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A preliminary investigation of dry gravity separation with low specific gravity ores using a laboratory Knelson Concentrator

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Abstract: It has become an active research area for treating low specific gravity (SG) deposits by centrifugal separation due to its high efficiency, low cost and minor environmental impact. Laboratory Knelson Concentrator has shown its potential for processing high density ores on a dry basis. This study investigated the feasibility and the optimum operating conditions when processing a dry low SG feed with a modified Knelson Concentrator. A synthetic mixture of magnetite and quartz with a grade of 1% magnetite was used to mimic a low-density ratio ore. Bowl speed (G), air fluidizing pressure (psi) and solids feed rate (g/min) were chosen as the operating variables. Box-Behnken design was used to design the experiments and response surface method was used for optimization. The effects of each individual factors and their interactions on concentrate grade and magnetite recovery were evaluated. The dry process achieved up to 60 % magnetite recovery with an upgrade ratio of 5. The optimized values for the concentration with the highest recovery and grade of bowl speed, solids feed rate and air fluidizing pressure are 27 G, 200 g/min and 12 psi, respectively.

Keywords: Knelson concentrator, dry gravity separation, response surface method, Box-Behnken design

1. Introduction

The separation of low specific gravity (SG) deposits with the Knelson Concentrator has become an active area of research due to its relatively low cost and small environmental impact when compared to other separation techniques such as froth flotation (Okanigbe *et al.*, 2018). Previous researches have confirmed the reliability of the lab-scale Knelson unit for processing various low-density minerals (SG 1.1-7.6), including cassiterite (SG 7) (Angadi *et al.*, 2017), chromite (SG 4.6) (Akar Sen, 2016), colemanite (SG 2.4) (Savas, 2016), coal (SG 1.1-1.4) (Majumder *et al.*, 2007; Rubiera *et al.*, 1997; Uslu *et al.*, 2012), magnetite (SG 5.2) (Ghaffari and Farzanegan, 2017; Marion *et al.*, 2018; Sakuhuni *et al.*, 2015), pentlandite (SG 4.6-5) (Klein *et al.*, 2016), rare earth minerals (SG 3.8-6.3) (Jordens *et al.*, 2016), gold bearing sulphides (SG 5.0-7.6) (Klein *et al.*, 2010), tantalum bearing minerals (SG 6.5-7.2) (Burt *et al.*, 1995) and heavy mineral sands (SG 4.2-4.8) (Gonçalves and Braga, 2016; Premaratne and Rowson, 2004).

Centrifugal gravity concentrators such as the Kneslon Concentrator were developed to improve gold recovery (Knelson, 1992; Knelson and Jones, 1994; Laplante *et al.*, 1995b; Laplante *et al.*, 2000). Subsequently, centrifugal concentrators have been extended to recover PGMs (Xiao *et al.*, 2009; Xiao *et al.*, 2021) and materials of lower density, such as iron ore (Chen *et al.*, 2008; Sakuhuni *et al.*, 2016). Despite the effectiveness of this concentration method, its requirement for large volume of water (Laplante *et al.*, 1995a) has proven to be a huge challenge to the environment, particularly in areas such as South Africa (Habiyaremye, 2020), Chile (Alvez *et al.*, 2020) and China (Jiang, 2009) where water resource is in scarcity. It is therefore important to put every effort into reducing the water usage, a critical issue in mining areas as it affects not only the environmental but also processing costs become more apparent (Budnitz and Holdren, 1976). It should be pointed out then, problems associated with recycling and reuse of process water can be avoided with dry processes (Kökkılıç *et al.*, 2015).

Separation on a dry basis have been widely investigated and developed in the past decades (Luo *et al.*, 2019; Macpherson and Galvin, 2010). Pressurized air has been used to replace water as the fluidizing

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medium when the Knelson is used to concentrate certain ores (Greenwood *et al.*, 2013; Zhou *et al.*, 2016). Theoretically, centrifugal acceleration drives the feed solids to fill the inter-riffle spaces from bottom to top. During the process, heavy particles displace the light minerals and being trapped in the riffles to form the concentrate while the lighter particles are carried out of the concentrating bowl by air as tailings. The fluidization of the bed in the riffle, with constant pressured air coming through holes in the riffles, allows the substitution of dense particles for those of a lower density.

This study investigates both the feasibility, and the optimum operating conditions when processing low-density material using a modified laboratory scale Knelson Concentrator. Box-Behnken design (BBD) was used to design the experiments and response surface method (RSM) was used for optimization. The combination of BBD and RSM has been proven to be helpful in the analysis of the effects of various factors affecting the responses by simultaneously changing variables with a limited number of tests in a wide range of fields (Chaker *et al.*, 2021; Jose *et al.*, 2011; Varala *et al.*, 2016).

2. Materials and methods

2.1. Materials

A synthetic mixture of magnetite (1%w/w) and quartz (99%w/w) was used to mimic a low-density ratio ore. Magnetite (SG 5.2) used for this work was obtained from Gem and Mineral Miners Inc. (USA). Quartz (SG 2.65) (Unimin Canada Ltd.) was used as the gangue. The magnetite and quartz were pulverized using a LM2-P pulverizing mill (Labtechnics, Australia) and the magnetite was purified using a lab-scale WD (20) wet drum permanent magnetic separator (Carpco Inc., USA). Clean magnetite and quartz were then screened into -425+300 µm, -300+212 µm, -212+150 µm, -150+106 µm, -106+75 µm, -75+53 µm, -53+38 µm and -38 µm size fractions. Magnetite and quartz were well mixed to meet the particle size distribution of magnetite and quartz mixture as shown in Fig. 1. It is determined by (Ling, 1998) to be practical for wet processing using a laboratory Knelson Concentrator to separate low-density ratio minerals, which will be a good starting point for dry processing.

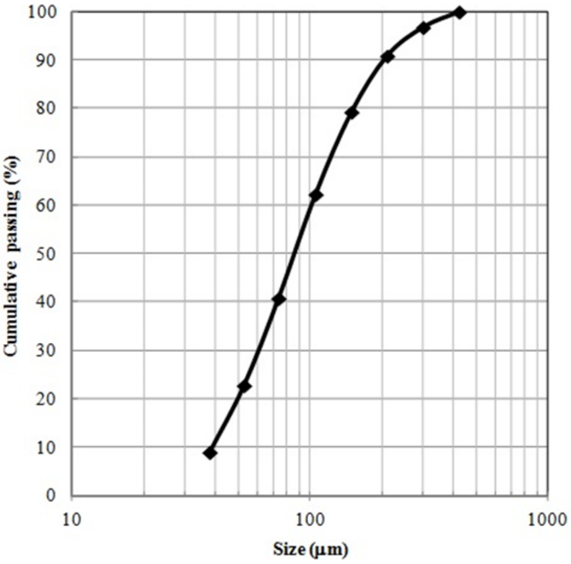


Fig. 1. Particle size distribution of magnetite and quartz mixture used for experiments. The mixture contains 99 % quartz in each size fraction

2.2. Dry Knelson Set-up

A modified KC-MD3 laboratory Knelson Concentrator was used for this study, the modifications having been described previously (Greenwood *et al.*, 2013; Kökkılıç *et al.*, 2015). For each batch test, 1 kg of synthetic mixture was used. Fig. 2 shows the dry Knelson test set-up. Feed comes from top constantly with a vibrating feeder where solids feed rate can be adjusted and measured to meet the required values before each test. However, the actual measured values of the solids feed rate were used since it is difficult to ensure the feed rate to be exactly the same as set out in Table 1.

Fig. 2. Modified dry laboratory Knelson Concentrator

2.3. Sample analysis

The concentrate collected from each test was screened into single size fractions and analyzed using a hand magnet (SP-90 Alnico V-six, Gilson, USA) to separate the magnetite from the quartz completely. Low pressured air flow was used to blow away most of any other impurities which could not be separated by hand magnet. The clean magnetite samples from each single size fraction were weighed and added up, followed by the calculation of concentrate grade and magnetite recovery of each batch test.

2.4. Experimental design

Response surface methodology was used to investigate the main and interaction effect of the variables. In order to save time and expense, BBD was employed to determine the optimal operating conditions. BBD has been proved to be more efficient when compared to the other designs for modelling RSM (Ferreira *et al.*, 2007). Three variables including bowl speed (G), solids feed rate (g/min) and air fluidizing pressure (psi), were chosen and their proper ranges were determined, with three levels coded 1, 0, -1 for high, medium, low level, respectively, and are presented in Table 1. The independent variables are designated as x_1, x_2 and x_3 and the predicted responses, grade and recovery, are designated as y_1 and y_2 respectively. For a 3^3 BBD, a total number of 15 experimental runs with three-times-central points are required. Each test was conducted twice to reduce random error.

The coded and actual values presented in the table above were then used to determine the actual levels of the independent variables for each of the 15 experiments as given in Table 2.

For each Knelson test, 1 kg synthetic ore with a grade of 1% magnetite was used and the bowl speed (G), solids feed rate (g/min) and air fluidizing pressure (psi) were changed successively during the tests with respect to the Box-Behnken design. The mathematical relationship between the three independent variables and responses can be approximated by a second order model such as Eq. 1:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \varepsilon \quad (1)$$

where y is the predicted response; β_0 is the model constant; x_1, x_2 and x_3 are the variables; β_1, β_2 and β_3 are linear coefficients; β_{12}, β_{13} and β_{23} are cross-product coefficients; and β_{11}, β_{22} and β_{33} are the quadratic coefficients (Montgomery, 2017).

Table 1. Independent operating variables and their levels

Variables	Symbol	Coded variable level		
		Low	Centre	High
		□1	0	+1
Bowl Speed (G),	x_1	20	35	50
Solids Feed Rate (SFR), g/min	x_2	100	200	300
Air Fluidizing Pressure (AFP), psi	x_3	6	10	14

Table 2. Coded and actual levels of three variables of Knelson tests

Run	Coded levels of variables			Actual levels of variables		
	x_1	x_2	x_3	BS (G)	SFR (g/min)	AFP (psi)
1	1	0	-1	50	200	6
2	0	-1	1	35	100	14
3	-1	0	1	20	200	14
4	1	-1	0	50	100	10
5	-1	0	-1	20	200	6
6	0	1	1	35	300	14
7	-1	1	0	20	300	10
8	0	0	0	35	200	10
9	-1	-1	0	20	100	10
10	1	0	1	50	200	14
11	0	1	-1	35	300	6
12	0	0	0	35	200	10
13	0	0	0	35	200	10
14	1	1	0	50	300	10
15	0	-1	-1	35	100	6

2.5. Statistical analysis

At the end of the experiments, using experimental data based on grade and recovery, two second-order regression models which describe concentration are produced. Analysis of Variance (ANOVA) was used to determine the regression coefficients and to detect the harmony of the second-order regression models. By using the Fischer (F) test and p-values, statistical momentousness of each factor on responses can be found choosing 95% confidence level. The F-test for the model indicates the level of significance of the model prediction. If the calculated F value from the ANOVA table is higher than the F value found from the related F-statistics Table (in this case the related F-statistics Table is with 0.05 P-values) the regression model is considered acceptable. Using the 5% significance level, a model is considered significant if the *p*-value (significance probability value) is less than 0.05. R^2 and correlation factors were examined by comparing model values and real values. These models were analysed with response surface methods and optimization was realized by response surface and contour plots for different interactions of any two independent variables, while holding the value of the third variable constant at the central (0) level. All statistical analysis was produced by using the statistical software package "Minitab® 19 Statistical Software".

3. Results and discussion

After conducting experiments, concentrate grade and magnetite recovery were calculated and listed as shown in Table 3.

The empirical models representing concentrate grade (y_1) and magnetite recovery (y_2), were

Table 3. Result of concentrate grade and magnetite recovery

Run	Coded levels of variables			Actual measured levels of variables			Responses	
	x_1	x_2	x_3	BS (G)	SFR (g/min)	AFP (psi)	Grade (%)	Recovery (%)
1	1	-1	0	50	188.1	6	2.8	37.8
2	0	1	-1	35	93.5	14	4.9	56.1
3	-1	1	0	20	182.4	14	4.5	55.8
4	1	0	-1	50	78.6	10	3.3	41.2
5	-1	-1	0	20	203.4	6	4.0	52.2
6	0	1	1	35	303.0	14	4.6	56.6
7	-1	0	1	20	301.5	10	4.5	56.5
8	0	0	0	35	197.4	10	4.2	52.4
9	-1	0	-1	20	93.6	10	4.4	55.3
10	1	1	0	50	172.4	14	4.0	47.6
11	0	-1	1	35	294.1	6	3.4	42.3
12	0	0	0	35	188.7	10	4.7	59.8
13	0	0	0	35	212.8	10	4.8	59.1
14	1	0	1	50	276.5	10	3.8	46.6
15	0	-1	-1	35	105.1	6	3.7	44.7

expressed as a function of bowl speed (x_1), solids feed rate (x_2) and air fluidizing pressure (x_3). The coded model Eq.s are presented in Eq.s 2 and 3:

$$y_1 = 4.6 - 0.432x_1 - 0.011x_2 + 0.537x_3 - 0.451x_1^2 - 0.143x_2^2 - 0.311x_3^2 + \\ +0.044x_1x_2 + 0.184x_1x_3 + 0.005x_2x_3 \tag{2}$$

$$y_2 = 57.13 - 5.77x_1 + 0.27x_2 + 5.14x_3 - 4.17x_1^2 - 2.83x_2^2 - 4.38x_3^2 + \\ +0.45x_1x_2 + 1.66x_1x_3 + 0.83x_2x_3 \tag{3}$$

To estimate the significance and accuracy of the developed models, ANOVA table was applied (Table 4).

Table 4. Summary of ANOVA table for regression models

Response	*F*-value	*p*-value	R^2 (%)	Standard deviation
Grade	6.36	0.028	91.97	0.30
Recovery	5.94	0.032	91.44	3.44

From Table 4, the calculated *F*-values of grade and recovery are shown to be 6.36 and 5.94 respectively, both greater than the *F*-value found in the *F*-statistics Table with p=0.05 ($F_{0.05(9,5)}$ =3.48). Accordingly, it can be concluded that the regression models are considered acceptable and fit well. Moreover, the *p*-values (P) of the regression models which are 0.028 for grade and 0.032 for recovery are smaller than 0.05, thus these models are considered suitable for modelling the response behaviours.

The qualities of the fit of the polynomial model was expressed by R^2 values and can be calculated using experimental results and the predicted values which were produced using the models and are tabulated in Table 5. As can be seen from these results, good agreements between experimental and predicted values are obtained. Also, the R^2 value for the concentrate grade and magnetite recovery are 0.92 and 0.91, respectively. From the value, it can be assumed that a good correlation was obtained, indicating a good fit by the model, for which an $R^2 \geq 0.80$ is suggested (Montgomery, 2017). It can be concluded that the regression models are considered acceptable fits. The standard deviations of both the predicted models are 0.30 and 3.44 for grade and recovery respectively which are acceptable values.

Once the model was verified, Student's *t*-test was performed to estimate the quantitative effects of the variables and their interactions. Student's *t*-test results including the *p*-value and T-value of each variable are presented in Table 6. The *p*-values indicate the significance of variables and their interactions, with 95 % confidence; and T-values are the result of Student's *t*-test and indicate whether each significant variable has a positive or negative effect on the response, as well as how significant they are. All variables and interactions with a p-value ≤ 0.05 are considered as significant, with the magnitude of the T-values indicating the level of significance (greater the magnitude greater the significance).

Table 5. Observed and predicted values of concentrate grade and magnetite recovery

Run	Grade (%W)			Recovery (%)		
	Observed	Predicted	Residual	Observed	Predicted	Residual
1	2.8	2.7	0.12	37.8	36.0	1.81
2	4.9	4.7	0.25	56.1	53.5	2.60
3	4.5	4.6	-0.13	55.8	57.6	-1.82
4	3.3	3.5	-0.15	41.2	42.1	-0.95
5	4.0	3.9	0.06	52.2	50.8	1.36
6	4.6	4.7	-0.04	56.6	56.0	0.59
7	4.5	4.4	0.16	56.5	55.6	0.87
8	4.2	4.6	-0.38	52.4	57.1	-4.72
9	4.4	4.5	-0.08	55.3	55.7	-0.42
10	4.0	4.1	-0.07	47.6	49.0	-1.37
11	3.4	3.6	-0.22	42.3	44.6	-2.28
12	4.7	4.6	0.12	59.8	57.1	2.73
13	4.8	4.6	0.22	59.1	57.1	1.98
14	3.8	3.7	0.11	46.6	46.1	0.50
15	3.7	3.6	0.05	44.7	45.6	-0.89

Table 6. Summarized Student's t-test for concentrate grade and magnetite recovery

Term	Grade		Recovery	
	p-value	T-value	p-value	T-value
x_1	**0.010**	-4.05	**0.006**	-4.64
x_2	0.923	-0.10	0.835	0.22
x_3	**0.004**	5.09	**0.009**	4.18
x_1^2	**0.033**	-2.92	0.069	-2.31
x_2^2	0.386	-0.95	0.169	-1.61
x_3^2	0.100	-2.02	0.059	-2.44
x_1x_2	0.782	0.29	0.804	0.26
x_1x_3	0.271	1.24	0.381	0.96
x_2x_3	0.975	0.03	0.651	0.48

From Table 6, linear factor effects (T) value of bowl speed for grade and recovery are 4.05 and 4.64, respectively and the sign of these coefficients are negative. This means that the response y_1 (concentrate grade) and y_2 (magnetite recovery) were significantly affected by a negative linear effect of bowl speed, with a p-value of 0.010 and 0.006 for grade and recovery, respectively. The factor effects (T) of air fluidizing pressure for grade and recovery are 5.09 and 4.18, respectively and the sign of these coefficients are positive, with a p-value of 0.004 and 0.009 for grade and recovery, respectively. The linear negative effect of bowl speed causes a decrease in grade and recovery while increasing the bowl speed; and the positive linear effect of air fluidizing pressure causes an increase of grade and recovery while air fluidizing pressure increases.

The T value of the quadratic term of bowl speed for grade is 2.92 and the sign of this value is negative, with a p-value of 0.033. This means that it has a negative quadratic effect on the grade. A negative relation suggests that for low values of factors, the relation might be positive, but for high values the relation becomes negative. In this case, grade increases when bowl speed decreases, however, further decrease in bowl speed causes decrease in grade.

Solids feed rate does not have any significant effect on the responses. There is no significant interaction effect on responses either. The significant and similar influence of bowl speed and air fluidizing pressure on grade and recovery suggests that similar operating conditions will yield a maximum grade and a maximum recovery at the same time.

To better understand the effects of operating variables on responses, contour plots for grade and recovery are presented in Fig. 3 and Fig. 4, respectively. The Figs. demonstrate the relationship between two variables and a response while the other variable is held constant at the centre (0) level (Table 1).

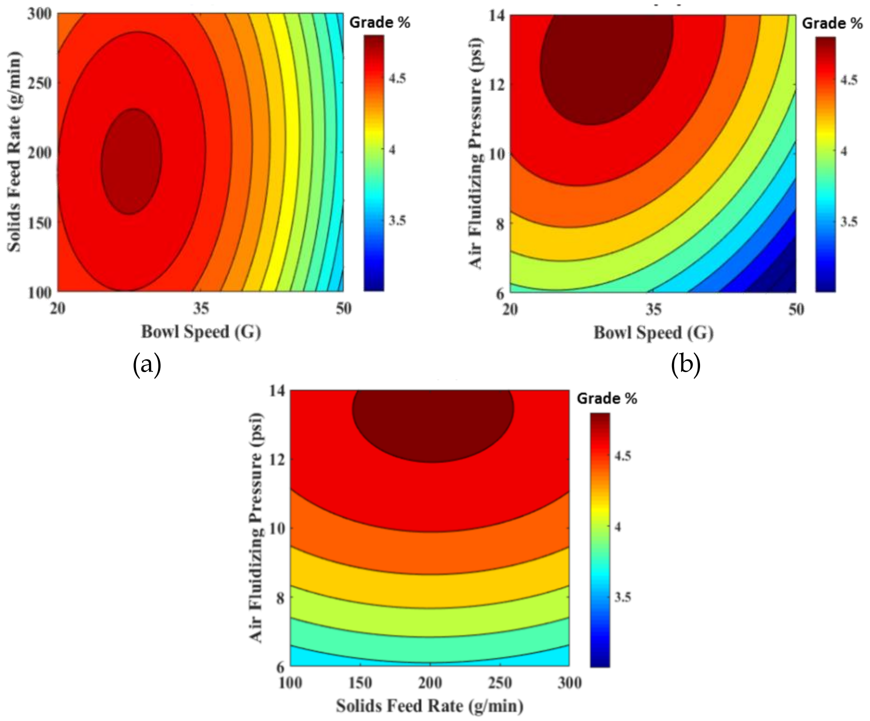
High grades are obtained with low bowl speeds from Fig. 3a and 3b. Decreasing the bowl speed decreases the centrifugal acceleration on particles, decreasing the chance of gangue particles being trapped in the grooves, which results in higher grades. Fig. 3b and 3c shows that grade increases when decreasing the bowl speed and increase the air pressure simultaneously. Increasing the air pressure increases the drag force acting on particles, which results in better gangue rejection.

Fig. 4a and 4b show that to achieve a high recovery, a low bowl speed is required. Bowl speed dominates the effect on recoveries followed with air pressure. It should be seen that solids feed rate does not have too much effect on recovery until the recovery needs to be maximized. An intermediate feed rate is required to achieve highest recovery for optimization; however, the effect of solids feed rate is negligible.

Fig. 3 and Fig. 4 reiterate the fact that high magnetite grade and high magnetite recovery will occur at the same operating conditions as the operating variables show similar trends of effect on grade and recovery.

Although contour plots give a general idea of how independent variables affect the responses and show regions where high grade and recovery can be obtained, they may not indicate the optimum separation conditions. These plots keep one variable at its medium point, therefore, if the optimum conditions are not located at the medium level, they cannot precisely show them. More accurate information about the optimum operating conditions and how they affect both grade and recovery simultaneously can be obtained by drawing overlaid contour plots as shown in Fig. 5.

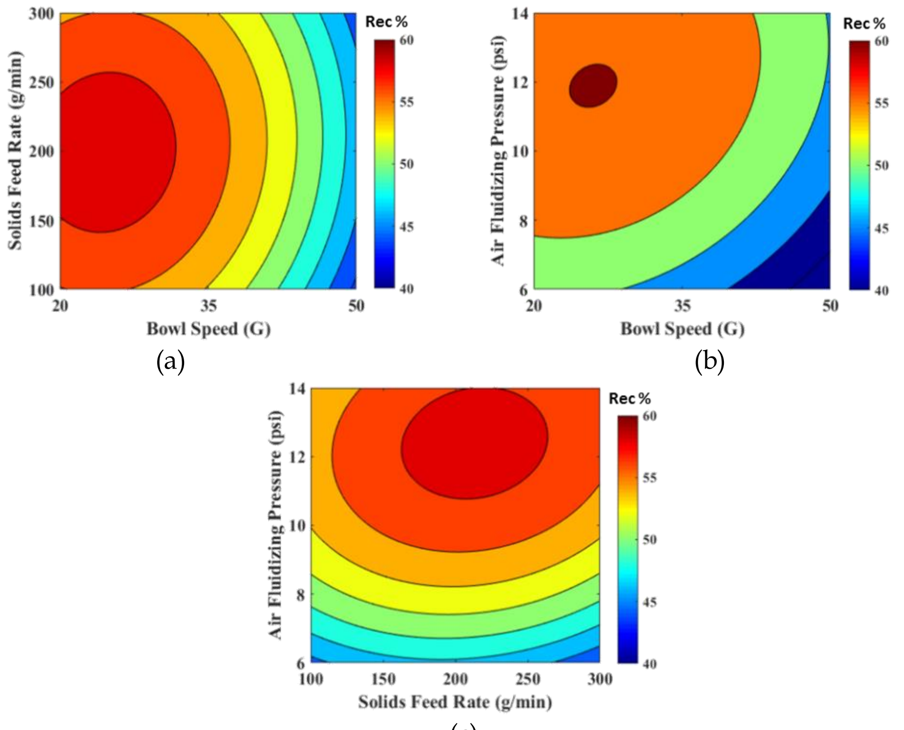
From Fig. 5a, it can be seen that both grade and recovery increase as the bowl speed decreases. However, further decrease of bowl speed will result in slight decrease of grade which corresponds well with the negative quadratic effect of bowl speed shown in Table 6. The intersection of highest grade and



(a) (b)

(c)

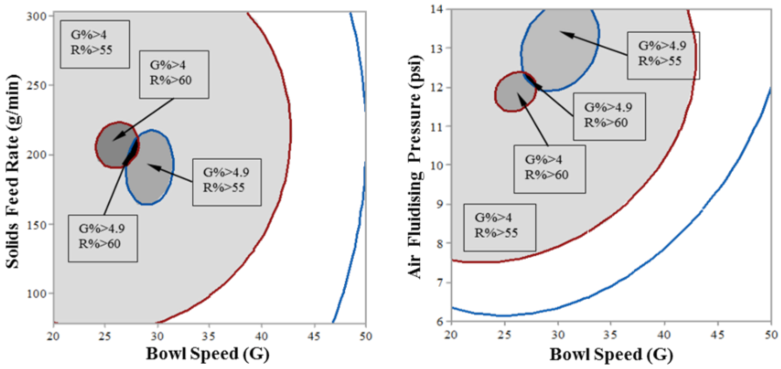
Fig. 3. Response surface plots for concentrate grade showing the relationship between (a) bowl speed and solids feed rate, (b) bowl speed and air fluidizing pressure and (c) solids feed rate and air fluidizing pressure



(a) (b)

(c)

Fig. 4. Response surface plots for magnetite recovery showing the relationship between (a) bowl speed and solids feed rate, (b) bowl speed and air fluidizing pressure and (c) solids feed rate and air fluidizing pressure



(a) (b)

Fig. 5. Concentrate grade and magnetite recovery behaviour at different (a) bowl speed and solids feed rate and (b) bowl speed and air fluidizing pressure

highest recovery indicates that with a bowl speed around 27 G and a solids feed rate of 200 g/min yield the highest grade and recovery at the same time. Fig. 5b shows that grade and recovery increase when air fluidizing pressure increases and bowl speed decreases at the same time. Relatively high air fluidizing pressure and low bowl speed are required to achieve a higher grade and recovery. In order to maximize the grade and recovery, an air fluidizing pressure of 12 psi with a bowl speed of 27 G is suggested.

Once the optimum operating conditions were obtained, to confirm the validity of the proposed Eqs., further experiments were carried out at the optimal conditions and two sets of random conditions. The

calculation of optimal point using the desirability function was performed to confirm the result and random points were selected from the grey area and white area shown in Fig. 7 as well. The validation test was repeated three times for each set of conditions. The comparisons between the actual and model predicted data are presented in Table 7. It can be seen that the model accurately predicted the results of the optimal point with errors less than 2%. Random point 1 from larger grey area results showed good prediction with errors less than 5%. Random point 2 has larger relative errors as it was chosen from the white area as shown in Fig. 5. It has been shown that when the random points are chosen away from the optimal area, the errors increase as the distance between the random point and optimum point increases (Ma *et al.*, 2017), which corresponded well with the results of random points. Overall, it can be considered that the proposed Eq.s adequately predict magnetite grade and recovery.

The concentrate mass of each test does not vary much due to the fixed volume of the concentrating bowl, which means the more magnetite recovered, the higher grade achieved. This corresponded well with the trends of responses found in contour and overlaid plots. It also supports the finding of operating conditions resulted in optimum grade and recovery at the same time.

Table 7. Comparative data at optimum condition and random conditions for validation purpose. OC=Optimum condition, RC1=Random condition 1, RC2=Random condition 2

	Operating Variables			Predicted Response		Validation Tests			
	Bowl Speed (G)	Solids Feed Rate (g/min)	Air Fluidizing Pressure (psi)	Grade (%)	Recovery (%)	Grade (%)	% Error	Recovery (%)	% Error
OC	27	200	12	4.84	60.1	4.91 ± 0.09	1.4	59.1 ± 1.2	-1.7
RC1	20	125	9	4.43	56.3	4.39 ± 0.14	0.9	54.5 ± 0.7	-3.2
RC2	45	275	13	4.36	53	3.79 ± 0.02	13.1	46.7 ± 0.4	-11.9

Lower magnetite recovery at the optimum condition was obtained when compared to that of a wet Knelson process which yielded a maximum magnetite recovery approximately 89% (Ling, 1998). With size-by-size analysis of magnetite recoveries from all tests, the main loss is from the poor recoveries under 106 μm regardless of the test conditions, where magnetite recovery decreases as the particle size decreases. The force balance acting on a particle played a great role in recovering fine magnetite. Due to the much smaller density difference between the two minerals, slightly coarser silica particles will have the same settling velocities as fine magnetite particles, thus it is much harder for fine magnetite to settle in the concentrating grooves to form the final concentrate. The size range of particles processed should be carefully controlled to minimize the negative effect of coarse gangue particles on recovering fine values.

Future work will be focused on investigation into fine magnetite recovery mechanism, as well as magnetite grade effect on dry Knelson performance.

4. Conclusions

This initial study investigated the dry Knelson process when processing low-density ratio minerals. Box-Behnken design and response surface method were used to examine the effect of dry Knelson operating variables (bowl speed, solids feed rate and air fluidizing pressure) on grade and recovery of magnetite from a synthetic ore consisting of magnetite and quartz. The main conclusions are as follows:

1. The empirical regression Eq.s as a function of the independent variables were derived by the RSM model for the grade and recovery of magnetite.

2. The regression models are considered acceptable and fit well. The regression models have calculated *F*-values higher *p*–values *F* value from the *F*-statistics Table with P=0.05 ($F_{0.05(9,5)}$=3.48) and *p*-values less than 0.05 for magnetite grade and recovery, indicating that the selected models are significant to the responses.

3. Bowl speed and air fluidizing pressure are significant operating variables. The order of importance of the variables can be shown as bowl speed (G) > air fluidizing pressure (psi) > solids feed rate (g/min).

4. The dry process achieved up to 60 % magnetite recovery with an upgrade ratio of 5. From the optimization studies, it can be found that the optimized values for the concentration with the highest recovery and grade of bowl speed, solid feed rate and air fluidizing pressure are 27 G, 200 g/min and 12 psi, respectively.

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