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Celestite upgrading by jigs in presence of steel balls as ragging material

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Abstract: Gravity separation using jigs is widely used for coarse particle sizes separation. However, fine sizes reduce jig performance. In this study, the upgrading of celestite ore by jig was investigated at different size fractions in the presence of ragging material. Three size fractions, i.e., -15+2 mm, - 2.0 + 0.50 mm and - 0.50 + 0.08 mm were used. The steel balls were used, as ragging material, to improve the separation of fines as well as to improve the concentrate quality. The statistical design was used to correlate celestite grade and recovery with studied operating variables, i.e., the ragging number of layers, ragging balls diameter, and separation time, at a fixed water flow rate and stroke length. The design results indicated that the ragging balls diameter and their number of layers play an important role. The smaller the ragging balls diameter and the higher the ragging number of layers are the better the concentrate grade but the longer the separation time. A celestite concentrate of (> 95% SrSO4) with 74.5% recovery was obtained for - 2.0 + 0.50 mm size fraction at the optimum conditions; i.e., 3.1 mm ragging balls diameter, one ragging layers, and 15 minutes separation time.

Keywords: celestite, calcite, jigging, ragging material, gravity separation, statistical analysis

1. Introduction

Celestite, strontium sulfate ($SrSO_4$), is the principal strontium mineral. Strontium sulfate has limited industrial usage. Its conversion to other strontium compounds, mainly strontium carbonate and strontium nitrate, is a mandatory step to be used in several industrial applications (USGS, 2019).

Although the gravity separation is an old technique, it is a relatively low-priced technique that depends mainly on the difference in specific gravity between valuable minerals and their associated gangues. Jigging is one of the widely used gravity concentrators used for almost 200 years in to separate particles (Rao, 2006), especially for coarse size particles. It was used as the main separating device or as a pre-concentration step. Separation of coal, as light material, from other minerals by Denver jig was investigated using 3D response surface methodology (Kumar, Venugopal, 2017). The jigging process is mainly activated by substitute strokes of pulsation and suction through a particle bed relaxing on top of a screen. The pulsation stroke starts to dilute to separate the particles due to differential acceleration followed by hindered settling. Whereas, the suction assists in the stratification of the bed according to density and consolidation trickling of fine particles (Kumar and Kumar, 2018; Haldar, 2018). Jigs have been conducted for many years, initially with hand jig (Kumar and Kumar, 2018), and a modified jig known as hybrid jig was implemented to separation of mixed-plastics with similar densities efficiently (Ito et al., 2019).

The processing of celestite ores by gravity separators in general and by jig in particular is recommended due to the difference in specific gravity between celestite as a valuable mineral and calcite

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and silica as main impurities in most of celestite ores (Selim et al, 2010; El-Midany et al, 2011; El-Midany and Ibrahim, 2011).

Depending on size, a combination of jigging and shaking-table or spiral were used to upgrade celestite ores. For very fine size fractions, Mozley multi-gravity separator was used. A concentrate of a grade reaching 94.40% SrSO4 with a recovery of 87.35% was obtained (Aslan 1996; 2007).

On the other hand, ragging material is not only one of the important controlling factors in jigging separation but also it extends the jig usage to finer sizes than the conventional jigs do. The ragging material size and its density play a crucial role in jig separation (Wills and Finch, 2015; Gupta and Yan, 2016). An intermediate layer, with a settling ratio between tail and concentrate was used to separate the light components of car scrap from the heavy ones (Jong and Dalmijn, 1997). Likewise, the optimization of the of jigging process using allflux separator for cleaning semi-coking coal with a size range of -1+0.1 mm was studied taking into account the usage of coarse quartz particles (-15+10 mm) as a ragging material with fixed size and amount in all studied experiments (Tripathy et al, 2016). Besides, Kumar, Venugopal (2017) investigated the jig performance in cleaning coal, and found that ragging material bed height was the most effective parameter on the jig separation performance of coal with -4.76 mm + 3 mm size fraction.

Searching the literature indicates that studying the jigging process, especially in the presence of ragging material is limited for various minerals and especially for the celestite ore. Furthermore, investigating the jigging process at different ragging material sizes and the number of layers had inadequate attention.

Therefore, in this study, the beneficiation of celestite by jigging process in the presence of steel balls, as a ragging material, were investigated using the design of experiments (DOE) to estimate the significant factors in terms of ragging material size and number of layers on the celestite concentrate grade and recovery.

2. Materials and methods

2.1. Materials

A representative sample of about 2 tons of celestite ore, Wadi-Essel locality, Egypt, was kindly provided by the Egyptian Geological Survey Authority. The sample was primarily crushed with a "Denver" jaw crusher to -15 mm. Chemical analysis of the original ore sample using "Perkin-Elmer Analyst 200" atomic absorption was conducted. Mineralogical phases of the original sample were identified by the X-ray diffractometer model "PW 1010".

2.2. Jigging separation

The primary crushed sample (-15 mm) was divided into three size fractions, i.e. -15.0+2.0 mm, -2.0+0.50 mm, and -0.50+0.08 mm. Two jig devices were used due to the large variability of the feed particle sizes. Therefore, the -15+2.0 mm was subjected to separation using the over-screen jig, "Denver Mineral Jig", with a 2 mm jig screen. The - 2.0 + 0.50 mm and - 0.50 + 0.08 mm were treated using, through-screen jig "Denver Mineral Jig, No. 1M", with two different jig screens, 2.5 mm and 0.8 mm, respectively. The stainless-steel balls with various diameters were used as an artificial ragging material. Figure 1 shows the experimental setup of the used jig. The separation products were dried, weighed, and chemically analyzed in terms of Loss-on-ignition (LOI)% and SrO%.

Pulsation of the jig was achieved mechanically by the plunger–diaphragm system. The water flow-rate was adjusted to keep the level of the water fixed during separation. In all experimental runs, the stroke length and water flowrate were maintained at 164 strokes/min and 0.5 L/min, respectively according to the previous study for the authors (Abdel-Fattah, 2008).

0.5 kg of the studied size was used in each experiment. The sample slurry is fed above the screen, where the agitation keeps the lighter materials in suspension, which is then drawn off, and the heavier material falls onto or through the screen to be collected according to the used jig type. In jigging through the screen, all particles in the feed are smaller than the screen aperture and thus have the potential to drop through the screen and collect in the hutch. To stop the light fraction falling through the screen, a false support is provided in the form of a layer of coarse heavy particles called ragging which when contacting the screen surface pack down to effectively closes off the screen apertures to the feed particles. During the pulsation cycle, the ragging is also dilated and will allow the particles that have formed on top of the ragging, by segregation, to get their way through the ragging and the screen into the hutch.

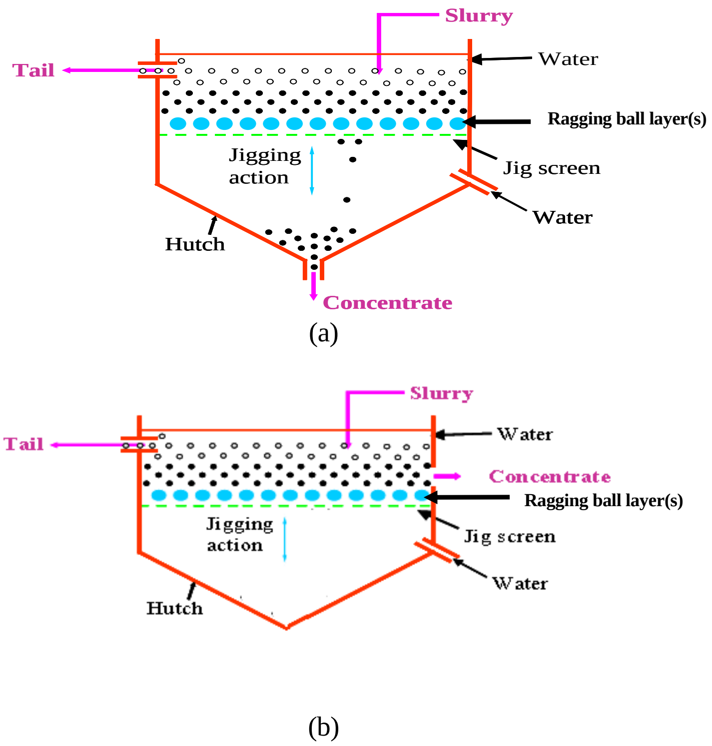

Fig. 1. Used jig units (a) through-screen jig, and (b) over-screen Jig

2.3. Statistical analysis and optimization (Box-Behnken design)

Box-Behnken design, (Box and Behnken, 1960; Tripathy, Biswal, and Meikap, 2016) was used to optimize the jigging process in presence of ragging material. The effects and significance of various factors; namely, ragging layers, ragging balls diameter, and separation time on the grade and recovery of celestite mineral were determined. The water flow rate and stroke length were excluded from the design, due to their insignificant effects on the jig separation, as indicated by Abdel-Fattah (2008).

According to this design, the optimal conditions were estimated using a polynomial function by which correlations between studied factors and responses (SrO grade, SrO recovery, and misplacement index) were generated. The software package, Design-Expert 13.0.3, Stat-Ease, Inc., Minneapolis, USA, was used for regression analysis of experimental data and to plot response surface. Analysis of variance (ANOVA) was used to estimate the statistical parameters. The extent of fitting the experimental results to the polynomial model was expressed by the determination coefficient, R2, and standard deviation. F-test was used to estimate the significance of all terms in the polynomial equation within a 95% confidence interval (Box and Behnken, 1960, Tripathy, Biswal, and Meikap, 2016).

The design-matrix consists of 15 experimental runs. Table 1 shows the levels of studied factors used in the design. For each run, the concentrate was chemically analyzed in terms of Loss-on-ignition (LOI)% and SrO%. Consequently, the SrO % and SrO recovery were calculated to determine the optimum conditions.

Table 1. Factor levels used in Box Behnken design

Symbol	Parameter	Unit	(-)	(0)	(+)
A	Ragging balls diameter	mm	3.10	3.90	4.70
B	Ragging balls	Layer	1	3	5
C	Separation time	minute	5	15	25

3. Results and discussion

3.1. Characterization of celestite ore sample

The X-ray diffraction pattern of the original celestite sample is shown in Fig.2. XRD analysis indicated that the celestite is the main valuable mineral and the calcite is the main gangue. While, the chemical analysis of the original sample indicates that the ore contains 66.80% SrSO4, yet it is out of the economic criteria (i.e. at least 92-94% SrSO4) for its conversion to other important strontium salts. Meanwhile, the sample has relatively high limestone content, reaching 27.71% CaCO3 (Table 2). In addition, Table 3 shows the chemical analysis of the prepared size fractions to be used in the celestite separation by jigging technique due to the difference in the specific gravity between the celestite (about 3.95) and calcite (about 2.8).

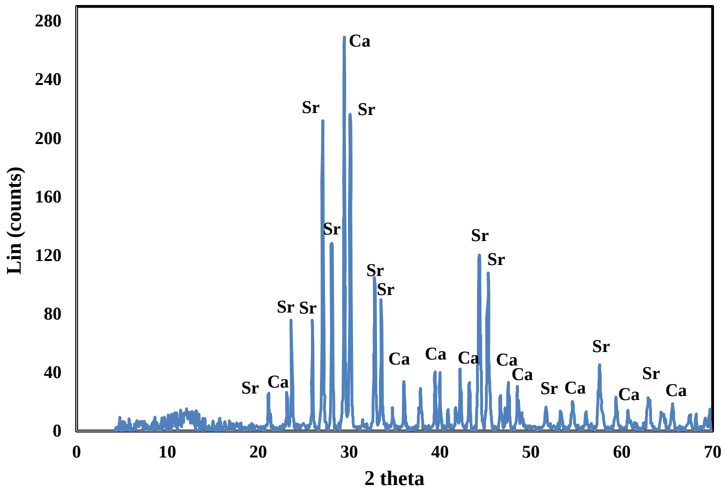

Fig. 2. XRD of the original celestite ore sample

Table 2. Chemical analysis of celestite original ore sample

Constituent	Assay Wt.%
$SrSO_4$	66.80
$CaCO_3$	27.71
SiO_2	2.05
Al_2O_3	0.44
Fe_2O_3	0.20
TiO_2	0.051
MgO	1.45
Na_2O	1.19
BaO	0.11
L.O.I.	11.90

Table 3. Chemical analysis of the studied celestite size fractions.

Size, mm	Wt%	SrO %	SrSO4%	CaCO3%	LOI%
-15+2.0	64.38	35.26	62.84	33.98	14.95
-2.0+0.50	19.47	46.25	81.96	18.05	7.94
-0.50+0.080	11.94	44.90	79.56	20.43	8.99

*LOI : Loss-on-ignition

3.2. Preliminary testing of separation by jig

To determine the suitability of jigging as a gravity separation process to celestite ore, a concentration criterion (C.C.) is commonly used which is defined by Eq. 1:

$$C.C. = \frac{D_H - D_F}{D_L - D_F} \quad (1)$$

where $D_H = 3.95$, $D_L = 2.71$ and $D_F = 1.00$ are the density of heavy mineral (celestite), light mineral (calcite) and fluid (water) respectively. Thus, C.C. of celestite ore is 1.73, and Fig. 3 shows the limitations graphically over a separation curve described by Burt (1984). Separation is possible above the line and impossible for concentration criteria below the line (Gupta et al, 2006). For C.C. of celestite ore at 1.76, gravity separation is effective to particle size coarser than 150 micron.

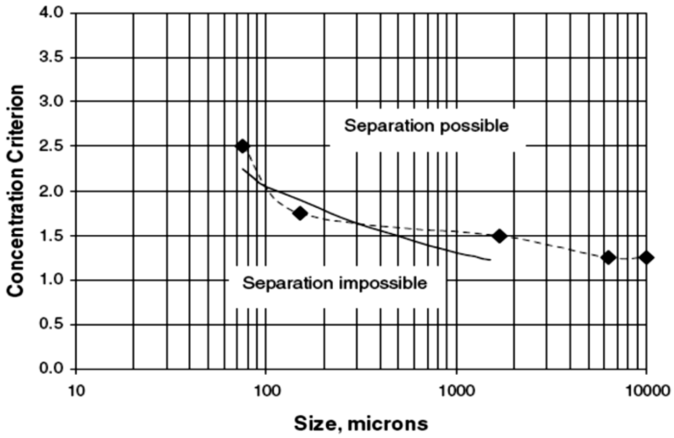

Fig. 3. Size limit curve for gravity separation

Table 4. Sink-float analysis for different size fractions of celestite ore

Particle Size, mm	Products	Wt.%	Grade		Recovery %	
			SrO%	LOI%	SrO%	LOI
-15.0+11.2	Heavy	15.93	52.55	3.03	24.53	77.42
	Light	52.25	23.39	25.76	35.81	19.80
	Mid.	31.82	42.56	10.82	39.67	100.00
	Total	100.00	34.75	16.91	100.00	2.40
-11.2+8.0	Heavy	18.23	53.70	2.13	27.45	83.70
	Light	58.02	26.49	23.35	43.07	13.90
	Mid.	23.75	44.29	9.47	29.49	100.00
	Total	100.00	35.68	16.18	100.00	1.37
-8.0+6.68	Heavy	27.79	55.50	0.73	41.15	79.53
	Light	48.06	25.07	24.45	32.15	19.10
	Mid.	24.14	41.44	11.69	26.69	100.00
	Total	100.00	37.48	14.78	100.00	2.71
-6.68+3.35	Heavy	41.01	55.33	0.86	57.05	83.49
	Light	41.74	23.11	25.98	24.26	13.80
	Mid.	17.25	43.11	10.39	18.70	100.00
	Total	100.00	39.77	12.99	100.00	4.79
-3.35+2.0	Heavy	52.33	55.19	0.97	67.41	89.71
	Light	41.06	26.74	23.15	25.63	5.50
	Mid.	6.61	45.13	8.81	6.96	100.00
	Total	100.00	42.84	10.59	100.00	19.35
-2.0+0.50	Sink	79.53	54.01	1.89	92.43	80.65
	Float	20.47	17.19	30.60	7.57	100.00
	Total	100.00	46.47	7.77	100.00	14.91
-0.50+0.08	Sink	77.35	54.23	1.72	93.23	85.09
	Float	22.65	13.44	33.52	6.77	100.00
	Total	100.00	44.99	8.92	100.00	100.00

For the gravity separation process to be efficient the degree of liberation was identified by using sink-float analysis for different size fractions of celestite ore, and the results are shown in Table 4. From Table 4. for all size fractions, there are free celestite particles with high SrO grade values above 52%. Whereas SrO recovery increases from 24.33% to 93.23% with reducing the particle size from -15.0+11.2 mm to -0.50+0.08 mm.

The response to separation is higher for the larger size fraction than the smaller ones. The difference in grade (SrO%) between the feed and its concentrate is about 15 units (i.e., from 35.26 to 51.43%) for -15.0+2.0 mm and about 8-9 units for - 2.0 + 0.5 mm and - 0.5 + 0.08 mm (i.e., from 46.25 to 55.3% and from 44.90 to 52.87%, respectively). More interestingly that the SrO recovery was almost the same, i.e., about 60% for the three size fractions.

The best grade was achieved for the feed with the particle size of -2.0 + 0.50 mm as shown in Table 5. These results can be attributed to the higher grade in this size feed and to the presence of a higher degree of liberation as reported by Abdel-Fattah (2008).

Table 5. Jigging separation in terms of feed particle size

Size, mm	Product	Wt.%	Grade		Recovery	
			SrO%	LOI%	SrO%	LOI%
	C	27.19	51.43	3.90	61.60	10.26
	T	37.19	24.45	24.94	38.40	89.74
	Calc.	64.38	35.84	16.05	100.00	100.00
	Orig.	64.38	35.26	14.95	100.00	100.00
-2.0+0.5	C	10.25	55.30	0.88	61.75	6.40
	T	9.22	38.08	14.31	38.25	93.60
	Calc.	19.47	47.15	7.24	100.00	100.00
	Orig.	19.47	46.25	7.94	100.00	100.00
-0.5+0.08	C	5.97	52.87	2.78	57.59	16.93
	T	5.97	38.94	13.64	42.41	83.07
	Calc.	11.94	45.90	8.21	100.00	100.00
	Orig.	11.94	44.90	8.99	100.00	100.00

*LOI : Loss-on-ignition

3.3. Statistical analysis

Table 6 shows the results of different experimental runs of the statistical design in terms of SrO% and its recovery in the concentrate. In addition, Tables 7-8 show the analysis of variance tables for SrO grade and recovery. The ANOVA tables indicate the significance of the used models where the standard deviation and R-Squared for SrO grade and recovery in the concentrate are 0.17, 0.9997, and 10.82, 0.9532, respectively. The larger the diameter of the ragging balls as well as the lower the number of the ragging layers, is the lower the separation.

3.4. SrO grade and recovery

Figure 3(a-b) shows the contour plot of the concentrate grade at different levels of the studied factors. For instance, at one layer of ragging balls, the high-grade concentrate (about 55% SrO) is obtained at a small ball diameter and with separation time up to 15 minutes, Fig.4-a. It is obvious that a cleaner concentrate is obtained not only by increasing the ragging balls layers to 3 layers (Fig.4b), but also by reducing the diameter of the ragging balls. It is worth to mention that either reducing the ragging balls diameter, lower than 3.9 mm, or increasing the ragging layers resulted in longer separation time. This behaviour can be attributed to the size of pores between the balls, which plays an important role in regulating the flow inside the separation bed.

Similarly, Fig. 5(a-b) shows the response surfaces for the SrO recovery in the concentrate at different values of the studied factors. It is noticed that the SrO recovery is about 100% (i.e. no separation due to the passage of all particles, either celestite or its gangues, to the concentrate fraction) using one ragging layer (Fig. 5a). Increasing the ragging layers with using smaller ragging balls diameter increases the grade as previously mentioned but on expenses of the recovery (Fig. 5b).

Table 6. Box-Behnken design results in terms of different responses

No.	A Ragging ball dia., mm	B Ragging layers	C Separation time, min	SrO%	SrO Recovery %
1	3.1	1	15	53.34	75.1
2	4.7	1	15	43.7	100
3	3.1	5	15	53.78	2.9
4	4.7	5	15	43.7	100
5	3.1	3	5	54.12	4.8
6	4.7	3	5	53.1	63.6
7	3.1	3	25	53.87	30.6
8	4.7	3	25	43.7	100
9	3.9	1	5	43.7	100
10	3.9	5	5	53.1	16.1
11	3.9	1	25	43.7	100
12	3.9	5	25	53.8	48.2
13	3.9	3	15	53.8	64.9
14	3.9	3	15	53.64	69.4
15	3.9	3	15	53.92	59.9

Table 7. ANOVA for SrO grade

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	330.83	11	30.08	1026.85	< 0.0001	significant
A	31.30	1	31.30	1068.80	< 0.0001	
B	95.06	1	95.06	3245.68	< 0.0001	
C	0.1225	1	0.1225	4.18	0.1334	
AC	20.93	1	20.93	714.63	0.0001	
BC	0.1225	1	0.1225	4.18	0.1334	
A^2	5.93	1	5.93	202.40	0.0008	
B^2	55.86	1	55.86	1907.22	< 0.0001	
C^2	6.45	1	6.45	220.35	0.0007	
A^2B	45.41	1	45.41	1550.43	< 0.0001	
A^2C	13.39	1	13.39	457.18	0.0002	
AB^2	9.10	1	9.10	310.53	0.0004	
Residual	0.0879	3	0.0293			
Lack of Fit	0.0484	1	0.0484	2.45	0.2578	not significant
Pure Error	0.0395	2	0.0197			
Cor Total	330.91	14				

It is known that the particle shape plays an important role in the separation of particles (Brożek and Surowiak, 2007). In this study, the aspect ratio of the celestite particles range from 1:2 to 1:4 which may explain the purer concentrate in case of smaller ragging balls diameter where the celestite particles can orient themselves and pass-through the voids easier than the gangue particles.

Correlations of SrO grade and recovery in the concentrate with the studied operating parameters are given by regression equations (2) and (3), respectively.

$$\text{SrO grade} = +53.79 - 2.80*A + 4.87*B + 0.175*C - 2.29*A*C + 0.175*B*C - 1.27*A2 - 3.89*B2 - 1.32*C2 - 4.77*A2*B - 2.59*A2*C - 2.13*A*B2 \quad (2)$$

$$\text{SrO recovery} = +64.73 + 31.7*A - 33.93*B + 11.79*C + 18.05*A*B + 8.03*B*C - 5.78*A2 + 10.55*B2 - 9.20*C2 + 15.87*A2*B \quad (3)$$

where A is ragging balls diameter (mm), B is ragging balls number of layers and C is time of separation (min).

Table 8. ANOVA for SrO recovery

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	17316.28	9	1924.03	50.28	0.0002	significant
A	7825.01	1	7825.01	204.51	< 0.0001	
B	4603.62	1	4603.62	120.32	0.0001	
C	1111.56	1	1111.56	29.05	0.0030	
AB	1303.21	1	1303.21	34.06	0.0021	
BC	257.60	1	257.60	6.73	0.0486	
A^2	123.32	1	123.32	3.22	0.1326	
B^2	410.64	1	410.64	10.73	0.0221	
C^2	312.80	1	312.80	8.18	0.0354	
A^2B	504.03	1	504.03	13.17	0.0151	
Residual	191.31	5	38.26			
Lack of Fit	146.15	3	48.72	2.16	0.3323	not significant
Pure Error	45.17	2	22.58			
Cor Total	17507.59	14				

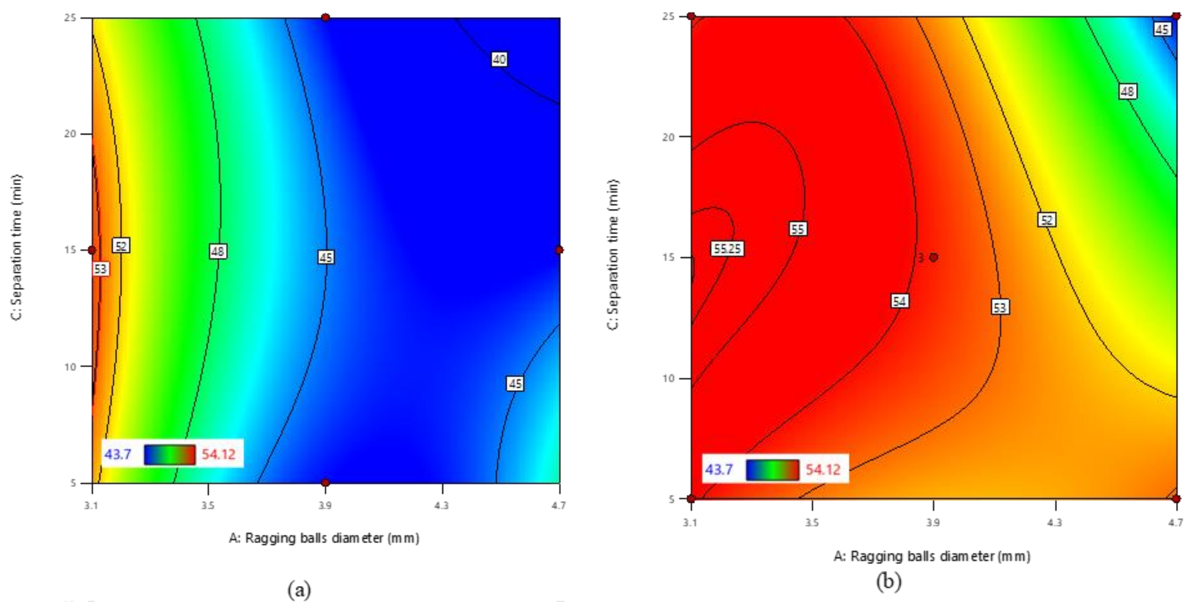

Fig. 4. Concentrate grade in terms of separation time and ragging balls diameter at a) one ragging layer, b) three ragging layers

3.5. Effect of ragging balls: diameter and number of layers

Considering two arrangements of ragging balls; namely, triangle and square arrangements as the extreme possible arrangements (Fig.6), where other arrangements are located between them. The square arrangement creates wider voids than triangle arrangements as indicated by equations (4) and (5). Of course, during the dilatation of the bed, the voids between the particles are certainly between the void sizes of these two arrangements which allow the penetration of concentrate particle through.

For square arrangement: $$d = \left(\sqrt{2}-1\right)D = 0.4\ D \tag{4}$$

For triangle arrangement: $$d = \left(\frac{2\sqrt{3}}{3}-1\right)D = 0.155\ D \tag{5}$$

where d is the voids between ragging balls and D is the ragging ball diameter.

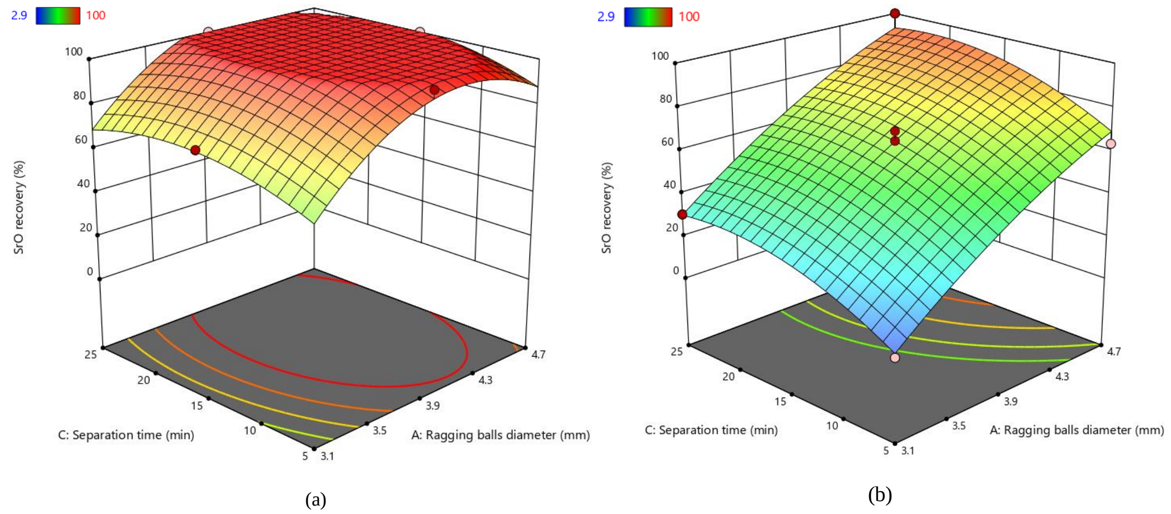

Fig. 5. Response surfaces for the SrO recovery in the concentrate as a function of separation time, ragging balls diameter, and different ragging layer(s), a) one layer, b) three layers

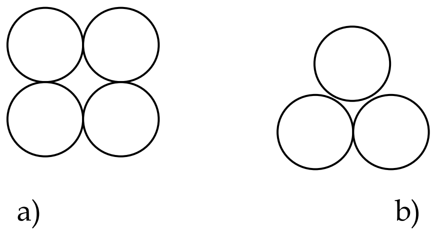

Fig. 6. Possible arrangements for ragging balls a) square, b) triangle.

The smaller the ragging balls size is the smaller the pores and the higher the localized flow velocity that consequently helps in better stratification of the particles. On the other hand, at a higher number of ragging layers, longer separation time is needed to achieve more proper stratification especially for the heavier particles (i.e., celestite particles) due to the higher the resistance and the longer the particle trajectory from the separation bed to the concentrate fraction (Fig.4).

In addition, Fig.7 shows the results of jigging separation for 15 min in terms of concentrate grade as a function of numbers of ragging layers at different ragging balls sizes. The celestite grade increases by increasing the number of layers till 3 ragging layers for different balls diameters. Using more than 3 layers, the decline in the concentrate grade begins to be rectified as the ragging ball diameter gets smaller. The highest grade (> 55 % SrO) was obtained using 3.5 mm balls into 4 layers.

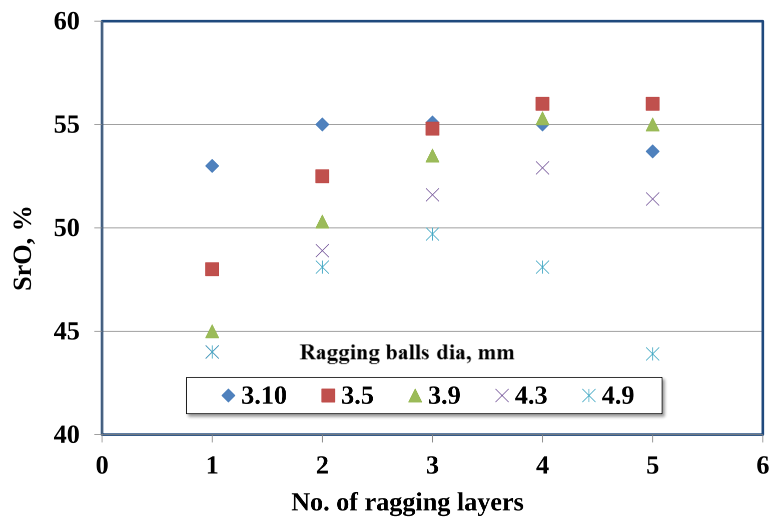

Fig. 7. Concentrate grade as function of ragging layers and their balls diameters at 15 min of jigging.

The observed behavior can be explained in terms of the weight of the ragging balls and their layers and the opening (voids) between balls. In other words, the larger the balls or the number of layers is the heavier the ragging bed and the poorer degree of stratification. Accordingly, the needed water flow to lift the balls and dilate the bed is higher. On the other hand, the larger the balls is the larger the voids between them which allow the passing of the celestite as well as the gangue minerals. Fig. 8 confirms this finding where the larger the ragging balls the higher the SrO recovery, which explains the behavior of 4.9 mm balls especially at a lower number of layers. However, at a higher number of layers, the high resistance to water flow due to the weight of different layers elongates the separation time. In addition, the high resistance of thick ragging layers leads to high flow velocity through the voids and turbulence that resulted in the entire bed mixing, low degree of stratification, and lower SrO grade and recovery. In the case of 3.1 mm balls, it follows the same trend as other balls diameters till number of its layers reach 3 layers after which the high velocity of water coming through the voids leads to the turbulence, due to very high resistance to flow, which reduces the grade and unreasonably elongate the stratification time which consequently affects the SrO recovery. For instance, the SrO recovery equals zero at 5 layers of 3.1 mm balls which means that there are no particles were passed through the ragging layers or no particles were reported in the concentrate fraction.

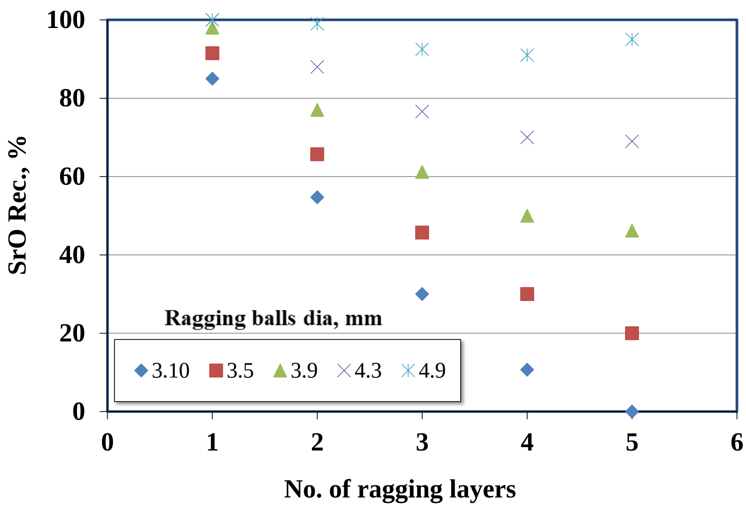

Fig. 8. SrO recovery as function of ragging layers and ragging balls diameters at 15 min separation time

Therefore, the optimum separation conditions in terms of the ragging balls diameter and their number of layers depend mainly on the bed porosity from one side and the resistance because of the number of layers from the other side. In other words, the voids control the SrO recovery while the resistance controls the grade of the produced concentrate. The SrO recovery is higher in the case of the larger balls in ragging bed due to the larger the voids which allow the passage of higher wt % and the lower resistance to water flow which leads to better bed stratification. For instance, the one layer of 3.1 mm balls produces the same grade of the two layers of 3.5 mm balls but the SrO recovery is higher in case of one layer of 3.1 mm balls. Numerically, to achieve the concentrate grade that meets the industrial applications can be achieved by using one layer of 3.1 mm balls where the SrO grade and recovery are 53.4% and 74.5%, respectively. Moreover, the highest grade (54.1% SrO) with a SrO recovery of 55.3% can be achieved using two layers of 3.1 mm balls.

4. Conclusions

Celestite upgrading by jigging was investigated in the presence of ragging material. Three sizes fraction -15+2 mm, -2+0.5 mm, -0.5+0.08 mm were tested under different conditions of ragging balls size, numbers of ragging layers, and separation time. These conditions and their mutual interaction on the SrO grade and recovery of the concentrate were investigated and optimized using statistical design of experiments. The celestite grade and recovery were correlated to operating variables. The results indicated that the ragging balls diameter and the number of ragging layers are the most significant parameters. It was found that the smaller the ragging balls diameter and/or the higher the ragging number of layers is the better the concentrate grade at fixed separation time. A celestite concentrate contains more than 95% SrSO4 with 74.5% recovery, can be produced at optimum conditions; i.e., 3.1 mm ragging balls diameter, one layer of ragging balls, and 15 minutes separation time.

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