

THE EFFECT OF MAGNETIC FIELD ON THE PERFORMANCE OF A DENSE MEDIUM SEPARATOR

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The application of a vertically oriented magnetic field external to a dense medium cyclone can be used to manipulate the density differential within the cyclone by influencing the cyclone's internal ferrosilicon distribution. Tests were conducted on a well-defined dense medium system using a pilot-plant cyclone equipped with a solenoid magnet. The objective was to determine the yield to the dense medium cyclone underflow of a sample consisting predominantly of quartzite material, as a function of the magnetic field strength of the solenoid magnet, and as a function of solenoid position. It was observed that for a specific selection of magnetic field strength and solenoid position, the concentrate yield was reduced. A decrease in yield to concentrate is advantageous in that it reduces the mass of material to be processed downstream. The yield reduction was found to be a function of the applied magnetic field strength. Furthermore, it was found that a disruption in the ferrosilicon flow pattern inside the cyclone may occur beyond a certain magnetic field strength which leads to impaired cyclone operation.

Keywords: Magnetic cyclone; Dense medium separation; Density differential; Magnetic field; Solenoid magnet; Ferrosilicon

1. INTRODUCTION

It has been shown by Svoboda *et al.* [1,2] that by applying a vertically oriented magnetic field, the density differential, defined as the difference between the underflow and overflow medium densities, within a cyclone can be manipulated. This occurs by manipulating the distribution of the ferrosilicon within the cyclone. The additional external magnetic force supplements the gravitational and centrifugal forces that cause classification and separation.

Numerous tests were previously conducted on a pilot-plant cyclone by Svoboda *et al.* [2] with the objective of establishing the relationship between the solenoid position,

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magnetic field strength, density differential and cut point density. Subsequent test work by Myburgh [3] carried out on production scale showed that by the application of a suitable magnetic field, the yield to the concentrate could be reduced. Owing to the variable nature of the ore feed to the production plant, this observation could not be confirmed at the time. Therefore, additional pilot-plant scale test work was conducted in an attempt to confirm, in a well-defined dense medium system (DMS), the effect of the magnetic field on the DMS yield to the concentrate. The purpose of this test work was to determine the yield into the sinks fraction as a function of the magnetic field strength and solenoid position.

2. EXPERIMENTAL PROCEDURE

2.1. Sample

A $-4+1.6$ mm ore sample was obtained from a diamond prospect plant at Namaqualand Mines. The predominant ore type in the sample was quartzite. The sample consisted of approximately 1 ton of DMS tailings and 20 kg of de-diamondized DMS concentrate. From this sample, a test sample containing 0.2% DMS concentrate by mass was constituted to simulate typical DMS feed conditions at Namaqualand Mines.

The sample used for the test work was passed through a SWECO screen before being washed. A sample of 20 kg of $-4+2$ mm material was used as the starting material. The sample showed some degradation over time. The material was screened after the first six gravel tests and then after every three gravel tests. Table I gives the size distribution of the gravel after screening. It is possible that the sample contained other material besides quartzite, which degraded.

2.2. DMS Plant

The test work was performed at a fully instrumented pilot DMS plant equipped with a 100 mm cyclone as is illustrated in Fig. 1. The flowsheet of the plant is shown in Fig. 2. Material of a known mass was fed from a hopper via a vibrating feeder into a mixing box, where it was mixed with a dense medium. The medium feed line between the correct medium sump and the mixing box was fitted with a demagnetizing coil. The dense medium consisted of milled 270D ferrosilicon and water, which were added to the correct medium sump, in a ratio that would give the required feed density. The cyclone was gravity fed. Automated mixing box level control ensured a constant cyclone inlet pressure. Density separation of the material took place in the cyclone according to the cut point and separation efficiency, which is dependent on medium density, medium rheology, cyclone inlet pressure, cyclone geometry and ore

TABLE I Size distribution of the sample after the gravel runs

	-2 mm (kg)	+2 mm (kg)	Total mass (kg)
After 6 runs	8.26	11.65	19.91
After 9 runs	8.29	11.49	19.78
After 12 runs	8.32	11.30	19.62

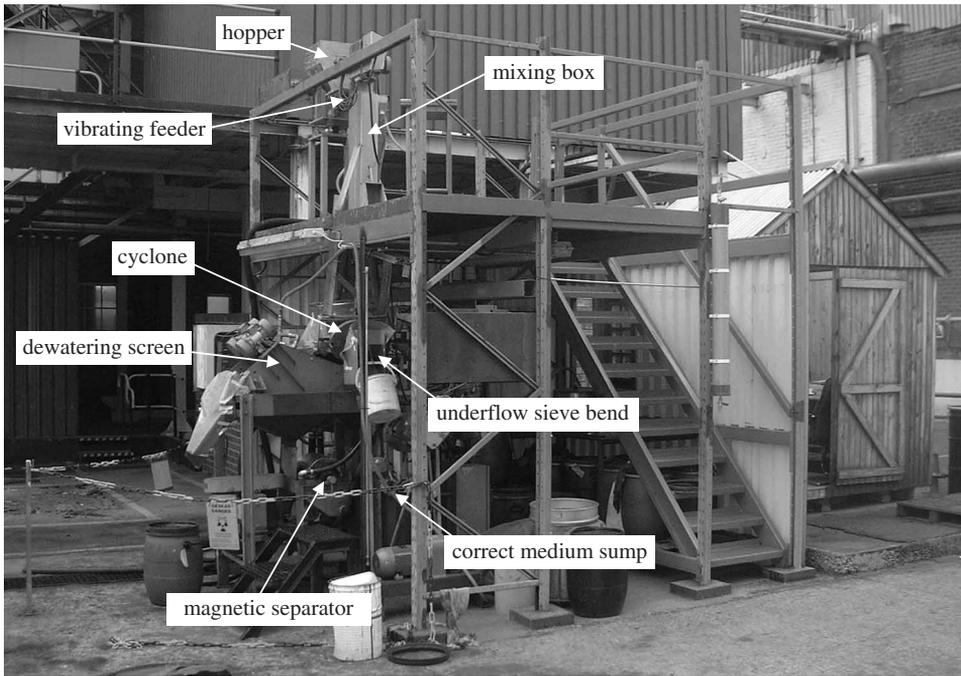


FIGURE 1 De Beers TSS pilot-scale DMS plant.

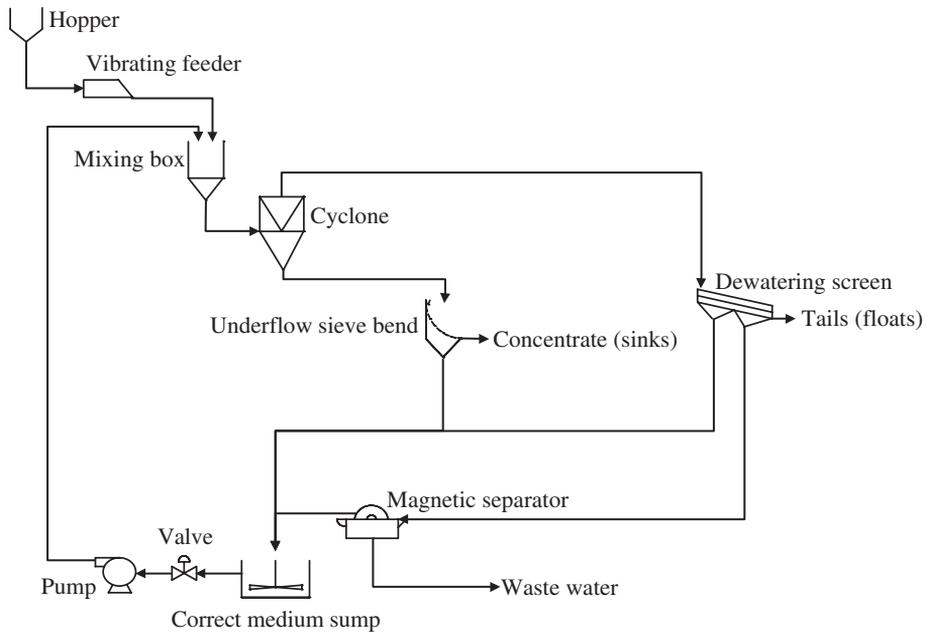


FIGURE 2 Flowsheet of the pilot-scale DMS plant.

characteristics. The dense material, or concentrate, reported to the cyclone underflow. The cyclone underflow reported to a sieve bend from where the medium was drained from the ore and returned to the correct medium sump. The underflow ore was collected, washed and weighed to determine the yield of material to the sinks.

The cyclone overflow reported to a drain and rinse screen. The medium was drained from the ore on the first section of the screen and returned to the correct medium sump. On the second section of the screen any remaining medium was washed from the ore. The diluted medium reported to a magnetic drum separator for densification. The overflow ore was collected in the tailings bin. The mass of material to floats was calculated by difference from the original material and underflow masses.

The pilot-scale DMS plant had online nuclear density gauges for the measurement of the densities of the feed, underflow and overflow medium. This facility allowed for elegant and easy density measurements. The density measurements together with the pump speed, medium temperature and other variables were recorded online. This allowed for verification of all relevant variables during test runs and after completion of the test work should any anomalies have arisen in the results. The plant was controlled using a SCADA system.

2.3. Solenoid Magnet

The solenoid coil in the form of a shallow annulus was located concentrically around the cyclone cone. Two different solenoid coil designs were evaluated prior to the onset of the tracer tests. The dimensions of the cyclone and positioning of the solenoid coil are shown in Fig. 3. Two solenoid positions were selected for the test work namely, the top and middle positions. Positioning the coil at the bottom of the cyclone cone would disrupt ferrosilicon flow patterns to such a degree that effective separation of

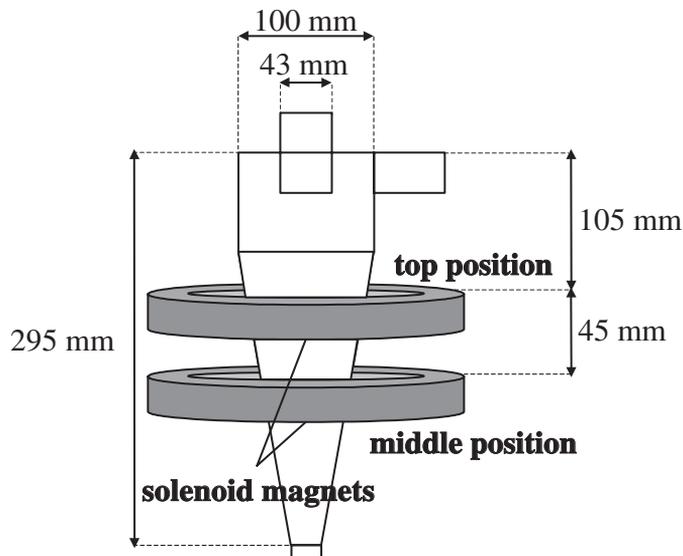


FIGURE 3 Cyclone dimensions and magnet positions.

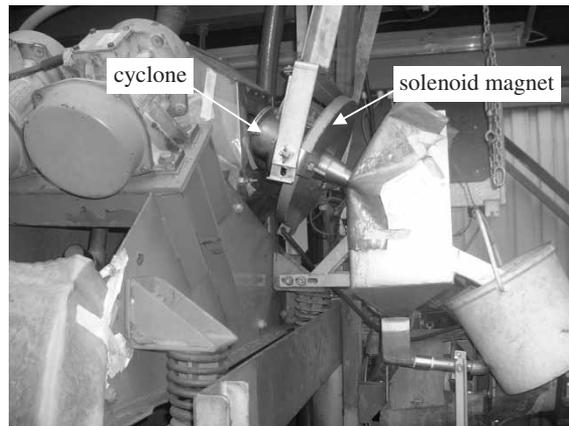


FIGURE 4 Solenoid magnet position at the middle of the cyclone.

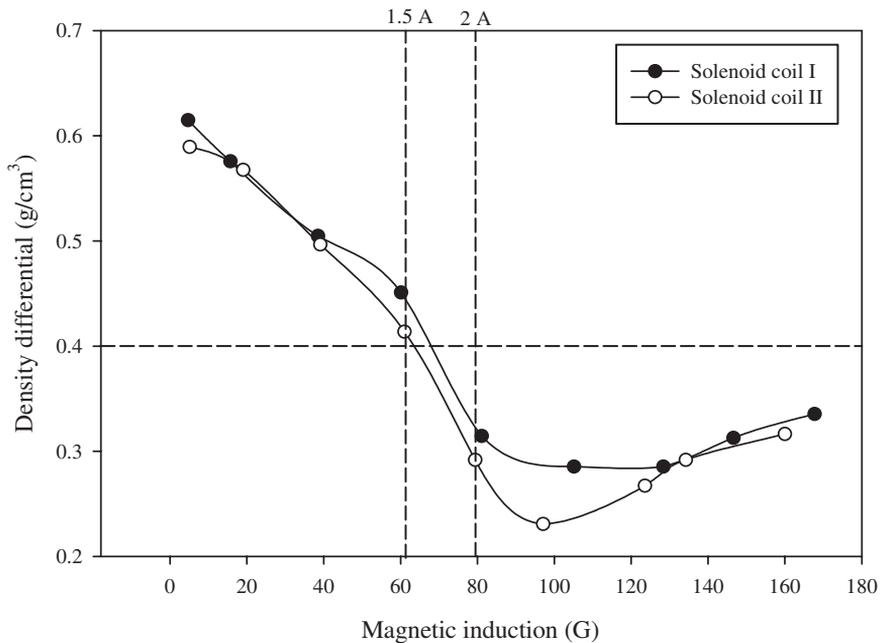


FIGURE 5 Plot of the density differential for the two solenoid coils.

material would most likely not take place. A photograph of the solenoid magnet and the cyclone is shown in Fig. 4. Figure 5 shows a plot of the density differential for various values of magnetic induction for the two coils.

The minimum density differential for solenoid coil I occurred at the magnetic induction of around 110 to 128 G, whilst that for solenoid coil II occurred around 97 G. It was observed that when the magnetic induction was increased above 128 and 97 G for coils I and II, respectively, the density differential started to increase. The reason

for this behaviour is the onset of magnetic flocculation of ferrosilicon particles which distorts the flow pattern inside the cyclone, as described by Svoboda *et al.* [1,2].

Based on preliminary tests, coil II was employed for all the subsequent tracer and gravel tests. The magnetic induction of 61 G (the electric current setting of 1.5 A indicated in Fig. 5) and 79.4 G (the current setting of 2 A) were selected. The value of 79.4 G was selected rather than 97 G (at 2.5 A), although the minimum density differential was obtained at the higher magnetic field strength setting. The lower value was chosen because, during one of the preliminary runs, it was observed that the cyclone underflow pipe had blocked at the higher setting. The ferrosilicon used for the plots as depicted in Fig. 5 had been used for preliminary test work and may have degraded slightly. It is possible that when the blockage of the underflow pipe was observed, a newer ferrosilicon had been added to the system or that the magnet had been on for too a long time and caused the ferrosilicon to become slightly magnetized. This phenomenon could be significant for this particular setup since the pilot-scale DMS circuit is rather small and it is possible that the demagnetizing coil does not demagnetize the ferrosilicon sufficiently well if the magnet is left on for an extended period. In larger DMS circuits, it is unlikely that such phenomena will be encountered.

Fluctuations in stability of the densities were observed if the magnet was left on for extended periods of time. To minimize the likelihood of this happening, the magnet was switched off between runs. To avoid the possibility of blockages occurring during the experimental test work, the slightly lower field setting was chosen.

The values of the magnetic induction at which to perform the tests should have ideally been selected in such a way so as to generate a density differential smaller than 0.4 g/cm^3 (indicated in Fig. 5). A density differential of less than 0.4 g/cm^3 is recommended by Scott to limit the loss of efficiency owing to excessive particle recirculation within the cyclone [4]. However, an analogue power supply was used to set the current to the coils and the next most accurate setting that could be set on the analogue current dial was 1.5 A.

The feed density used to determine the density differential as shown in Fig. 5, was 2.5 g/cm^3 . It transpired from previous test work that the density differential was essentially independent of the feed density within the narrow range that would be employed during the test programme [2].

Figure 6 shows a plot of the effect of the magnetic field on the underflow and overflow densities for a magnetic induction of 61 G, with the magnetic coil located in the middle position. The feed, underflow and overflow densities were recorded online and the effect of the magnetic field on the latter two densities is clearly visible.

2.4. Test Method

When the magnetic field was applied to the cyclone, the underflow density and the cut point decreased, in agreement with previous magnetic cyclone tests [2,3]. Consequently the inlet density was adjusted for each magnet setting to maintain the cut point between 3.10 and 3.20 g/cm^3 .

Colour-coded density tracers with densities ranging from 2.8 to 3.5 g/cm^3 were used. The density interval of the tracers in the region around the cut point, that is from 3.0 to 3.25 g/cm^3 was 0.05 g/cm^3 , while for the rest of the tracers a density interval of 0.1 g/cm^3 was used. 52 mm tracers of each density were used during each tracer test.

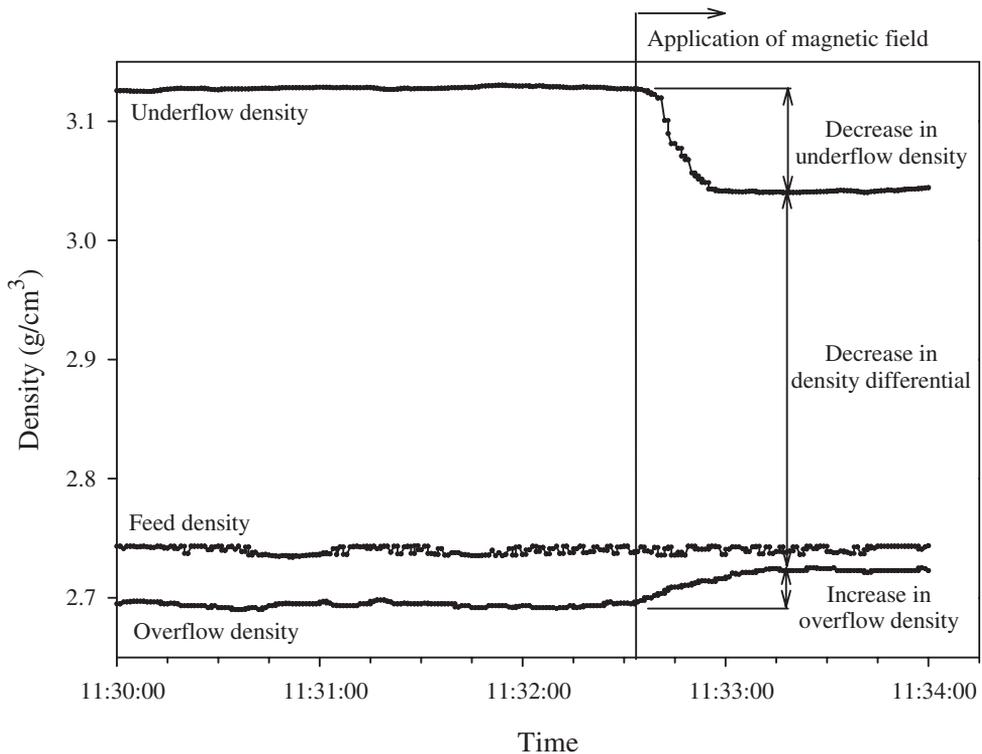


FIGURE 6 An example of the effect of the magnetic field on the underflow and overflow densities.

The tests were performed at two solenoid positions and with two different magnetic field strengths and the results were compared to those results obtained in the runs without application of the magnetic field. The tests were performed either with ferrosilicon medium only or with ferrosilicon and gravel. Each run was repeated three times.

The cyclone feed, underflow and overflow densities were recorded throughout the test work. For the gravel runs, the underflow and overflow masses were also recorded. The gravel was fed at a rate of approximately 1 kg/min. After each run, the DMS concentrate and tailings were weighed and the yield was calculated. The tracers which reported to the concentrate were sorted and counted and their distribution in the concentrate and tailings fractions recorded.

The percentage recovery and percentage yield to sinks were calculated using Eqs. (1) and (2), respectively.

$$\% \text{ recovery to sinks} = \frac{\text{number of tracers in sinks}}{\text{total number of tracers fed}} \quad (1)$$

$$\% \text{ yield to sinks} = \frac{\text{mass of gravel to sinks}}{\text{total mass fed}} \quad (2)$$

Tromp curves were plotted from the data and the mean error Ep , given by Eq. (3) was calculated. The experimental error in terms of the standard deviation was included on

the Tromp curves. Tromp curves are plots of the percentage recovery to the sinks or floats fraction of the material as a function of tracer density. The E_p describes the gradient of the Tromp curve between two densities, ρ_{75} and ρ_{25} , where ρ_{75} is the density at which 75% of the material reports to sinks and ρ_{25} is the density at which 25% of the material reports to sinks.

$$E_p = \frac{\rho_{75} - \rho_{25}}{2} \quad (3)$$

3. RESULTS AND DISCUSSION

As an example, Tromp curves produced in the tests when the magnet was in the top position and generated a magnetic induction of 61 G, with tracers only and with tracers and gravel, are given in Fig. 7(a) and (b) respectively. Each Tromp curve represents the average of three runs at the same set of conditions. The E_p and cut point (CP) are indicated on the graphs.

Table II shows the average densities of the feed, underflow and overflow and the density differential for the three repeats at each set of conditions. Without the application of a magnetic field, the density differential varied from 0.59 to 0.63 g/cm³. With the application of a magnetic field, the density differential was reduced to the range of 0.2 to 0.38 g/cm³ depending on the magnetic field strength.

Table III shows the cut point, E_p , yield and standard deviation for the average of the repeats of the runs at each set of conditions. The cut point was maintained between 3.1 and 3.2 g/cm³, with the exception of the tracer runs with the magnet in the middle position generating a magnetic induction of 61 G, where the average cut point was slightly higher at 3.21 g/cm³. Figure 8 displays a plot of the percentage yield to sinks versus the magnetic induction for the top and middle positions of the solenoid magnet.

As can be seen from Fig. 8, the yield initially decreases with the application of an external magnetic field, for the solenoid coil in both positions. As has been mentioned previously, according to Scott [4], a density differential of less than approximately 0.4 g/cm³ is recommended for the optimum cyclone efficiency. Large density differentials may result in unstable cyclone operation where discharge of material occurs in

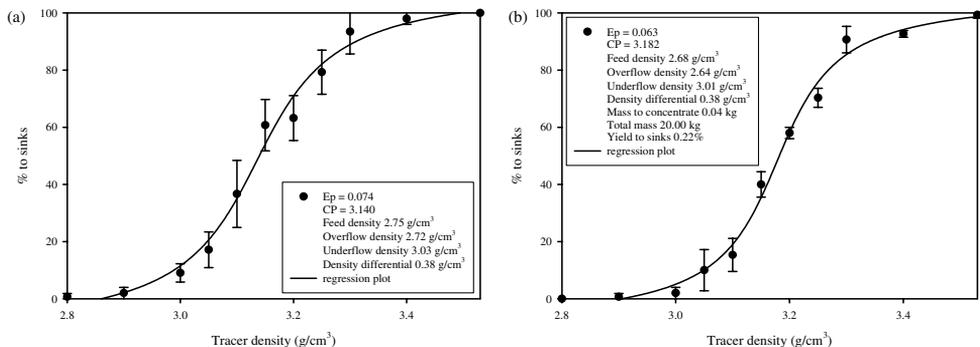


FIGURE 7 Tromp curves for the runs with the magnet in the top position (magnetic induction of 61 G) with (a) tracers only and (b) with tracers and gravel.

TABLE II Feed, underflow and overflow densities and density differential for the runs

	Magnetic induction (G)	Feed density (g/cm ³)	Overflow density (g/cm ³)	Underflow density (g/cm ³)	Density differential (g/cm ³)
<i>Top position</i>					
Tracers	0	2.53	2.44	3.02	0.59
	61	2.75	2.72	3.03	0.31
	79.4	2.73	2.73	2.93	0.20
Gravel	0	2.46	2.35	2.98	0.63
	61	2.68	2.64	3.01	0.38
	79.4	2.72	2.71	2.93	0.22
<i>Middle position</i>					
Tracers	0	2.53	2.44	3.02	0.59
	61	2.75	2.74	3.06	0.32
	79.4	2.73	2.74	2.96	0.23
Gravel	0	2.46	2.35	2.98	0.63
	61	2.74	2.70	3.04	0.34
	79.4	2.73	2.71	2.96	0.25

TABLE III Cut point, E_p , yield and standard deviation for the runs

	Magnetic induction (G)	Cut point (g/cm ³)	E_p	Yield to sinks (%)	Standard deviation (for yield)
<i>Top position</i>					
Tracers	0	3.1	0.071	—	—
	61	3.14	0.074	—	—
	79.4	3.135	0.089	—	—
Gravel	0	3.137	0.054	0.29	0.03
	61	3.182	0.063	0.22	0.01
	79.4	3.183	0.073	0.23	0.01
<i>Middle position</i>					
Tracer	0	3.1	0.071	—	—
	61	3.210	0.076	—	—
	79.4	3.188	0.074	—	—
Gravel	0	3.137	0.054	0.29	0.03
	61	3.198	0.080	0.20	0
	79.4	3.162	0.081	0.29	0.01

surges, mainly through the apex of the cyclone. With the application of the magnetic field, the density differential was reduced from between 0.59 and 0.63 g/cm³ to less than 0.4 g/cm³, a value that is more conducive for effective separation.

The data obtained in this test work shows that the minimum yield was achieved at the magnetic induction of about 70 G for the magnet in the top position, and 60 G for the magnet in the middle position. As the field strength is increased beyond these minima, the yield again increases as a result of a disruption of the flow pattern inside the cyclone. It appears from Fig. 5, which exhibits the density differential *versus* magnetic induction for the two coils, that significant magnetic flocculation only occurred above approximately 100 G. However, it is possible, depending, for example, on the ferrosilicon feed density, or on the state of the ferrosilicon and length of time that the magnet had been switched on (which could magnetize the ferrosilicon) that the onset of magnetic flocculation could occur at lower field strength values.

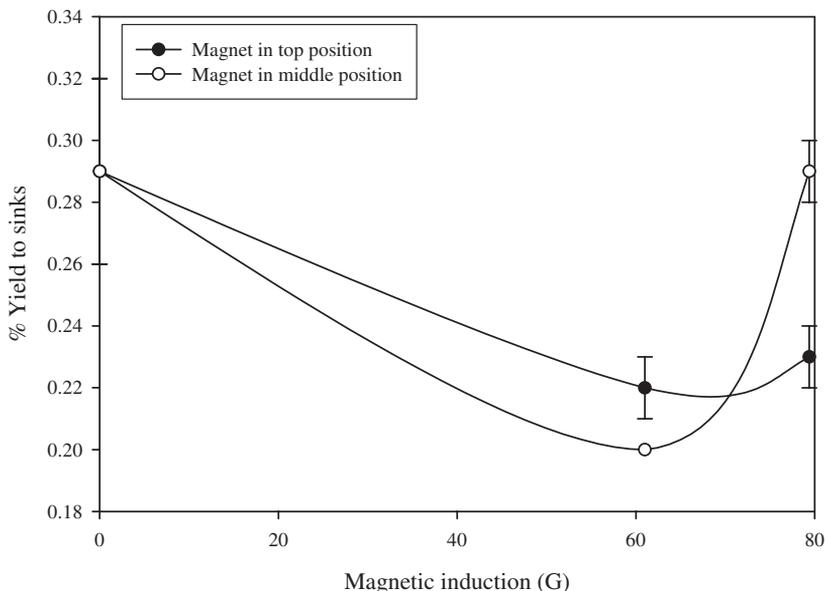


FIGURE 8 The yield to sinks as a function of the magnetic induction.

The main classification or separation of material takes place in a region in a cyclone known as the 'turnaround zone' [5]. This zone is situated approximately 2/3 down the cyclone cone (excluding the spigot). All material, including the overflow material, moves to this zone before proceeding either upwards to the vortex finder or to the spigot outlet. In the case of the 100 mm cyclone, this zone would be situated approximately 151 mm down the cone.

The curve that is fitted for the coil in the middle position, as is shown in Fig. 8, seems to indicate that this positioning results in a greater decrease in yield than for the top position. This applies to a situation when a suitable magnetic field strength is used, in this case around 60 G. The application of the magnetic field to the cone thus stabilises the medium in the region critical to separation, resulting in a more constant cut point. The material moving through this section of the cyclone is separated more accurately according to density than in areas where the ferrosilicon distribution is less uniform.

When the coil is situated in the middle of the cyclone, it is located 71.6 mm down the cone and the influence of the magnetic field is greater than when the coil is situated in the top position, 26.6 mm down the cone. The coil located in the middle can therefore influence to a larger degree the ferrosilicon in this 'turnaround zone'. The particles reporting to the underflow are removed immediately because of their close proximity to the outlet and they report to the correct fraction.

More selective separation also occurs with the application of a suitable field when the magnet is in the top position. The magnet in this position does not, however, influence the 'turnaround zone' to the same extent as when it is placed in the middle position. Less effective separation may therefore occur (as compared to the magnet in the middle position) and there is therefore not as great a decrease in yield to sinks.

The yield to sinks above the values of the magnetic induction of 60 and 70 G appears to increase more rapidly for the magnet in the middle position than for the top position.

The influence of the magnetic field in the middle section appears to be more significant possibly because the coil is again located closer to the region where most separation occurs. As the magnetic field is increased, the flow pattern in the 'turnaround zone' is adversely affected resulting in poorer separation. The yield for the solenoid coil in the top position closer to the vortex finder did not appear to differ significantly for the two different field strength settings (61 and 79.4 G). Both settings appeared to have an almost equal effect on the density distribution in this section and there is no significant disruption in flow as experienced in the more sensitive 'turnaround zone'.

It was observed during test work that once the bulk of the material had been fed through the cyclone, a small fraction of middlings (approximately 30 g in total) continued to exit the cyclone. This middlings mass, although small, could contribute to up to 50% of the sinks mass if it were to report to sinks. The quartzite density is approximately 2.65 g/cm³. Without the application of a magnetic field, the ferrosilicon feed density is lower than the average material density (approximately 2.5 g/cm³) and the middlings may remain trapped in the cyclone for an extended period of time. Ultimately, a portion of the middlings may report to sinks. With the application of the field, the feed density is raised (to above at least 2.68 g/cm³) to ensure that the cut point remains constant. The increased density is higher than the average material density. For this material, the change in feed density could assist the middlings in reporting to the floats immediately. A decrease in yield, because of a more selective separation in terms of mass of material, is thus obtained with the application of the field. The middlings that may have reported to the sinks now report to the floats.

4. CONCLUSIONS

This test work confirmed that by the application of a magnetic field to a DMS cyclone, the density differential could be varied. For a specific selection of the magnetic field strength, which gives a suitable density differential, and with a suitable positioning of the coil, the concentrate yield was reduced. It transpires from the tests that the greatest reduction in yield to concentrate is obtained for the coil located in the middle of the cyclone. A suitable magnetic induction must be maintained to ensure that the ferrosilicon flow patterns are not disrupted.

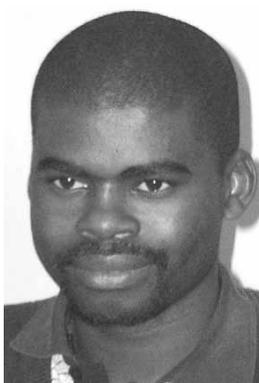
The effect of the magnetic field on DMS yield is currently under evaluation at a diamond production plant with a 570 mm cyclone to supplement the work described in this article.

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Mmakgudi Richard Kekana graduated with B.Tech degree in Chemical Engineering from Technikon Witwatersrand (South Africa). He has been involved in R&D projects in both industrial and gem diamonds for the past ten years. His main area of interest is the chemical process industry. He was involved in optimization of recovery processes by acid dissolution and appreciation of the environmental impact of the process has given him joy in his career. His current focus is on the optimization of comminution and liberation processes and the modelling of concentration by DMS cyclones.