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BENEFICIATION OF OXIDE ORES USING DENSE MEDIUM CYCLONES. A SIMULATION STUDY

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Abstract: Recent investigations of particle behavior and segregation phenomena in a cyclone underline that little is known about particle distribution within a heavy medium separation. For this purpose, density profiles in a heavy medium cyclone (HMC) is measured with techniques such as computational fluid dynamics (CFD) in combination with discrete element modelling (DEM), electrical resistance tomography (ERT), X-ray tomography, particle dynamics analyzer (PDA) etc. Along with these modern efforts of determining the performance of HMC, traditional methods depending on empirical inferences based on experimental data are still important and in progress. The aim of this research was to investigate the possibility of using HMC for the concentration of problematic ores which are not coarsely aggregated. Towards this purpose, current empirical methods were applied to experimental data which were derived from float-sink tests of selected heavy minerals and Fe, Mn, and Cr ore samples. Low density difference between particles made the enrichment difficult using other gravity methods like jigs and shaking tables. After determining physical and mineralogical properties of the samples, appropriate size fractions were prepared for float-sink tests. Combination of sodium polytungstate and tungsten carbide powder were used to prepare non-toxic heavy liquids with density up to 3.5 g/cm^3. Using the sink-float test results and existing empirical models for high-density DMC plants simulations were performed. The results of the simulations followed by experimental studies showed that HMCs are applicable to process Fe, Mn, and Cr ores with acceptable grade and recovery.

Keywords: *heavy medium cyclone, heavy liquid, simulation, iron ores, manganese, chromite*

Introduction

Dense medium cyclones (DMCs) provide more precise separation than other gravity processing methods, especially when the amount of material float/sink within ±0.1 density range is above 10% (Burt, 1984;Wills and Napier-Munn, 2006).

The DMCs are used extensively in coal preparation plants. They have been installed in over one-quarter of the coal preparation plants worldwide (Reeves, 2002).

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De Korte (2000) reported that approximately 93% of 58 coal preparation plants in South Africa employ DMCs.

Although the number of applications is not comparable to that of coal, DMCs are also applied to a variety of metalliferous and industrial minerals (Burt, 1984). Iron ore beneficiation (Krige, 1987; Mason and McSpadden, 2002), diamond preconcentration (Dardisl and Mack, 1987; Rylatt and Popplewell,1999; Waanders and Rabatho, 2004), lead–zinc and silver beneficiation (Scott, 1985), copper ore preconcentration (Walter et al., 1999), andalusite ore beneficiation (Munnih, 1994), chromite concentration (Burt, 1984; Francis, 2009), fluorspar preconcentration (Burt, 1984), manganese concentration (Sassos, 1984), and tungsten preconcentration (McNiel, 1982) are examples of DMC use in mineral beneficiation.

The amenability of dense medium separation is evaluated by using heavy liquid tests (Burt, 1984). However, the availability and use of high-density liquids such as Clerici's solution is limited or prohibited in many countries. A promising alternative is sodium polytungstate–tungsten carbide powder mixtures with densities up to 4 g/cm^3 (Koroznikova et al., 2007).

For better phenomenological understanding of the process, computational fluid dynamics (CFD) in combination with the discrete element method (DEM) and empirical models based on parameters such as density, turbulence, and cyclone dimensions are used (Narasimha et al., 2007; Azadi et al., 2010; Kepa, 2013; Elsayed and Lacor, 2013). Even though the CFD–DEM method is a thriving and promising engineering tool, further development is still needed to predict DMC performance.

On the other hand, empirical models have been improved over the past few decades in order to predict the metallurgical performance of a given unit (Scott, 1988). Such models enable prediction of the effects of alternative operating procedures without the need for a mass of planned test work. However, these models require a large quantity of experimental data. Complications in calculations involving parameters such as the presence of swirling turbulence or an air core and segregation of the medium and particles are challenging. Furthermore, the presence of multiple phases, i.e., air, water, mineral/coal, and magnetite/ferrosilicon particles of different sizes, densities, and other properties make DMC modeling extremely complicated (Scott et al., 1990). Although there is still not an ultimate model for low- and high-density separation, current models for specific operations have been substantially improved.

Most of the existing models are based on low-density operations and are useful for coal washing plants. In the case of high-density operations, certain models have been published to predict the performance of DMCs for the preconcentration of lead–zinc ore in the Mount Isa concentration plant (Scott, 1988). In addition, DMC models for diamond ore have been studied (Scott et al., 1990).

Except for a few earlier applications in chromite and magnesite, current application of DMCs in Turkey is limited to coal washing, although its application would be beneficial for some problematic ores (Aghlmandi, 2014). In that study, application of DMCs for iron, manganese, and chromite ores were evaluated using simulations.

Experimental studies

Materials

The samples of iron, manganese, and chromite ores were selected because gravity separation methods such as jigging and shaking tables are not efficient. After determining the physical and mineralogical properties of the samples, the samples were prepared in appropriate size fractions for the sink–float tests. The results of the initial particle-size distribution analysis of the samples are shown in Fig. 1.

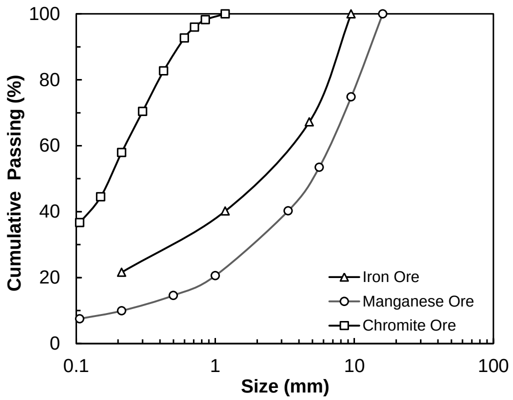

Fig. 1. Particle-size distribution of samples

The Fe content of the iron ore sample was 31.9%. The X-ray diffraction (XRD) analysis revealed that the ore consisted of hematite (Fe_2O_3) with density of 5.26, goethite [FeO(OH)] 3.3–4.3, and silicates 2.6–2.8 g/cm^3. The overall density of the sample was measured as 3.18 g/cm^3. The iron ore sample was screened to −9.5+4.75 mm, −4.75+1.18 mm, −1.18+0.212 mm, and −0.212 mm size fractions for sink–float tests.

The density of the manganese ore sample was measured as 3.07 g/cm^3, and the Mn content of the sample was 25.47%. The XRD analysis showed that the main manganese mineral in the sample was pyrolusite (MnO_2), with density of 4.4–5.06 g/cm^3, and that the main gangue mineral was quartz (2.65 g/cm^3). The manganese ore sample was screened into four size fractions (−16+5 mm, −5+1 mm, −1+0.2 mm, and −0.2 mm) for sink–float tests.

The chromite ore sample was obtained from rod mill discharge of an operating mine in the Adana region of Turkey. The ore consisted of magnesiochromite ($(Mg,Fe)(Cr,Al)_2O_4$) with density of 4.2 g/cm^3, magnesite ($MgCO_3$, 3–3.2 g/cm^3), chromite ($FeCr_2O_4$, 4.5–4.8 g/cm^3), lizardite ($Mg_3(Si_2O_5)(OH_4)$, 2.38 g/cm^3), and chrysotile [$Mg_3(Si_2O_5)(OH)_4$, 2.53 g/cm^3). The mean density of the feed sample was 2.58 g/cm^3.

Chromite ore has a challenging mineralogy. Because of low amount of free particles which leads to a small degree of liberation, the sink–float tests at coarser size fractions were not satisfactory. Therefore, size reduction to -1.18 mm was performed. The degree of liberation (Table 1) and size-by-size Cr_2O_3 distribution (Table 2) were determined for different size fractions.

Table 1. Degree of liberation for different size fractions of chromite ore

Size Fraction (µm)	Degree of Liberation (%)
−850+600	3.89
−600+425	26.77
−425+300	35.21
−300+212	53.39
−212+150	71.97

Table 2. Cr_2O_3 content of different size fractions of chromite ore sample

Size Fraction (µm)	Weight (%)	Cr_2O_3 (%)	Cr_2O_3 Distribution (%)
−1180+425	18.28	3.53	11.48
−425+212	24.75	5.84	25.71
−212+150	13.44	7.50	17.93
−150+106	7.83	9.19	12.80
−106+75	7.64	9.00	12.23
−75+53	4.36	7.42	5.75
−53+38	3.60	6.10	3.91
−38	20.10	2.85	10.19
Total	100.00	5.62	100.00

Table 1 clearly shows that the liberation would be incomplete unless the fine grinding is applied. In this case, however, too much fine material would be generated, increasing the losses in gravity concentrators such as spirals and shaking tables. The total reserve in the area is 200 Tg divided among several mines having similar mineralogy. Considering the lower feed grade, high operating costs, and declining chromite prices, DMCs are expected to recover more material at this coarse particle-size range or remove barren gangue for further processing.

Methods

Heavy liquids have been widely used in the laboratory for the appraisal of gravity separation techniques. Most high-density heavy liquids are organic and highly toxic, and thus working with them requires close attention, even in a laboratory environment (Burt, 1984). Aqueous solutions of sodium polytungstate (SPT) have certain advantages over organic liquids in that they are non-volatile and non-toxic with densities of up to 3.1 g/cm^3. For higher densities, Koroznikova et al. (2007) developed a technique using a finely ground tungsten carbide (TC) suspension in SPT to obtain densities up to 4 g/cm^3.

In this study, a tetrabromoethane (TBE) and acetone mixture was used to prepare the heavy liquids with density of 2.7 and 2.9 g/cm^3. The suspensions of sodium polytungstate (SPT) and tungsten carbide powder (TC) were used to prepare the heavy suspensions with density of 3.2 and 3.5 g/cm^3.

The SPT-TC suspension was prepared as follows. An SPT solution with a 2.5 g/cm^3 density (viscosity will be somewhat low for fine particle separation) was prepared. About 20–30% of the SPT solution was transferred into a separate container and stirred. The TC powder was added very slowly to make a homogenous suspension. The TC–SPT suspension was mixed with the remaining SPT solution to obtain the desired density.

Results and discussion

After preparation of heavy liquids at the desired densities, the sink–float tests were performed. In the case of coarse samples (+1 mm), a normal beaker was used, but for fine size fractions (−1 mm) a special funnel was used. The results are presented in Tables 3–5 for iron, manganese, and chromite ores, respectively.

Table 3. Sink-float- results for the size fractions of iron ore sample

Size	Product	Weight (%)	Fe (%)	Recovery (%)	Cumulative to Sinks			
					Density (g/cm^3)	Weight (%)	Fe (%)	Recovery (%)
−9.5+4.75 mm	Sinks 3.5	27.78	70.74	56.97	3.5	27.78	70.74	56.97
	−3.5+3.2	13.09	47.43	17.99	3.2	40.87	63.28	74.96
	−3.2+2.9	16.18	27.87	13.08	2.9	57.05	53.23	88.04
	−2.9+2.7	11.35	13.55	4.46	2.7	68.41	46.65	92.50
	Floats 2.7	31.59	8.19	7.50		100	34.50	100
	Total	100	34.50	100				
−4.75+1.18 mm	Sinks 3.5	32.82	67.71	63.73	3.5	32.82	67.71	63.73
	−3.5+3.2	12.17	48.12	16.79	3.2	44.99	62.41	80.52
	−3.2+2.9	13.54	25.56	9.92	2.9	58.53	53.89	90.44
	−2.9+2.7	9.59	12.81	3.52	2.7	68.12	48.11	93.97
	Floats 2.7	31.88	6.60	6.03		100	34.87	100
	Total	100.00	34.87	100.00				
−1.18+0.212 mm	Sinks 3.5	38.58	61.68	68.94	3.5	38.58	61.68	68.94
	−3.5+3.2	10.78	43.51	13.59	3.2	49.36	57.71	82.53
	−3.2+2.9	17.26	25.68	12.84	2.9	66.62	49.41	95.37
	−2.9+2.7	4.33	9.13	1.14	2.7	70.95	46.95	96.51
	Floats 2.7	29.05	4.14	3.49		100	34.51	100
	Total	100.00	34.51	100.00				

The difficulty in gravity concentration processes can be evaluated using heavy-liquid test results. When the amount of near-gravity particles is higher than 10%, it is difficult to obtain good results with jigs, tables, spirals, and other gravity methods; the only efficient gravity method is heavy medium separation (Wills and Napier-Munn, 2006). Table 6 shows the amount of near-gravity particles for difference ores at different size fractions which calculated based on the sink-float test results.

It is apparent from Table 6 that the amount of near-gravity particles in all these ores is more than 10% in most of the size fractions. Therefore, these ores are relatively difficult to beneficiate with the above mentioned gravity methods, and thus the use of DMC is inevitable for their beneficiation.

Table 4. Sink–float results for the size fractions of manganese ore sample

Size	Product	Weight (%)	Mn (%)	Recovery (%)	Cumulative to Sinks			
					Density (g/cm^3)	Weight (%)	Mn (%)	Recovery (%)
−16+5mm	Sinks 3.5	10.25	41.05	14.96	3.5	10.25	41.05	56.97
	−3.5+3.2	24.46	40.27	35.01	3.2	34.71	40.50	74.96
	−3.2+2.9	30.16	39.42	42.26	2.9	64.87	40.00	88.04
	−2.9+2.7	5.69	10.61	2.15	2.7	70.56	37.63	92.50
	Floats 2.7	29.44	5.37	5.62		100	28.13	100
	Total	100	28.13	100				
−5+1mm	Sinks 3.5	19.69	40.35	34.31	3.5	19.69	40.35	63.73
	−3.5+3.2	12.05	39.88	20.76	3.2	31.74	40.17	80.52
	−3.2+2.9	28.10	32.91	39.94	2.9	59.84	36.76	90.44
	−2.9+2.7	5.09	8.52	1.87	2.7	64.93	34.55	93.97
	Floats 2.7	35.07	2.06	3.12		100	23.15	100
	Total	100.00	23.15	100.00				
−1+0.2mm	Sinks 3.5	14.19	37.33	26.67	3.5	14.19	37.33	68.94
	−3.5+3.2	20.84	33.22	34.86	3.2	35.02	34.88	82.53
	−3.2+2.9	26.58	25.94	34.72	2.9	61.60	31.03	95.37
	2.9+2.7	2.22	10.73	1.20	2.7	63.83	30.32	96.51
	Floats 2.7	36.17	1.40	2.55		100.00	19.86	100
	Total	100.00	19.86	100.00				

Table 5. Sink–float results for the size fractions of chromite ore sample

Size	Product	Weight (%)	Cr_2O_3 (%)	Recovery (%)	Density (g/cm^3)	Cumulative to Sinks Weight (%)	Cumulative to Sinks Cr_2O_3 (%)	Cumulative to Sinks Recovery (%)
−1.18+0.425mm	Sinks 3.5	1.25	45.82	18.89	3.5	1.25	45.82	18.89
	−3.5+3.2	0.65	31.17	6.63	3.2	1.90	40.83	25.53
	−3.2+2.9	2.38	22.18	17.38	2.9	4.29	30.45	42.91
	−2.9+2.7	3.18	13.77	14.41	2.7	7.47	23.34	57.32
	Floats 2.7	92.53	1.40	42.68		100	3.04	100
	Total	100	3.04	100				
−0.425+0.212mm	Sinks 3.5	6.50	50.25	68.95	3.5	6.50	50.25	68.95
	−3.5+3.2	2.73	22.15	12.76	3.2	9.23	41.94	81.71
	−3.2+2.9	1.08	16.95	3.87	2.9	10.32	39.32	85.57
	−2.9+2.7	3.09	12.21	7.95	2.7	13.40	33.08	93.52
	Floats 2.7	86.60	0.35	6.48		100	4.74	100
	Sinks 3.5	100	4.74	100				

Table 6. The amount of near-gravity particles for different ores

	Size fraction (mm)	Cum. Sinks Weight (%) –0.1 of Separation density	Cum. Sinks Weight (%) +0.1 of Separation density	Difference
Iron ore	−9.5+4.75	51.50	40.78	10.63
	−4.75+1.18	54.00	45.00	9.00
	−1.18+0.212	61.00	49.36	11.64
Manganese ore	−16+5	69.00	55.40	13.60
	−5+1	63.75	51.00	12.75
	−1+0.2	64.00	53.50	10.50
Chromite ore	−1.18+0.425	33.46	20.08	13.38
	−0.425+0.212	71.62	61.55	10.07

Simulation studies

All the DMC models are based on partition curves. A typical partition curve is given in Fig. 2.

The probable error of separation or the *Ecart probable* (*Ep*) is defined as half the difference between the density where 75% is recovered to sinks and that at which 25% is recovered to sinks. The *Ep* value generally increases with the increasing separation density and decreases with coarser sizes.

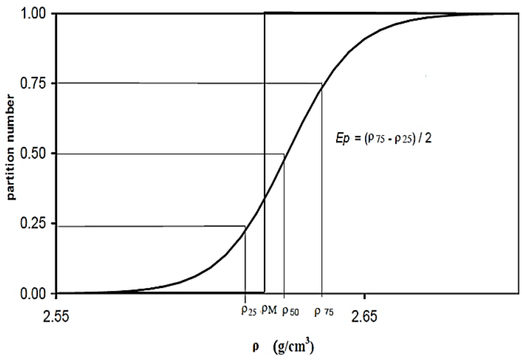

Fig. 2. Typical partition curve for sink product

Several mathematical expressions have been suggested in literature to describe the partition curve (Whiten, 1966; Rong and Lyman, 1895). One of the most widely used expressions is given in Eq. 1 (Scott, 1988):

$$Y_j = \frac{1}{1+\exp[\frac{1.099(\rho_{50}-\rho_j)}{Ep}]} \tag{1}$$

where Y_j - weight fraction of density species ρj in the feed which reports to underflow
ρ_{50}- separation density
E_p - probable error.

In the case of high-density separation, the *Ep* value can be calculated by the following equations:

$$Ep = Z + K.d^n \ (n = -1) \tag{2}$$

$$Z = 19.6 + 0.16\Delta\rho - 6.3Vmo \tag{3}$$

$$\ln(k) = 6.87 + 0.59\ \ln(\mu) + 0.30\ln(D_c) \tag{4}$$

where $\Delta\rho$ is the density differential in the cyclone, *Vmo* is the volumetric medium-to-ore ratio, μ is the heavy-medium viscosity, and D_c is the cyclone diameter.

In this study, the values of *Z* and *K* were taken as 4 and 52, respectively. They were calculated for 400 mm DMC of a diamond plant and were used to predict the *Ep* values for different size fractions (Scott et al., 1990). The values are presented in Table 7.

In this research, the Lave 1.0 program developed by Orhan et al. (2010) at the Department of Mining Engineering of Hacettepe University was used to carry out the simulation. The program uses the JKMRC model based on Eq. 1. For the size separation, the Whiten efficiency curve was used (Whiten, 1966).

Table 7. Calculated *Ep* values for different size fractions

Iron ore			Manganese ore			Chromite ore		
Size fractions (mm)	Mean size (mm)	Calculated *Ep*	Size fractions (mm)	Mean size (mm)	Calculated *Ep*	Size fractions (mm)	Mean size (mm)	Calculated *Ep*
−9.5+5.0	7.25	0.011	−16+5	10.5	0.009	−1.1+0.4	0.80	0.069
−5.0+1.0	3.0	0.021	−5+1	3.0	0.021	−0.4+0.2	0.31	0.172
−1.0+0.2	0.6	0.091	−1+0.2	0.6	0.091			

In the simulation studies, a simple circuit consisting of a sizing screen and a DMC was considered (Fig. 3). The *Ep* values are given in Table 7, and the separation densities from 2.5 g/cm^3 to 3.5 g/cm^3 in 0.1 g/cm^3 increments were used. The grade and recovery figures against the separation density for iron, manganese, and chromite ores are given in Figs. 4, 6, and 8, respectively. Figure 11 shows the relationship between grade and recovery for all ores.

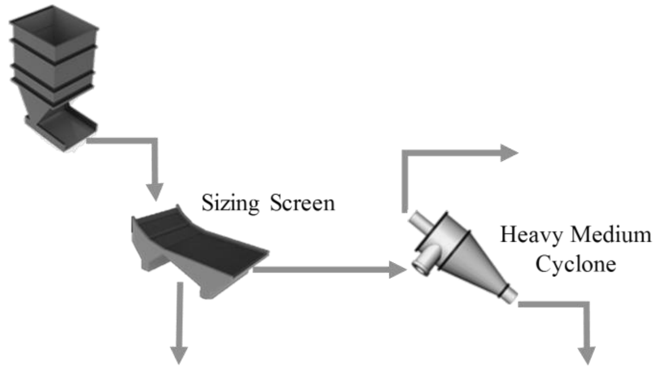

Fig. 3. Schematic illustration of the circuit used in the simulation studies

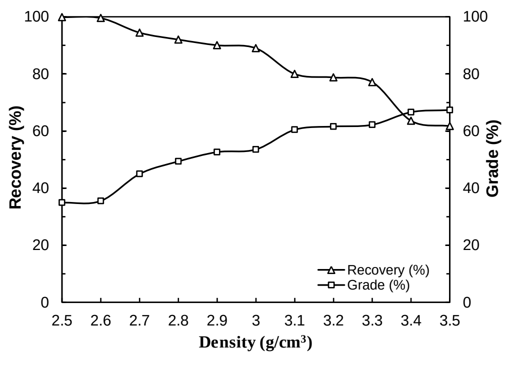

Fig. 4. Grade and recovery changes
as a function of separation density for iron ore

Using the data presented in Fig. 4, a separation density of 3.1 g/cm^3 was determined to be the optimum value. It is possible to obtain a concentrate having 60.46% Fe with 79.98% Fe recovery. Figure 5 shows the simulated performance of the circuit at 85 Mg per hour feed capacity.

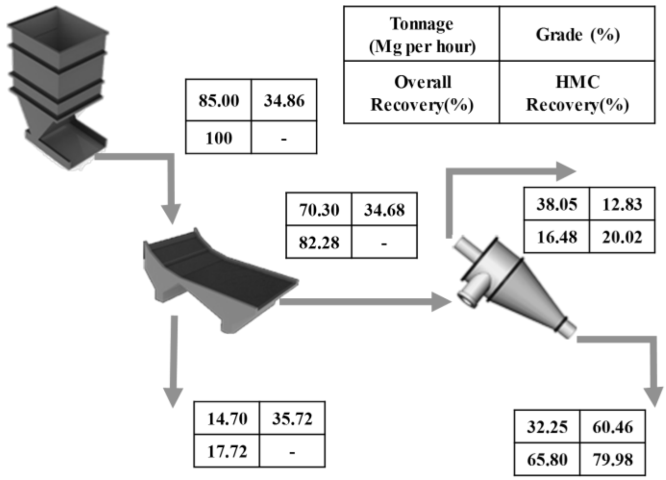

Fig. 5. Simulated performance of DMC plant for iron ore at a density of 3.1 g/cm^3

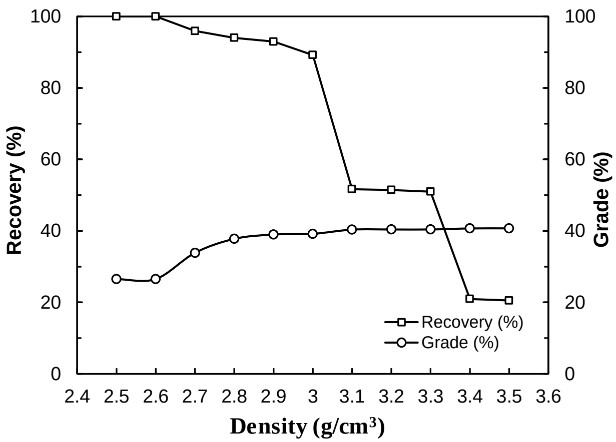

Fig. 6. Grade and recovery changes as a function of separation density for manganese ore density

A separation density of 2.9 g/cm^3 was the most favourable for the manganese ore circuit. A concentrate with 38.99% Mn grade and 93.02% Mn recovery that contained 63.31% of the heavy medium plant's feed was achieved. In addition, 36.80% of the cyclone feed with 5.03% Mn grade was rejected at this separation density. Figure 7 shows the simulated flowsheet for manganese ore with a 20 Mg per hour feed capacity and a separation density of 2.9 g/cm^3.

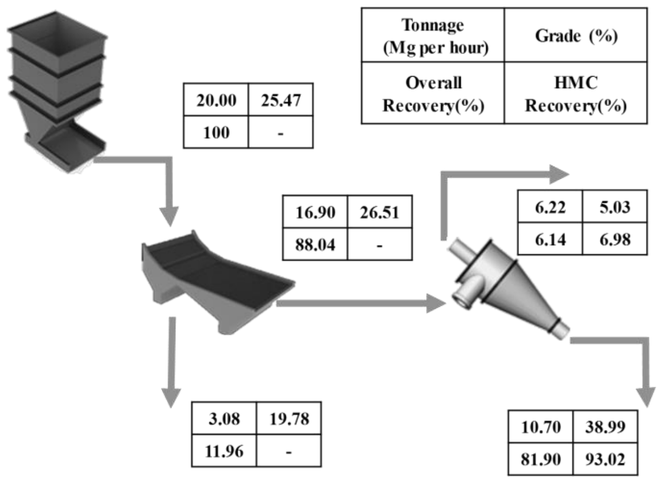

Fig. 7. The simulated performance of the DMC plant for manganese ore at a density of 2.9 g/cm^3 density

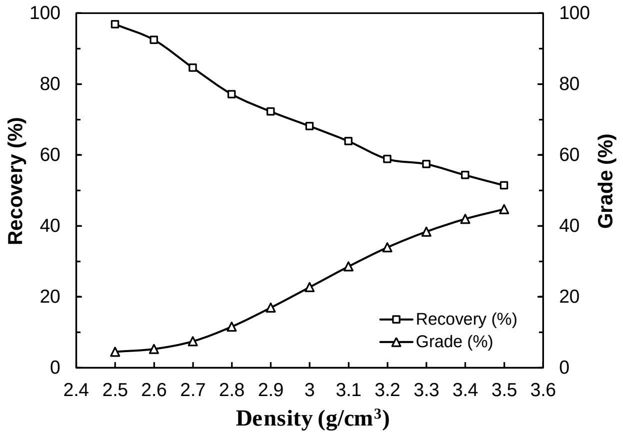

Fig. 8. Grade and recovery changes as a function of separation density for chromite ore density

For chromite ore, two separation densities, namely 3.5 g/cm^3 and 2.9 g/cm^3, were studied. Figure 9 shows the simulated flowsheet at a separation density of 3.5 g/cm^3. A concentrate with 44.75% Cr_2O_3 and 51.44% recovery was obtained using DMC.

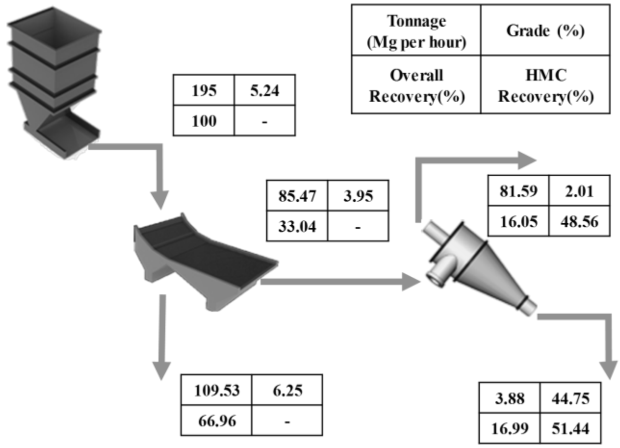

Fig. 9. The simulated performance of the DMC plant for chromite ore at a density of 3.5 g/cm^3

The simulation results for the pre-concentration of chromite ore are shown in Fig. 10. In this case, 25% of the plant feed was removed with a 1% Cr_2O_3 content and 15% metal loss.

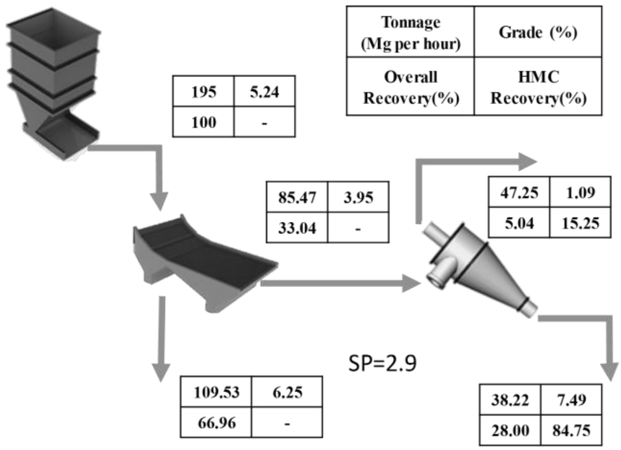

Fig. 10. The simulated performance of the DMC plant for chromite ore at a density of 2.9 g/cm^3

Application aspects

Based on the simulation results, the full mass balance including the medium was calculated. Then, using the approach proposed by Bosman (2006), the dimensions of the DMC cyclones were calculated. Bosman presented a series of equations to calculate the main parameters for DMC application. They are given in Table 8.

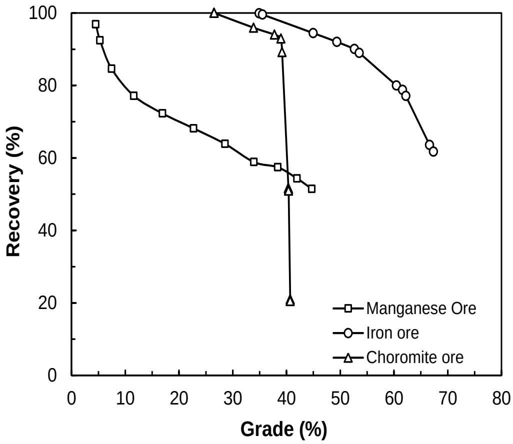

Fig. 11. Relationship between grade and recovery for different samples

Table 8. Equations used in DMC sizing (Bosnan, 2002)

Form	*y*	*x*	*a*	*n*
$y = ax^n$	Slurry capacity (m^3/h)	Cyclone diameter (mm)	0.000149	2.193722
$y = ax^n$	Spigot capacity (m^3/h)	Spigot diameter (mm)	0.004425	1.616769
$y = ax^n$	Breakaway size (mm)	Cyclone diameter (mm)	5.09E-0.5	1.665890
$y = ax^n$	Top size (mm) – square	Cyclone diameter (mm)	0.58638	1.001154
$y = ax^n$	Top size (mm) – rectangular	Cyclone diameter (mm)	0.037327	1.000175

For the iron ore, a DMC having a 500 mm diameter was calculated to be sufficient. The medium/ore ratio was taken to be 5, and the pressure was taken to be 12×diameter (182 kPa). The breakaway size was calculated to be 1.6 mm. For the manganese ore, a 300 mm diameter cyclone was sufficient for the volumetric flow. The medium/ore ratio was taken to be 5 and the pressure was taken to be 9× diameter (77 kPa).

One the other hand, the very problematic nature of chromite ore required special arrangements. A 2×250 mm DMC operating at a pressure of 20× diameter (162 kPa) satisfied the requirements for both volumetric flow and breakaway size. On the other hand, medium recovery circuit is complicated because of the finer particle size. The preconcentration application at lower densities removes only 25% of the original feed. Therefore, it is more sensible to obtain a final concentrate that has a lower grade than that usually required. This could be blended with the fine-size concentrate.

Conclusions

A mixture of SPT and TC was found to be convenient for heavy liquid testing, with densities up to 3.5 g/cm^3 and particle sizes down to 0.2 mm. An iron ore concentrate having 60.46% Fe was produced with 65.8% overall recovery. The DMC recovery is expected to be 80%. A manganese concentrate having 39% Mn was produced with 81.9% overall recovery. The DMC recovery is expected to be 93%. Although the mineralogy was very unfavorable, based on simulation results it was possible to obtain a chromite concentrate with 44.75% Cr_2O_3 with a 17% overall recovery. The DMC only recovery was approximately 50%. The simulation was found to be a valuable tool for evaluating the performance of DMCs.

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References

AGHLMANDI HARZANAGH A., 2014, *Simulation-aided investigations on non-coal applications of heavy medium cyclone*, M.S. Thesis, Department of Mining Engineering, Hacettepe University, Ankara, Turkey.

AZADI M., AZADI M., MOHEBBI A., 2010, *A CFD study of the effect of cyclone size on its performance parameters*, Journal of Hazardous Materials, 182(1-3), 835–841.

BEVILACQUA P., ZANIN M., 2002, *A simulation procedure for the design of dense medium separation circuits*, Eighth Samancor Symposium on Dense Media (pp. 1–13), Port Douglas, Australia.

BOSMAN J., 2006, *Dense medium cyclones – Sizing and selection*, Ninth Samancor Symposium on Dense Medium Separation.

BURT R.O., 1984, *Gravity Concentration Technology*, Amsterdam-Oxford-New York-Tokyo: Elsevier.

DARDISL K.A., MACK J., 1987, *The design and commissioning of the Argyle diamond mines heavy medium*, AuslMM Southern Queensland Branch, Dense Medium Operators' Conference (pp. 17–31).

DE KORTE J., (N.D.), 2014, *Index of South African Coal Preparation Plants*, retrieved February 25, 2014, from http://www.sacoalprep.co.za/information.htm.

ELSAYED K., LACOR C., 2013, *CFD modeling and multi-objective optimization of cyclone geometry using desirability function, artificial neural networks and genetic algorithms*, Applied Mathematical Modelling, 37, 8, 5680–5704.

FRANCIS R.S., 2009, *Coobina chromite fines plant designed on a shoestring, Built in a boom and commissioned in a bust*, Tenth Mill Operators' Conference.

KEPA A., 2013, *The efficiency improvement of a large-diameter cyclone*, CFD Calculations, Separation and Purification Technology, 118, 105–111.

KOROZNIKOVA L., KLUTKE C., KNIGHT S.M.C., HALL S., 2007, *The use of low-toxic heavy suspensions in mineral sands evaluation and zircon fractionation*, 6th International Heavy Minerals Conference "Back to Basics," The Southern African Institute of Mining and Metallurgy, 21–30.

KRIGE J., 1987, *Heavy medium separation at Iscor's Sishen*, AuslMM Southern Queensland Branch, Dense Medium Operators' Conference (pp. 65–73).

MASON T.F., MCSPADDEN G., 2002, *Performance enhancement at BHP Billiton's Newman Beneficiation Plant*, Metallurgical Plant Design and Operating Strategies.

MCNIEL M., 1982, *Panasqueira - The largest mine in Portugal*, World Mining, 52–55.

MUNNIK E.J., 1994, *An overview of the South African andalusite industry with specific reference to the dense medium separation techniques used*, 5th Samancor Symposium on DM Separation.

NARASIMHA M., BRENNAN M., HOLTHAM P.N., 2007, *Prediction of magnetite segregation in dense medium cyclone using computational fluid dynamics technique*, International Journal of Mineral Processing, 82,1, 41–56.

ORHAN E.C., GULSOY O., ERGUN L., 2010, Coal Washing Plant Simulator, Hacettepe University, Department of Mining Engineering, Ankara, Turkey.

REEVES R., 2002, *Types and characteristics of heavy-media separators and flowsheets*, in: Mular A., Halbe D., Barrat D. (Eds.), Mineral Processing Plant Design, Practice, and Control Proceedings, New York, 962–977.

RONG R.X., LYMAN G.J., 1985, *Computational techniques for coal washery optimization - Parallel gravity and flotation separation*, Coal Prepn., 2, 1, 51–69.

RYLATT M.G., POPPLEWELL G.M., 1999, *Diamond processing at Ekati in Canada*, Mining engineering, v.51, no.2, pp.19

SASSOS M.P., 1984, *Manganese: Gemco mines huge resources at Groote Eylandt*, Eng. & Min. J., 57–58.

SCOTT I.A., 1985, *Particle size effect in ore preconcentration using dense medium cyclones*, M.S. Thesis, The University of Queensland, Australia.

SCOTT I.A., 1988, *A dense medium cyclone model based on the pivot phenomenon*, Ph.D. Thesis, The University of Queensland, Australia.

SCOTT I.A., NAPIER-MUNN, T.J., TIMOTHY J., 1990, *A dense medium cyclone model for simulation*, 4th Samancor Symposium on Dense Media Separation: Dense Media 90 Australia, Cairns, Australia.

WAANDERS F.B., RABATHO J.P., 2004, *Recovery of heavy minerals by means of ferrosilicon dense medium separation and material*, 9th Latin American Conference on the Application of the Mossbanner Effect.

WALTER E., MCCULLOCH J., BHAPPU R.B., HIGHTOWER J.D., 1999, *Copper ore preconcentration by heavy media separation for reduced capital and operating costs*, Proceedings of Copper 99-Cobre 99 International Environment Conference, Volume II, Mineral Processing/Environment, Health, and Safety.

WHITEN W.J., 1966, *Winter School on Mineral Processing, Course Notes*, Department of Mining and Metallurgical Engineering, The University of Queensland, Australia.

WILLS B.A., NAPIER-MUNN T.J., 2006, *Mineral Processing Technology*, Elsevier Science & Technology Books.