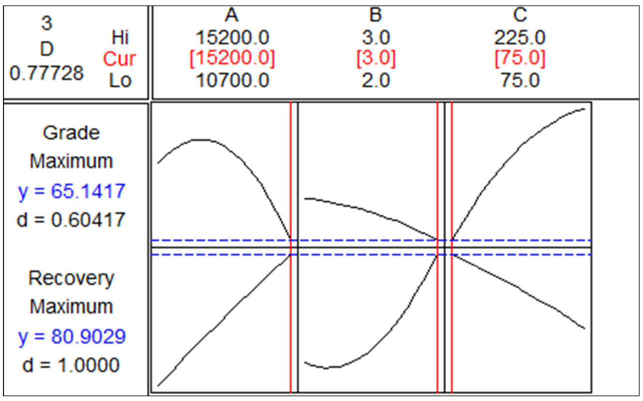


Figure 8. *Optimal processing conditions on the responses of VPHGMS.*

4. Conclusions

The present investigation on beneficiation of Iron ore slimes from Donimalai area showed that the de-sliming using hydro cyclone enriches the slimes from 55%Fe to about 60%Fe. The statistically designed experiments with Vertical ring Pulsating High Gradient Magnetic Separator for beneficiation of slimes after de-sliming showed that it was possible to get the concentrate assaying 65 to 67%Fe and Recovery varying from 60% to 80% The best results were obtained are at an intensity of 1.3T, ring revolution of 3 rpm and pulsation of 75 strokes per minute on de-slimed sample also shown optimization study in Figure 8. The concentrate obtained analyses 65.6%Fe with 80.3% Fe Recovery, The results indicate that the recovery model was significant than the Grade model and the optimization of the VPHGMS process variables were optimized using MINITAB 14 with combined desirability of 0.8 which shows slimy sample could be a viable alternative for beneficiation of rejects from iron ore washing plants mitigating environmental and mineral conservation problems.

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