Application of a magnetic cyclone on a magnetite dense medium separation process

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Dissertation accepted in fulfilment of the requirements for the degree Master of Engineering in Chemical Engineering at the North-West University

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DEDICATION

Dearest Daniel,

This one's for you, my love.

STUDY DELIVERABLES

A paper was delivered at the Southern African Coal Processing Society's 2019 Biennial Conference (Coal processing – extracting value from low grade reserves). The details of the paper are as follows:

DENSE MEDIUM SEPARATION USING A MAGNETIC CYCLONE

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SOLEMN DECLARATION

I, **Jeantelle Jarmaine Rust**, declare herewith that the dissertation entitled:

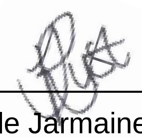
"Application of a magnetic cyclone on a magnetite dense medium separation process",

Which I herewith submit to the North-West University, is in compliance with the requirements set for the degree

Master of Engineering in Chemical Engineering

Is my own work, has been text-edited in accordance with the requirements and has not already been submitted to any other university.

Signed,



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Jeantelle Jarmaine Rust

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A person's achievements are rarely accomplished all on their own. There are usually external influences and circumstances which lend a hand, either directly or indirectly. I would like to acknowledge the people in my life, who helped me to get where I am today:

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"For I know the plans I have for you, declares the Lord, plans to prosper you and not to harm you, plans to give you hope and a future."

Jeremiah 29:11

ABSTRACT

The face of coal supply and demand is ever-changing, with the demand for clean coal rising and with a dwindling supply of high quality ore. Methods to efficiently clean the coal of worsening run-of-mine quality are desperately needed. There are many facets, aspects and directions in which one can go when it comes to the beneficiation of coal in a more efficient manner, so there is not one answer that will address all the challenges faced. Many small changes to processes can accumulate and make a large contribution to the bigger picture.

This dissertation focuses on one of the changes that can be made to a dense medium separation cyclone process in order to more efficiently beneficiate coal to meet the specific requirements so that the supply can keep up with the demand.

The work done was to determine whether a coarser media could be used in a dense medium cyclone separation system that would lead to a reduction in media losses, an increase in yield and ultimately a financial benefit to implementing such a system. Coarser media on its own would not work, as it would settle and cause media instability within a dense medium cyclone. Fortunately, a system of solenoids, known as SpecSep™, was designed to aid in the stabilisation of the coarse media.

From the study, it was found that adding coarse media to conventional media decreased the density differential quite significantly in instances where a magnetic field was applied. An optimum ratio of coarse-to-fine magnetite was established and tracer tests were done. From the tracer tests, it was evident that the efficiency of the dense medium cyclone could be improved when the SpecSep™ solenoids were applied, and also the cut-point could be lowered.

It was finally determined that there is a saving in costs relating to a reduction in magnetite losses for a SpecSep™ system, the payback period for the implementation thereof is fairly quick, and that there is a huge profit that can be made annually if the SpecSep™ system is used.

Key Words: *SpecSep™, magnetic cyclone, dense medium cyclone, density differential, magnetite.*

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LIST OF ACRONYMS

ACRONYM	DESCRIPTION
DMC	Dense medium cyclone
DSM	Dutch State Mines
Ep	Probable Error (see EPM)
EPM	Écart Probable (Moyen) (see Ep)
PSD	Particle size distribution
RD	Relative density (g/cm^3)
SG	Specific gravity

LIST OF SYMBOLS

SYMBOL	UNIT	DESCRIPTION
d_{25}	µm	Size at which 25 % of the particles passes
d_{50}	µm	Size at which 50 % of the particles passes
d_{75}	µm	Size at which 75 % of the particles passes
m_1	g	Mass of density bottle
m_2	g	Mass of density bottle, water and solids
$M_{magnetite}$	kg/m^3	Mass of magnetite
M_{slurry}	kg	Mass of slurry
m_{solids}	g	Mass of solid particles
M_{solids}	kg	Mass of solids
m_{water}	g	Mass of water
M_{water}	kg	Mass of water
n	-	Number of sample observations
R/hr	-	Rand per hour
R/ton	-	Rand per ton
s^2	-	Sample variance
s	-	Standard deviation
$SG_{magnetite}$	-	Specific gravity of magnetite
tph	-	Ton(s) per hour
v_d	cm^3	Volume of density bottle
V_{slurry}	m^3	Volume of slurry
V_{water}	m^3	Volume of water
P_i	-	Partition number (feed reporting to the sinks)
ρ_{50}	-	Separating density
ρ_i	-	Mean density of the density fraction
$\rho_{magnetite}$	-	Relative density of magnetite
ρ_{solids}	-	Relative density of solids
$\rho_{suspension}$	-	Relative density of a suspension
ρ_{water}	-	Relative density of water
$x_i-\dot{x}$	-	Sum of deviations

LIST OF EQUATIONS

Equation 2.1 $\rho_{solids} = \frac{(\rho_{suspension} - 1)}{\%\ Solids} \times 100 + 1$

Equation 3.1 $SG = \frac{m_{solids}(m_{water} - m_1)}{v_d(m_{water} - m_2 + m_{solids})}$

Equation 3.2 $RD = \frac{(\text{Cylinder Mass} + M_{slurry}) - \text{Cylinder Mass}}{V_{slurry}}$

Equation 3.3 $P_i = \frac{1}{1 + \exp\left[\frac{\ln 3\left(\rho_{50} - \rho_i\right)}{Ep}\right]}$

Equation D.1 $s^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}$

Equation D.2 $\text{Standard deviation} = \sqrt{s^2}$

Equation D.3 $s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$

Equation D.4 $\pm 2 \times \text{Standard deviation} = \pm 2s = \pm 2\sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$

CHAPTER 1: INTRODUCTION

This chapter aims to introduce the reader to the subject at hand, starting with the background and motivation, moving on to the scope of the investigation, research aims and objectives, the hypothesis and finally setting out the thesis structure for ease of reference.

1.1 Background and Motivation

The citizens of South Africa are heavily dependent on coal to cater for their energy requirements, as renewable energies have yet to be tapped into on a commercial and sustainable scale. According to the Minerals Council South Africa (2018:22), the total coal sales for 2018 was approximately R 146 billion, and the coal industry represents 19 % of the total employees in the mining sector as a whole.

What this says is that coal is of critical importance to South Africa specifically. Although the global trends are to move away from the mining and utilisation of coal, that is not a reality for South Africa due to it being heavily dependent on coal and also due to a lack of affordable alternatives. This remains the case for the foreseeable future. Coupled with this, is the fact that the quality of the remaining coal in the country is dwindling, and therefore it is necessary to make more efficient use of the coal available. This makes sense from a financial and environmental point of view.

One way of targeting the efficiency aspect, is to enhance the processing of coal so that it is more efficient and less costly. This study aims to focus on a specific area within the coal beneficiation process, namely dense medium separation using cyclones as a separation vessel. If this process can be optimised, it would result in greater efficiencies in the recovery of coal, which would yield a product that is within specification for further utilisation, and consequently a financial gain would be attainable.

Work has been done in this regard by De Beers in the 1990s to early 2000s in a diamond dense medium separation application. The results of these various studies that were done will be discussed in detail in Chapter 2. The essence of this work, however is that a vertically orientated external magnetic field applied to a dense medium cyclone, has the ability to stabilise the medium (ferrosilicon in that case) within such a cyclone and therefore increase the efficiency of such equipment. The aim of this dissertation is to study the effects that such a magnetic field might have on a magnetite dense medium separation application, which is typically used in the coal industry.

1.2 Research Aims and Objectives

The hypothesis of this study is that coarser medium in a coal cyclone dense medium separation system could be used and that it is possible to stabilise such a system by means of the application of a magnetic field to the process.

Thus the objectives are to:

1. Set up a dense medium cyclone rig equipped with an external magnetic field, which is to be generated by means of solenoids;
2. Determine the relationship between the magnetic intensity applied versus the current passing through the solenoids;
3. "Coarsen up" the magnetite feeding the cyclone in order to determine whether the industry can move away from using 100 % fine (conventional) magnetite, which is difficult to recover and which causes medium instability;
4. Determine the effect that the solenoid has on the difference in density between the cyclone underflow and overflow; and
5. Perform tracer tests on this system in order to determine the efficiency of the separation that can be attained by means of the application of the magnetic field;

This will assist in evaluating whether the focus of this study is on point, and whether there is a future for this application in an industrial platform. It is important to note that ore was not introduced to the system, and that this is not considered as part of the scope of this study.

1.3 Conclusion

The work that will be done here is relatively new and could change an aspect in the way in which coal is beneficiated in a dense medium separation process. The chapters to follow will set out how this could be achieved, as well as what the results of this study are.

Chapter 2 aims to set out the background concerning dense medium separation and some of the challenges faced with in such a system. This chapter will also provide more information on the studies that have been done in the past, and how these findings could be applied to the current study.

CHAPTER 2: LITERATURE STUDY

Coal is such an essential resource in energy production in South Africa, and still dominates its energy sector despite global concerns regarding the environmental impacts that coal and other fossil fuels have. Keeping these concerns in mind, it is of critical importance to use this key resource in such a manner that is as efficient as possible in order to minimize these negative impacts. Coal processing is one element which can be optimised in order to make the use of coal more efficient, thus reducing the negative footprint on the environmental front.

This Section aims to delve into the technical aspects of coal processing, focusing specifically on the dense medium separation within a dense medium cyclone and its related challenges. Previous studies will be summarised, and this will form the foundation of the work to follow.

2.1 Introduction

Coal dominates the South African energy sector as it makes up 70 % of the country's primary energy supply according to the Chamber of Mines of South Africa (2017). This includes electricity and liquid fuels. When looking at the South African coal sales by volume, 72 % constitutes exports, while the coal mining sector employs 90 000 people (Minerals Council South Africa, 2018:22).

Due to exports, energy supply and employment figures, it is evident that coal is a very important commodity for the country. With the dawning of climate change, environmental concerns regarding coal processing and utilisation are on the rise. It is thus important to optimise coal processes so as to minimize the negative impact that it has on the environment.

2.2 Dense Medium Separation

Dense medium separation (DMS) is used in coal processing to produce a coal that is within the required specifications for further use. The mechanism of DMS is simple: a fluid or medium of a certain density is made up and the coal is mixed with this fluid. The clean coal, which has a density lower than that of the medium, floats on top of the medium, while the gangue minerals, which are denser than the medium, sinks. Figure 2.1 below illustrates this principle:

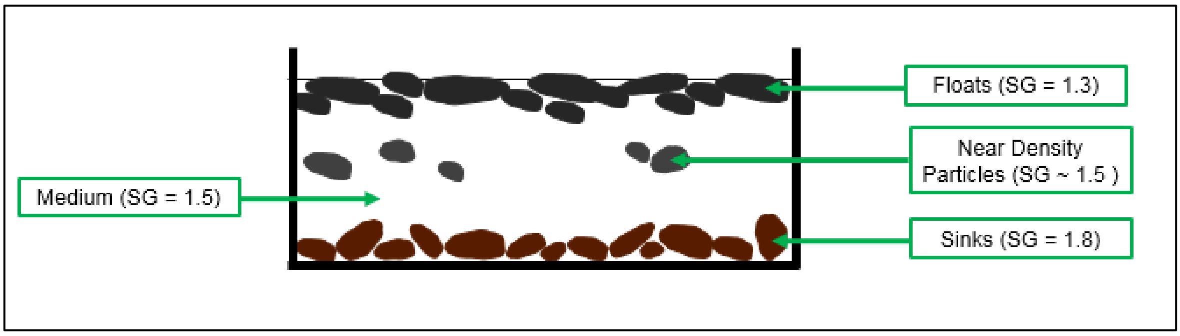

Figure 2.1: Principle of Dense Medium Separation

Some advantages of using DMS over other coal cleaning processes include (England *et al.*, 2002:150):

- Sharp separations at a variety of different densities are possible;
- Even with the presence of a high amount of near density material, a high degree of efficiency can be achieved;
- The relative density can be changed rather quickly to meet varying requirements;
- It is possible to treat a wide range of particle sizes (0.5 mm to 150 mm), although not in the same unit; and
- Quality fluctuations can be handled with ease.

2.3 Dense Media

A dense medium should have the properties of that of an ideal solution, which must be (Horsfall, 1993:18.3):

- Of high stability and low viscosity;
- Able to operate over a density range which is quite wide;
- Capable of rapidly adjusting density;
- Easily recoverable and easily concentrated;
- Readily available;

- Cheap; and
- Chemically stable so as not to be affected by coal washing.

For good separation within a dense medium cyclone, a solids concentration of 30 – 35 % by volume is recommended (Multotec, 117).

In the following equation, $\rho_{suspension}$ refers to the relative density (RD) of the suspension, and ρ_{solids} refers to the RD of the solids. Solving for ρ_{solids}, the following equation can be formulated:

$$\rho_{solids} = \frac{(\rho_{suspension} - 1)}{\%\ Solids} \times 100 + 1 \qquad \text{(Equation 2.1)}$$

Using this formula, the following can be calculated:

Table 2.1: Medium Relative Densities

Solids	$\rho_{suspension}$	ρ_{solids}
30 %	1.35	2.17
	1.48	2.60
	1.65	3.20
	2.00	4.30

With coal being treated in the RD range of between 1.35 and 2.0, a medium with a RD of approximately 4.3 would be required to cover this range. Thus, in addition to the fact that magnetite (RD 4.5 – 5.0) is easily recoverable, chemically inert, relatively cheap and readily available, makes it the medium of choice, specifically in coal DMS processes.

2.4 Dense Medium Cyclones

Figure 2.2 shows a dense medium cyclone consisting of the following components:

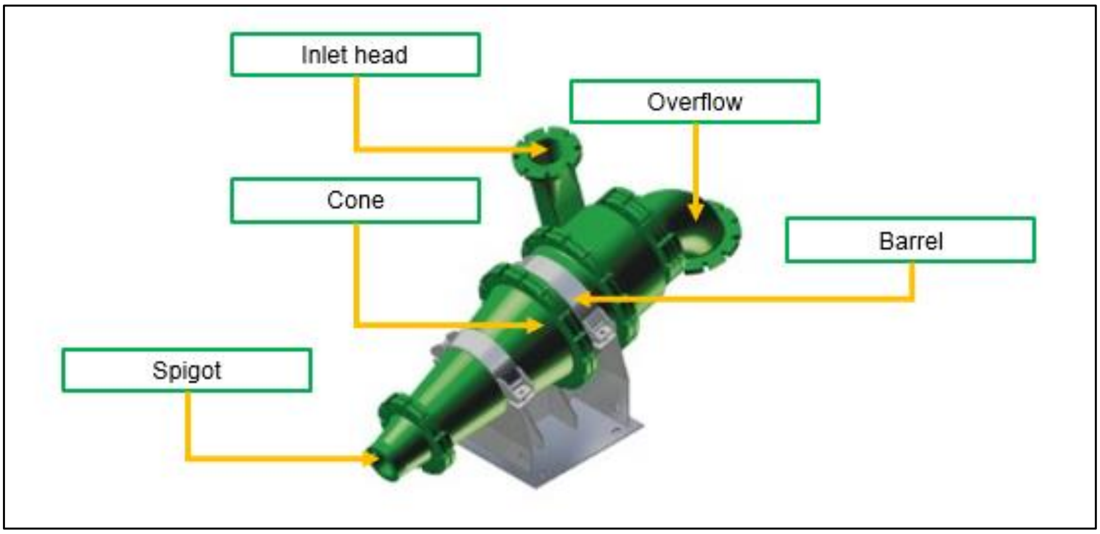

Figure 2.2: Dense Medium Cyclone Components

In a cyclone, the slurry is fed tangentially, causing the slurry to rotate at high speeds resulting in an air column (vortex) forming in the center of the vessel, as is illustrated in Figure 2.3.

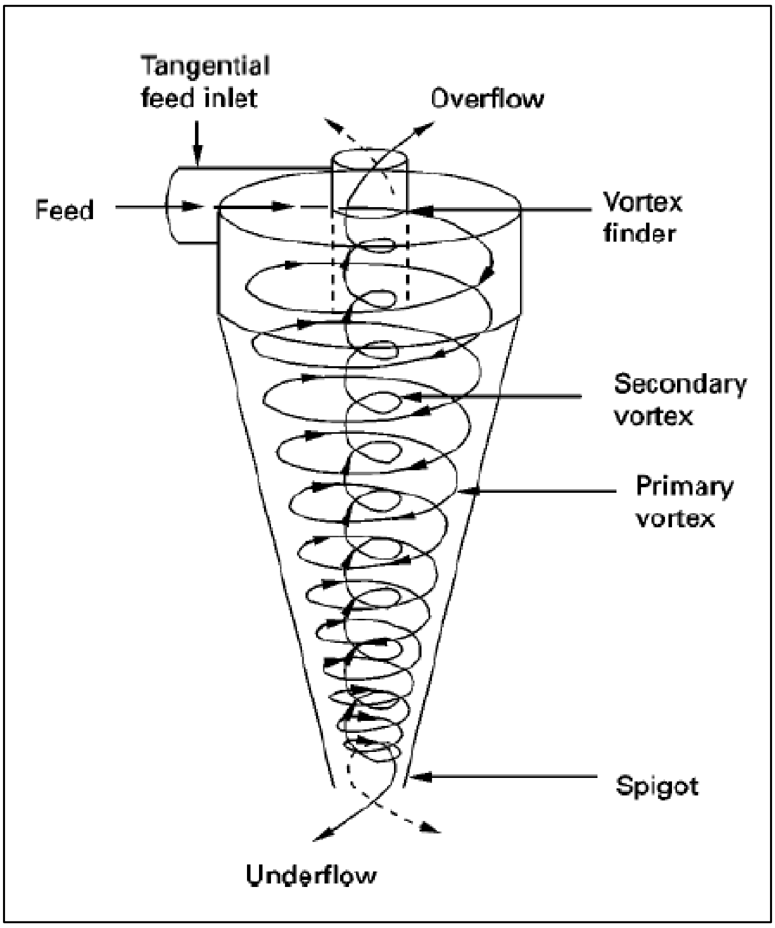

Figure 2.3: Schematic of Cyclone Operation (Singleton, 2013:5)

In a dense medium cyclone, the slurry is made up of the ore and medium. In this case, coal and magnetite. The gangue and magnetite, both with a higher RD than clean coal, will get pulled away from the air core due to its higher centrifugal force. This material will then migrate down the wall of the cyclone and exit through the spigot. The clean coal will get caught up in the upward current and eventually exit via the vortex finder through the overflow outlet.

Dense medium cyclones were developed by the Dutch State Mines (DSM) in the 1940s. Subsequently, the dense medium cyclone has become the unit of choice for processing a number of minerals, such as coal, diamonds, iron ore, etc. The DSM developed standard cyclone dimensions as per Table 2.2 (De Korte & Engelbrecht, 2014:50):

Table 2.2: DSM Standard Cyclone Dimensions

Cyclone Geometry	Recommended Dimension
Feed Head	9 x Cyclone Diameter
Inlet	0.2 x Cyclone Diameter
Vortex Finder	0.43 x Cyclone Diameter
Barrel Length	0.5 x Cyclone Diameter
Spigot Diameter	0.3 x Cyclone Diameter

Although these standards are being challenged within the industry, it is still widely used and seen as ‘the law” when it comes to the operation of a dense medium cyclone.

2.4.1 Efficiency of a Dense Medium Cyclone

The efficiency of a dense medium cyclone can visually be represented by means of a partition (Tromp) curve, using data derived from testing a dense medium cyclone. The partition factors (recovery of the total clean coal to the feed) are then plotted against the mean RD interval. The cut-point of the material would then be defined as the RD at which half of the material is rejected into the discard and the other half is recovered in the clean coal fraction. Figure 2.4 shows an example of such a curve:

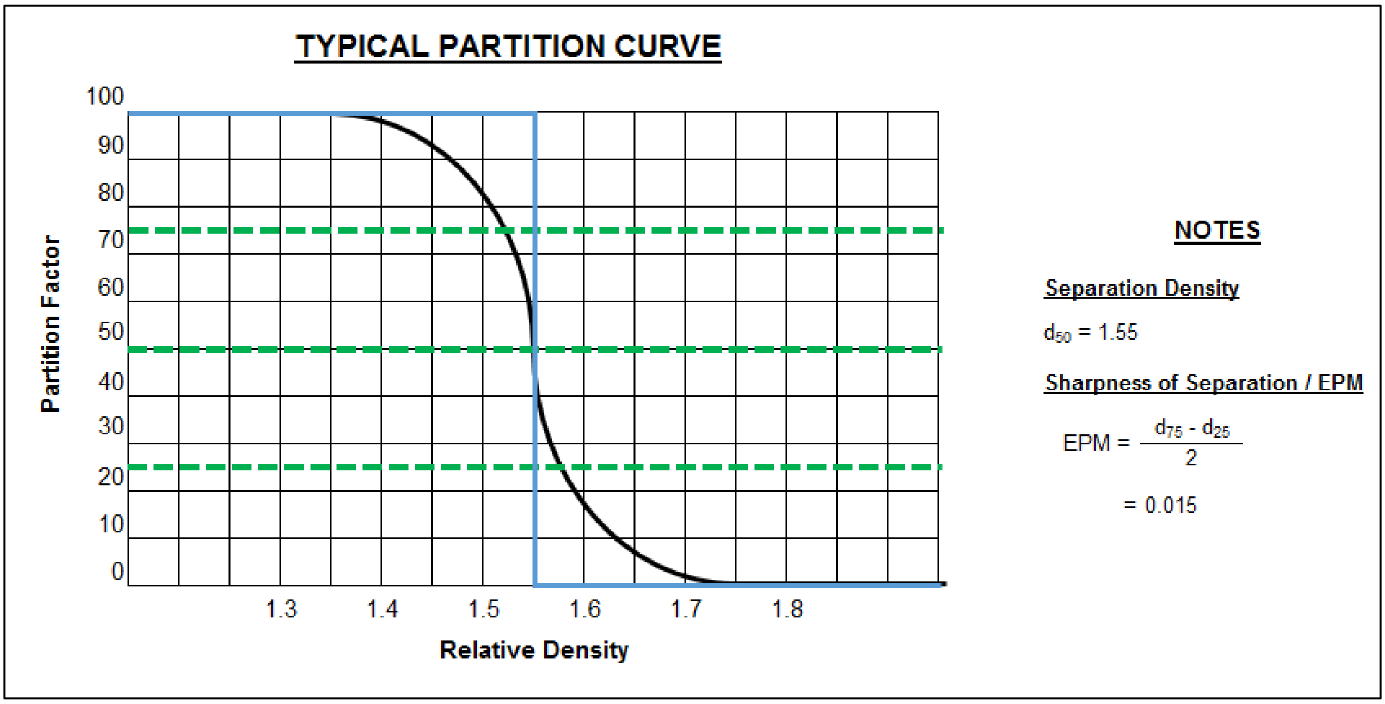

Figure 2.4: Partition Curve Example

From Figure 2.4, it can be seen that the cut-point, also referred to as the d_{50}, is at a RD of 1.55. The sharpness of separation can be determined by the EPM or the Écart Probable (Moyen), which, as can be seen from the figure above, is equal to the d_{75} minus the d_{25} divided by two. The EPM is also known as the "Probable Error" (England *et al.*, 2002:53) and is an independent criterion of equipment (dense medium cyclone) efficiency. The blue curve in Figure 2.4 represents perfect separation of which the EPM is zero. The closer the EPM is to zero, the sharper or more efficient the separation of the material (coal).

There are certain relationships within a dense medium cyclone that should be taken into account during operation, which are also indicators of cyclone separation efficiency. One of these relationships is the density differential between the cyclone overflow and underflow streams, which should ideally be between 0.2 and 0.5 g/cm^3 (Campbell & Coetzee, 1997:6). An excessive density differential causes a decrease in the separation efficiency due to a longer retention time of near density material within a dense medium cyclone and should thus be avoided. The density differentials will further be discussed in Section 2.5.

2.5 Challenges with Magnetite in Dense Medium Separation

Some factors affecting the efficiency of a dense medium cyclone are (Amini *et al*., 2016:393):

- Cyclone geometry;
- Operating conditions;
- Medium stability; and
- Medium rheology.

The medium properties play a significant role in the efficient operation of a dense medium cyclone as it influences the forces acting on the particles within a dense medium cyclone. Two of the most important properties of a suspension in a coal DMS process is stability and viscosity. Both these properties are influenced by the solids concentration (by volume) of the suspension. It should also be noted that instability and viscosity are at opposing ends of the scale.

Factors influencing the viscosity and stability of a medium are (Multotec, 119):

- Particle shape: the more angular the particle, the higher the viscosity;
- Residual magnetism of the magnetite particles (flocculation);
- Solids concentration;
- Particle size; and
- Contamination (presence of clay, for example).

Figure 2.5 below summarises the factors affecting separation efficiency within a dense medium cyclone, as well as the relationship between these factors (Amini, 2014:48):

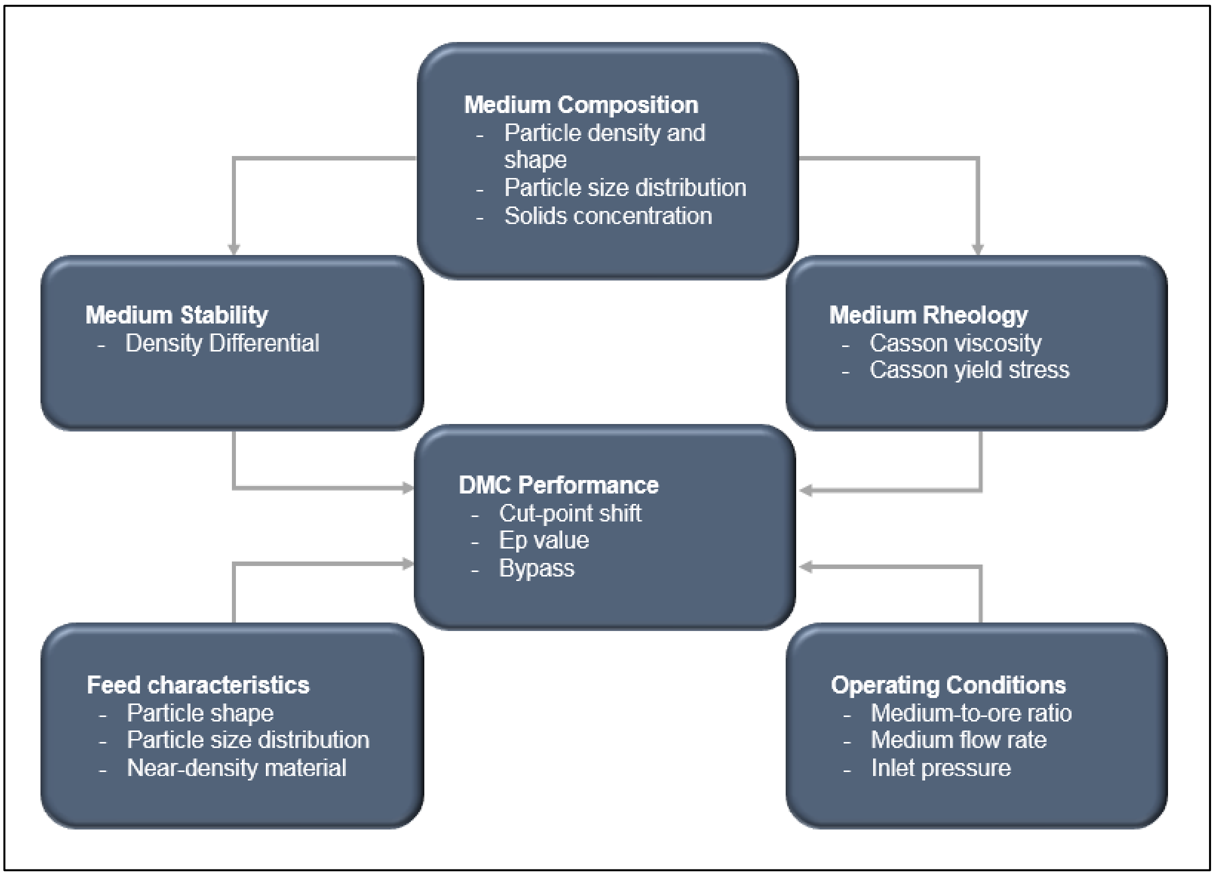

Figure 2.5: Summary of Factors Affecting Separation Efficiency

It can be seen that both the medium stability and rheology are influenced by the composition of the medium, which in turn influences the dense medium cyclone performance.

Due to the different particle types (magnetite, coal and clay), densities and size ranges present during operation, the flow behavior within a dense medium cyclone is of a complex nature. Three phases are usually present: air, water and solids. Density gradients thus occur within such a cyclone, and it is imperative to ensure that the medium is stable and that the rheology does not affect the particle flow in a cyclone, in order to ensure efficient separation.

2.5.1 Medium Stability

Medium stability is coupled with the settling rates of the particles, and therefore gives an indication of how close the suspension properties are to that of a homogenous liquid. The segregation of particles within a dense medium suspension is an indication of an unstable medium. An unstable medium will cause the misplacement of feed particles within a dense medium cyclone and thus negatively influence the efficiency of separation. Within a dense medium cyclone, there is an increase in medium concentration towards the cyclone spigot, resulting in a larger concentration of medium within the dense medium cyclone underflow stream (Narasimha, *et al.*, 2006:1036). According to Myburgh (2001:10), the medium stability is affected by the following external factors or combination thereof:

- Medium particle size and shape: A coarser medium will lower the medium stability;
- Inlet pressure: Higher pressures lower the medium stability and increase the density differential present within the dense medium cyclone.
- Cyclone geometry: The inlet pressure in conjunction with a reduced spigot size lowers the medium stability significantly.
- Medium contamination: According to O'Brien *et al*. (2014:122), the presence of clay and fine coal within the medium lowers the separation densities and density differentials within a dense medium cyclone, thereby increasing the stability of the medium.

2.5.2 Medium Rheology

The medium rheology involves how the medium flows and is increased by the following:

- Medium particle size distribution (PSD);
- Medium particle shape;
- Medium RD; and
- Medium solids concentration.

External factors also play a role in medium rheology, and may include:

- The presence of contaminants in the medium, such as clay;
- Medium magnetization resulting from the medium recovery process;
- The inlet pressure of the medium into the cyclone; and

- The geometry of the dense medium cyclone.

These factors mentioned above cause an increase in the medium viscosity and therefore increases the resistance of a particle to flow within such a medium, and in turn decreases the separating density within a dense medium cyclone (Napier-Munn & Scott, 1990:608).

2.5.3 Overcoming Challenges with Magnetite

A measure of cyclone stability would be the density differential, as referred to in Section 2.4.1. When such a differential is too low, it is an indication of inefficient operation and therefore affects the recovery of the coal. Should this differential be too high on the other hand, it indicates that there is a vast range of densities present within the dense medium cyclone, resulting in higher retention times for the near density material.

Studies have been done by Campbell and Coetzee (1997), Svoboda *et al.* (1998), Myburgh (2001), Vatta *et al.* (2003[1]) and Vatta *et al.* (2003[2]) regarding the application of a magnetic field around the cone of a dense medium cyclone in a diamond DMS application, and Fan *et al.* (2015) in a coal DMS application. This magnetic field influences the density differential achievable between the cyclone overflow and underflow streams. This then in turn has a stabilising effect on the dense medium flowing within the dense medium cyclone. The specific findings of these studies will be dealt with in Section 2.6, however it can be concluded that the introduction of a magnetic field to a dense medium cyclone might possibly be the answer in manipulating the medium stability and therefore increasing the separation efficiency of a dense medium cyclone.

2.6 Magnetic Cyclone – An Overview of Previous Work

The concept of a magnetic cyclone was initiated in the 1960s as an aid in the centrifugal and gravitational forces that is the cause of separation within a dense medium cyclone (Svoboda *et al.*, 1998:501). It is believed that the introduction of a magnetic field to a dense medium cyclone system would result in the manipulation of the behaviour of medium within a dense medium cyclone and thereby influence ore beneficiation and medium recovery.

Due to a lack of understanding and interest, as well as the limitation of dense medium cyclone size manufactured from non-magnetic material, this concept has not gained momentum in the mining industry and existing studies are therefore limited and in the early stages of development. Studies were mainly done on the application of an external magnetic field on a dense medium cyclone within the diamond DMS process. Some key studies are summarised below.

2.6.1 Campbell and Coetzee (1997)

These tests were done in conjunction with the De Beers Industrial Diamond Research Laboratories Minerals Processing Division, by means of a DMS pilot plant. The plant was equipped with a stainless steel cyclone with a diameter of 100 mm, fitted with a solenoid "capable of 250 gauss". The magnetic intensity of the solenoid as well as its position along the outside of the cyclone could be varied. Two different ferrosilicon grades were tested, namely 270D and Cyclone 60 grade, and the variables and constants were as follows:

- Variables:
    - Feed medium density
    - Solenoid magnetic intensity
    - Solenoid position
- Constants:
    - Feed pressure
    - Plant geometry
    - Cyclone geometry

These tests were run with a mixture of medium and tracers, which range from 2.0 g/cm^3 to 3.7 g/cm^3 at 0.1 g/cm^3 intervals.

The results showed the following:

- It is possible to manipulate the density differential by means of applying a magnetic field to the system.
- The influence of the magnetic field was the greatest when the solenoid was placed at the top of the cyclone, closest to the vortex finder.
- The cut-point density decreased with an increase in magnetic field intensity.

Therefore it was concluded that the ferrosilicon clearly responds to the applied magnetic field – a study that warrants further investigation.

2.6.2 Svoboda *et al*. (1998)

From this study, it also came to light that the following could be achieved (Svoboda *et al.*, 1998:501):

- The density differential within a dense medium cyclone could be controlled,
- The cut-point density could be manipulated,
- The sharpness of separation (EPM) could be manipulated, and
- The selectivity of separation could be influenced.

The medium PSD within a dense medium cyclone can be influenced not only by the application of a magnetic field around the cone of a dense medium cyclone, but also by the positioning of the source of the magnetic field.

Figure 2.6 below illustrates the forces acting on a particle within a dense medium cyclone which is exposed to a vertically orientated magnetic field:

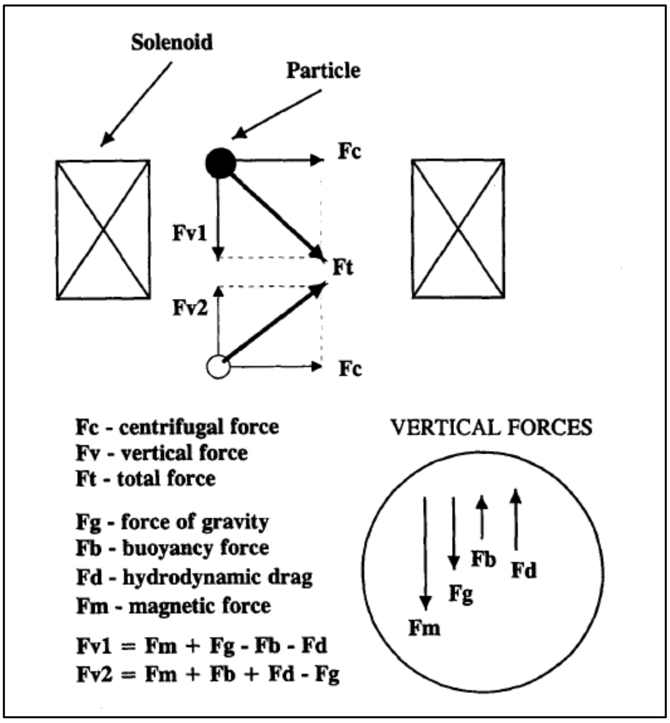

Figure 2.6: Magnetic Dense Medium Cyclone Particle Forces (Svoboda *et al.*, 1998:503)

From the figure above, it can be seen that the magnetic field induces a vertical force on the particle, and therefore the positioning of the magnetic source would make a difference in the effect of the magnetic field on a particle within a dense medium cyclone. The experimental arrangement followed by Svoboda *et al*. specifically related to the positioning of the magnetic source can be schematically illustrated in Figure 2.7:

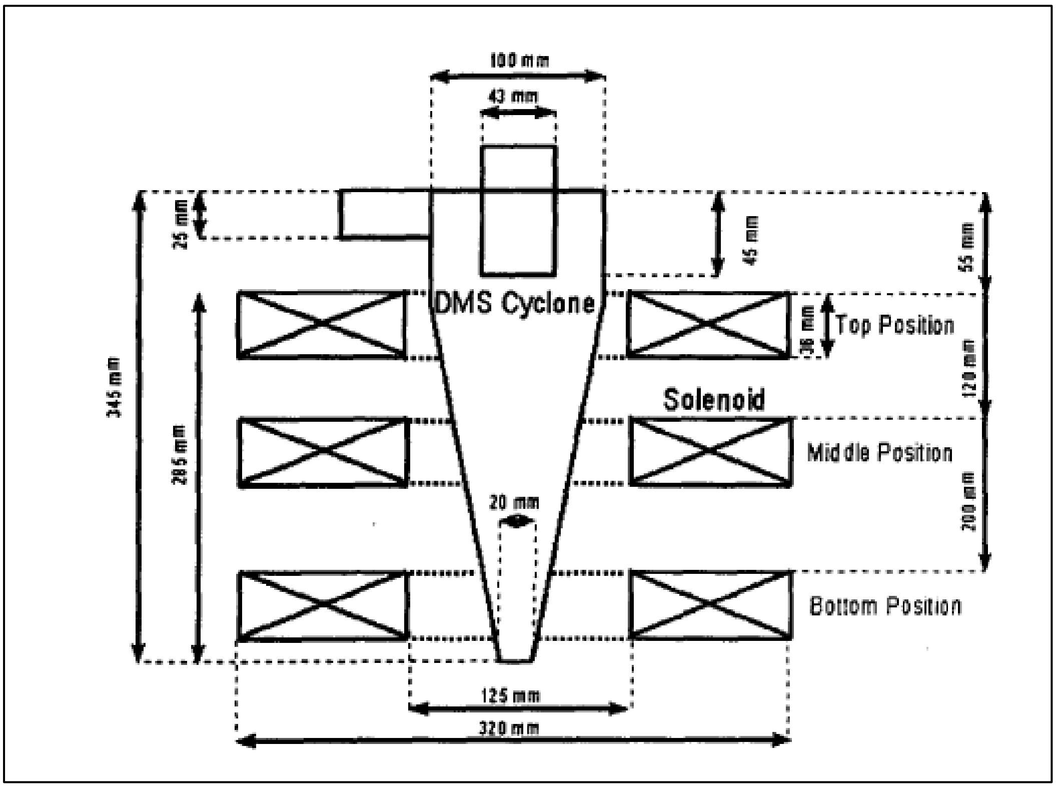

Figure 2.7: Schematic of Experimental Arrangement Regarding Solenoid Positioning (Svoboda *et al.*, 1998:504)

The study was done using two grades of ferrosilicon, and the results can be summarised as follows (Svoboda *et al*., 1998: 505-509):

- An increase in magnetic intensity causes a decrease in density differential up until an optimum minimum value, from where a further increase in magnetic intensity would result in an increase in density differential due to magnetic flocculation;

- The greatest density differential reduction can be achieved using a magnet in the top position (refer to Figure 2.7) as this position yields a more even medium distribution within a dense medium cyclone;

- In the investigated range of feed densities (2.35 – 2.65 g/cm^3), the density differential is independent of these densities;

- The minimum density differential could be achieved at 80 Gauss for the 270D grade ferrosilicon, and 40 Gauss for the Cyclone 60 grade ferrosilicon. This difference is due to the difference in PSD of the two grades: Cyclone 60 is a coarser grade than the 270D;

- The EPM can be decreased significantly to an optimum point, where after an increase in EPM can be seen again. Once again, due to the coarseness of the Cyclone 60 grade, this increase is more dramatic. The 270D grade EPM was reduced from 0.06 to 0.02 at 35 Gauss, while the Cyclone 60 grade EPM was reduced from 0.08 to 0.03 at 35 Gauss. The minimum EPM was achieved at a density differential of 0.25 g/cm^3 for the 270D grade; and

- The cut-point density decreases with an increase in magnetic intensities with a maximum reduction of 5 % at the magnetic intensity at which the EPM is the lowest. This is the result of a reduction in density differential, and thus the underflow density.

From this, it is once again evident that great potential lies within this application.

2.6.3 Myburgh (2001)

This study was done at the Koingnaas Mine on both a 250 mm diameter dense medium cyclone (1998) and a 510 mm diameter dense medium cyclone (2000) in a production scale operation. The variables were magnetic intensity, solenoid position, and medium inlet density. The following parameters were kept constant: dense medium cyclone configuration, medium grades and inlet pressure. In addition to this, two scenarios were tested, namely medium feed with and without the introduction of ore (Myburgh, 2001).

The findings from these tests were as follows:

- The effect of the magnetic field was similar on medium passing through both a small and large diameter dense medium cyclone.

- The effect of the magnetic field on the medium in both cases (with and without the addition of ore) was found to be similar.

- There was a reduction in medium segregation and this is a medium-stabilisation effect observed in all conducted tests. This resulted in an underflow medium density reduction.

- This was observed up until an optimum point where after, as before, magnetic flocculation took place causing a disrupted flow pattern within the dense medium cyclone.
- Evidently it was noted that the cut-point is primarily determined by the underflow density.

Therefore, according to the studies conducted by Myburgh (2001), it is evident that this application has the ability to improve separation efficiency due to the increase in medium stability, and also results in direct cut-point control, making the possibility of on-line dense medium cyclone control a reality.

2.6.4 Vatta *et al*. (2003[1])

Vatta *et al.* echoes the core findings from previous studies done. This specific study was done on a production scale, building on the work done by Svoboda *et al.* (1998), and it was observed that the yield to the concentrate could be decreased in this application.

The aim of this study was to confirm the results obtained by Svoboda *et al.* (1998) and to (Vatta et al., 2003[1])

- Determine the yield as a function of magnetic intensity; and
- Determine the yield as a function of the magnetic source (solenoid) position.

The material used was de-diamondised quartzite in the size range of 1.6 to 4 mm, and a density of approximately 2.65 g/cm^3. This material was made up of a blend of DMS tailings and de-diamondised recovered tailings (0.2 % recovered).

A cyclone with a diameter of 100 mm was used and the plant was equipped with online density gauges and a SCADA plant control system.

Two solenoid coils were tested, the main difference being the resistance (ohm) of the two coils.

- The density differential for both coils reached a minimum before increasing again with an increase in magnetic field strength. This minimum was reached at a magnetic intensity of approximately 97 Gauss for solenoid Coil II (with a resistance of

2.0 ohm) and approximately 110 – 130 Gauss for solenoid Coil I (with a resistance of 1.7 ohm).

- Due to dimension ratios, it was decided to use Coil II for the test work.

Vatta et al. continued with this study and this discussion will follow.

2.6.5 Vatta *et al*. (2003[2])

The work done in this instance made use of a pilot scale system, and also with the introduction of a sample consisting mainly of quartzite into said system during the course of the test work. The key objective was to determine the yield to the dense medium cyclone underflow as a function of the solenoid position and magnetic field strength.

2.6.6 Fan *et al*. (2015)

The purpose of this study was to investigate the effects of an applied magnetic field and solenoid position on the separation within a dense medium cyclone. The difference between this study and previous studies, is it made use of coal and magnetite as opposed to the diamond application. A similar setup to previous studies was used:

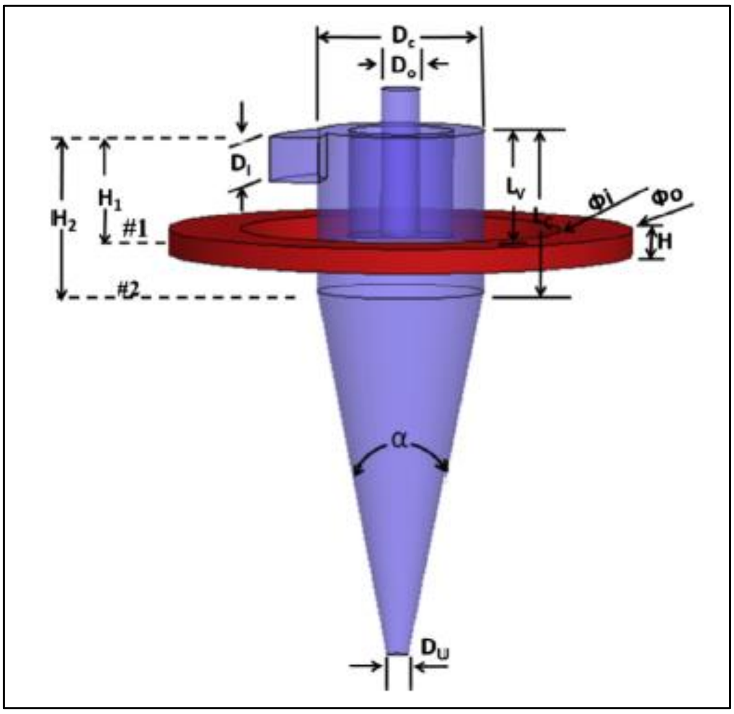

Figure 2.8: Experimental Cyclone Schematic (Fan *et al.*, 2015:89)

Two tests were performed and compared to baseline tests without the application of a magnetic field.

1. Medium distribution tests were performed at solenoid positions 1 and 2 as in Figure 2.8; and

2. Coarse coal slime was tested at solenoid position 1 as per Figure 2.8.

The work concluded the following (Fan *et al*., 2015:93):

- The separation density could be altered within a dense medium cyclone; and

- Medium stability could be improved.

This provides a solution for using inexpensive, low density media instead of a higher density medium, which is more expensive and which has a higher consumption rate than lower-density media.

2.7 Magnetic Cyclone – This study

Although the studies mentioned thus far have been specifically aimed at diamond DMS applications, the same principle of density differential manipulation is likely to apply to coal DMS applications, the modification being in the difference in medium, as well as operational and variable parameters.

For this specific study, SpecSep™ solenoids were used. As was the case with the previous studies, the SpecSep™ solenoids produced a very weak magnetic field and thus magnetic flocculation would be unlikely to occur. The theory behind the use of a solenoid to induce a magnetic field in which to stabilise the medium, suggests that a coarser magnetite grade can be used. The solenoids are most likely to produce a magnetic field which would stabilise the coarser media, thereby introducing the concept of using such media in an industrial application. The benefit of this would be that cheaper media could be used, as fine media is more expensive than coarse media due to the added milling costs. Also, the coarse media would be much easier to recover in the magnetic separation media recovery circuit, thus minimizing media losses and resulting in a financial saving.

Adding an extra component (magnetic force) to the system does bring about questions on the practical aspects of the effect of such a force. According to Dworzanowski (2010:644), fine particles (ferromagnetic) require a much higher magnetic intensity for recovery than its coarser counterparts. Due to the weak magnetic intensities used in this study (< 100 Gauss), it would make sense then that the magnetic field would have little to no effect on the finer particles, making room for coarser particles to be used. The magnetic field also weakens as it goes deeper into the cyclone, and therefore the force is not equal at the center of the solenoid and at the center of the cyclone. This emphasizes once again that the magnetic field would have an almost negligible effect on the finer, more conventional magnetite particles.

2.8 Conclusion

Dense medium separation within a dense medium cyclone is an intricate, subtle process which needs to be operated very carefully in order to ensure efficient separation within such a unit. Studies have shown that on a diamond application, a magnetic field applied to a dense medium cyclone process absolutely impacts the separation due to media stabilisation. Throughout all the studies covered in this chapter, it was found that the density differential could be manipulated along with the cut-point density and ultimately the separation efficiency.

Preliminary work has been done by Fan *et al*. (2015), which shows that there is potential for such a system to be applied to a coal process. This study aims to investigate this further and to determine to which degree such a process can be made more efficient and cost-effective.

Chapter 3 to follow sets out the experimental procedure that was followed, touching on the materials, tracers and equipment used to achieve a more efficient separation within this process, and by which method.

CHAPTER 3: EXPERIMENTAL METHOD

The experimental procedure is the heart and soul of any project. Careful consideration should be given to this task as it could make or break a project.

This section aims to set out the experimental procedure followed during the course of the test work. Upon receiving the magnetite, the sample Specific Gravity (SG) was measured using a density bottle and the Particle Size Distribution (PSD) was also measured, after which the cyclone rig was set up according to the specific configuration chosen. A calibration phase, commissioning phase and tracer tests followed. The methodology behind these tests will be discussed in this chapter.

3.1 Constants and Variables

Three categories are summarised in Figure 3.1 below:

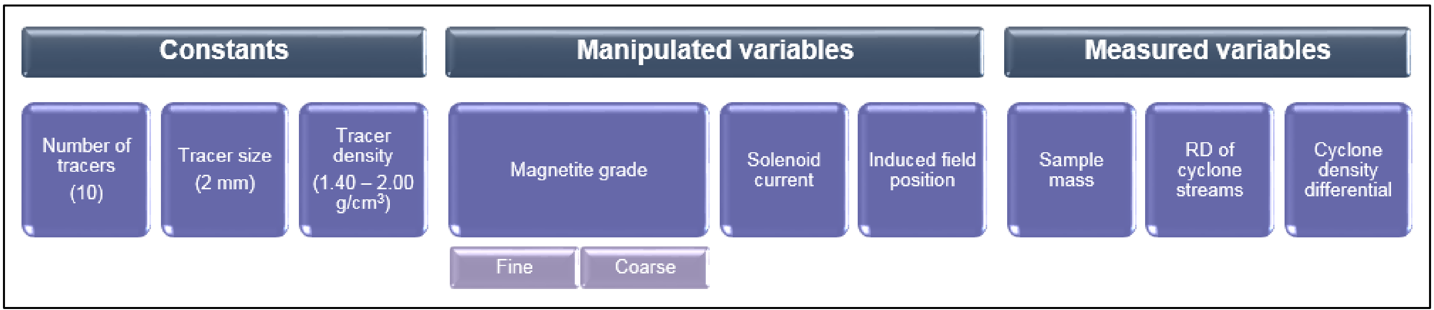

Figure 3.1: Experiment Constants and Variables

From Figure 3.1 it can be seen that the constants were as follows:

1. Ten (10) tracers were used per density interval;
2. The tracer size was kept constant at 2 mm so as not to introduce a classification effect in conjunction with the separation based on density during the process; and
3. The tracer densities ranged from 1.4 g/cm^3 to 2.0 g/cm^3 in intervals of 0.1.

Two magnetite grades were used, namely coarse and fine magnetite. This will be discussed in Section 3.2, and measured variables consisted of the sample mass, relative density of the cyclone streams and most importantly, the density differential between the cyclone underflow and overflow streams.

3.2 Materials Used

The tests were run without the addition of ore (coal) throughout, and two grades of magnetite were made use of. This will be discussed.

3.2.1 Magnetite

Two grades of magnetite were sourced, namely a "fine" grade from Martin and Robson, and a "coarse" grade from Kimony (Pty) Limited. The coarser grade is not conventionally supplied to the DMS industry, and is a by-product from mined beach sand. The coarse grade is readily available, as it is used in other industries besides the DMS applications. These particles are spherical in shape, and this is favoured by the SpecSep™ Solenoids, which will be discussed shortly. Henceforth, the SpecSep™ solenoids will be referred to as "solenoids"

The Figure 3.2 shows the measured particle size distributions of the two magnetite grades:

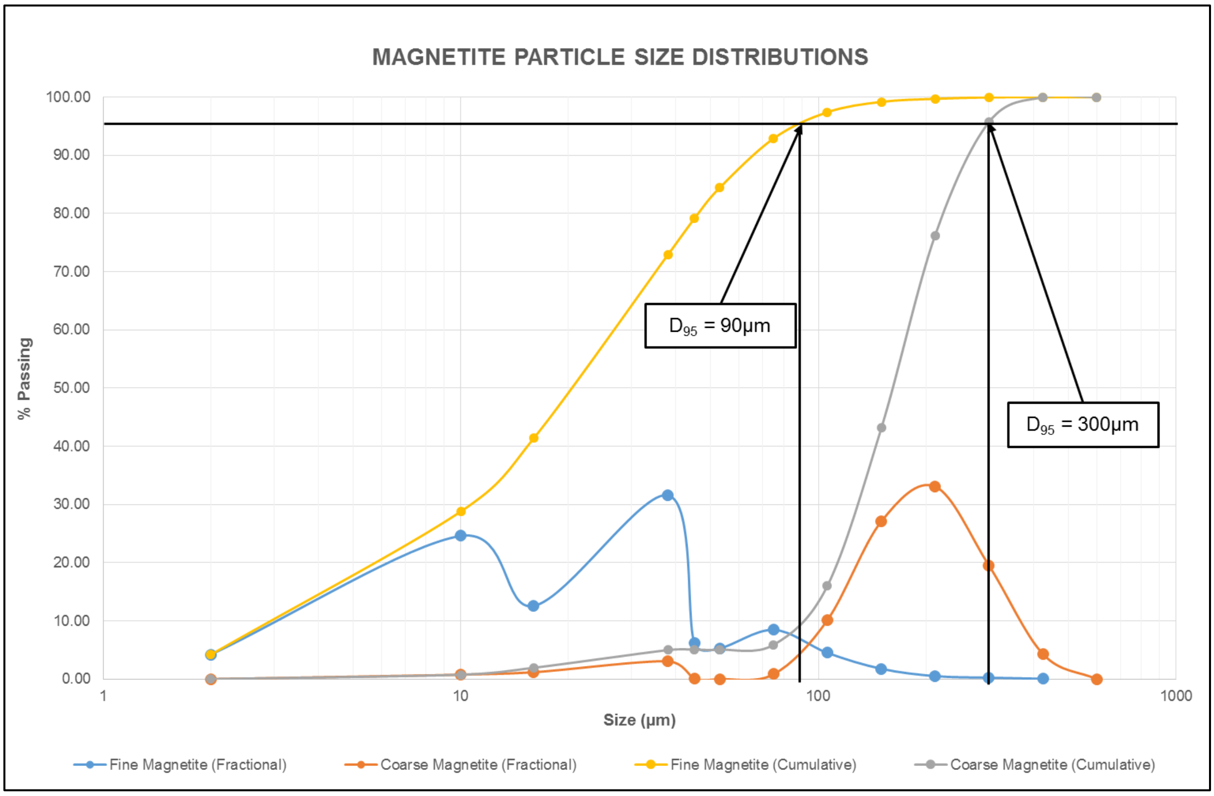

Figure 3.2: Measured Magnetite Particle Size Distribution

From the figure above it can be seen that the coarse magnetite has a D_{95} of 300 µm, while the fine magnetite has a D_{95} of 90 µm. Although it would not commonly be considered as coarse, for distinction purposes, the coarser grade of the two will henceforth be referred to as "coarse" magnetite, while the finer of the two will be referred to as "fine" or "conventional" magnetite.

3.2.2 Density Tracers

Non-magnetic density tracers (sourced from DG Laboratory Services) were used during the course of the test work. Ten tracers per density were used during the tracer tests mentioned in Section 3.1. Tracers with densities ranging from 1.40 to 2.00 g/cm^3 were used, and are depicted below:

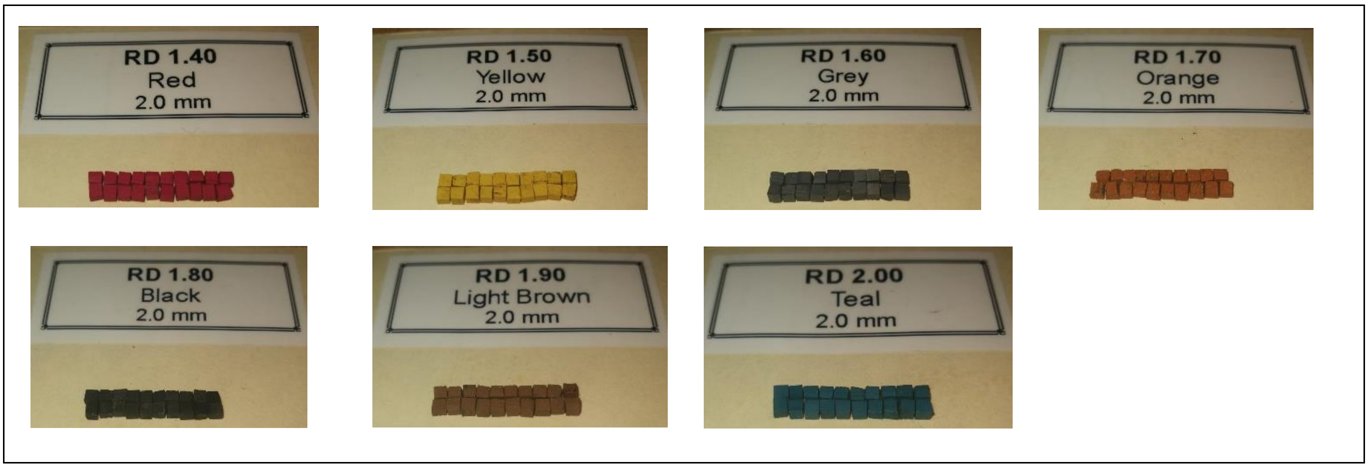

Figure 3.3: Density Tracers

Where density tracer colours were not as easily distinguishable, the tracers were added to the system in separate batches so as to avoid confusion/misrepresentation of that specific RD. An example would be the difference in colour between the grey (1.60 g/cm^3), black (1.80 g.cm^3) and teal (2.00 g/cm^3) tracers. These colours would be increasingly difficult to distinguish after being exposed to the black magnetite, which has the tendency to "stain" the tracers.

3.3 Sample Preparation

Upon receipt of the magnetite, the two grades were individually blended and split into more manageable batches (25 liter buckets). A sub-sample of one bucket from each of the two grades of magnetite was taken for SG analyses. The SG is used to determine the ratio in which the magnetite and water is to be mixed in order to make up the required RD of the slurry being fed to the cyclone. The SG was determined using a density bottle, as depicted in Figure 3.4 below:

Figure 3.4: Density Bottle

Prior to the determination of the SG, it is important to ensure that the sample is completely dry and contains no surface moisture. The sample was left to dry in an oven at 100°C until the mass of the sample remained constant. When the sample was dry, the mass of the empty density bottle and cap was measured and recorded as m_1. The volume of the density bottle, v_d is engraved on the bottle itself. Solids were then added to the density bottle, and this mass, which should be approximately 10 grams, was recorded as m_{solids}. Water was subsequently added to the density bottle and the total mass of the bottle, cap, water and solids was recorded as m_2. The mass of the water added to the flask was recorded as m_{water}. The following equation was consequently used to determine the SG of each magnetite grade:

$$SG = \frac{m_{solids}(m_{water}-m_1)}{v_d(m_{water}-m_2+m_{solids})} \quad \text{(Equation 3.1)}$$

The coarse magnetite SG was found to be 4.73, while the fine magnetite SG was found to be 4.60.

3.4 Experimental Apparatus

Tests such as these make use of a vast range of experimental, test and analytical equipment. The different types of equipment used during the tests are described below:

3.4.1 SpecSep^{TM} Solenoids

The idea for the design of solenoids sprung from the research that was done by the authors mentioned in Section 2.6 in the previous chapter. Specifically the work done by Prof. Campbell and Dr. Svoboda (1996). According to the creator of the SpecSep^{TM} Solenoids, the concept of using such solenoids was proven at the University College of Dublin in 2014. A company (Eco-nomic Innovations Ltd.) was formed since to commercialise the idea and the following patents were granted:

- US Patent (US Patent No. US9901932B2, 2015);
- South African Patent (South African Patent No. 2016/06592,2015); and
- Chinese Patent (China Patent No. CN106061615A, 2015)

The European Patent (Europe Patent No. Application 15710734.3, 2015) is still pending.

Figure 3.5 below illustrates the cyclone and solenoid configuration:

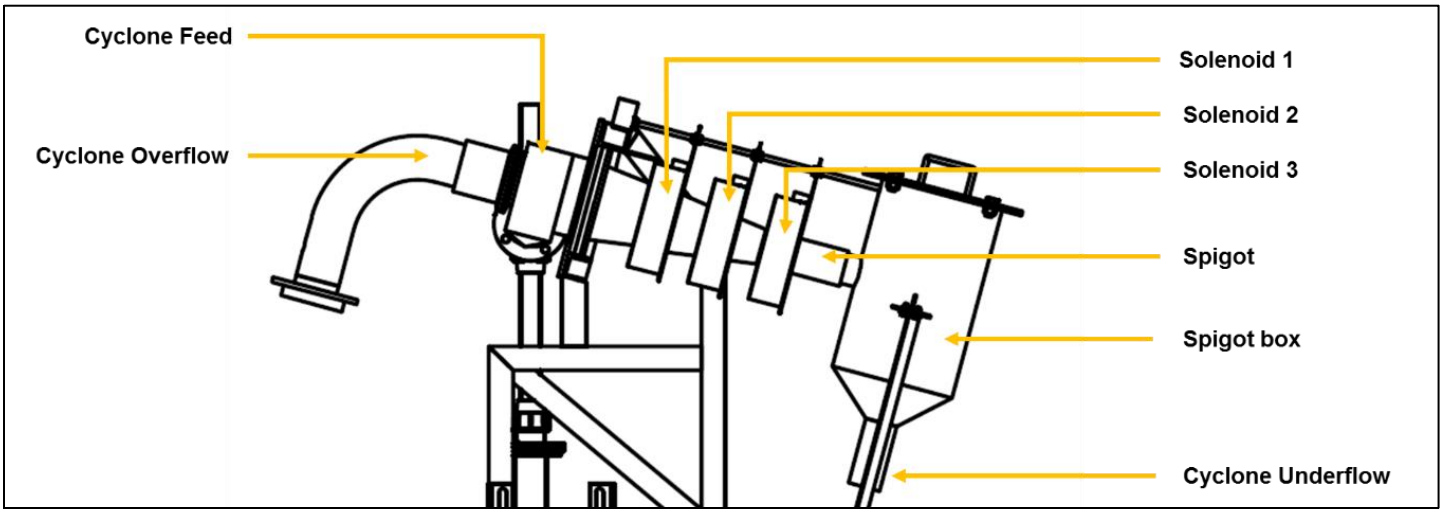

Figure 3.5: Cyclone Experimental Setup Schematic

The solenoids were manufactured in South Korea, and the power supply is an Aim and Thurlby Thundar Instruments MX100T, which is a triple output DC power supply with a total capacity of 315 watts. This is shown in Figure 3.6 below:

Figure 3.6: DC Power Supply

The power supply allows for independent setting of currents for each solenoid.

3.4.2 Magnetic Cyclone

The magnetic cyclone configuration is illustrated in Figure 3.7 below:

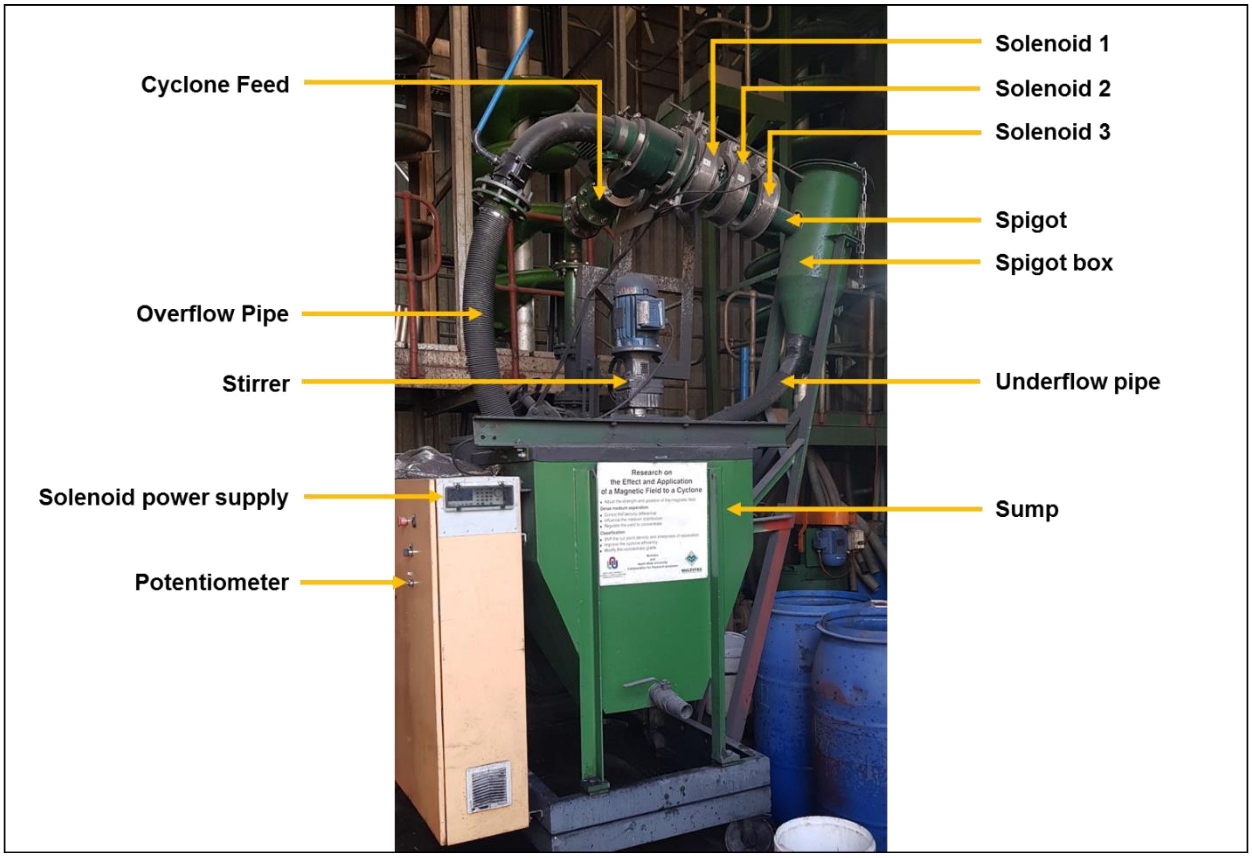

Figure 3.7: Magnetic Cyclone Configuration

The cyclone is a VV165-15 polyurethane unit, which means it has a 165 mm diameter and a 15° cone angle. The spigot used was 35 mm, and the pressure was kept constant at 9D, which in this case, translates to 25 - 50 kPa. Extra care was taken to ensure that there were no magnetic fittings in close proximity to the cyclone so as not to interrupt the flow within the dense medium cyclone apart from the intended flow disruption.

The sampling points were located at the cyclone feed bypass line, the overflow pipe and the underflow pipe.

3.5 Experimental Method

The experimental method details the steps that were followed to generated results which makes sense.

3.5.1 Calibration

The calibration phase took place as follows:

1. As a first attempt, the magnetic flux density on the edge and center of each solenoid was determined while the solenoids were mounted onto the cyclone. It was discovered that the spigot box was magnetic, and therefore created an interference with the magnetic fields. The spigot box has since been replaced with a non-magnetic spigot box.
2. Consequently, the magnetic flux density was determined while the solenoids were not mounted onto the cyclone.
3. A current was passed through the solenoids, and a handheld gauss meter was used to determine the magnetic flux density at the edge and center of both sides of each solenoid. The figure below shows a schematic of each solenoid, and gives the distance between each solenoid, as well as an indication of where the magnetic flux densities were taken.

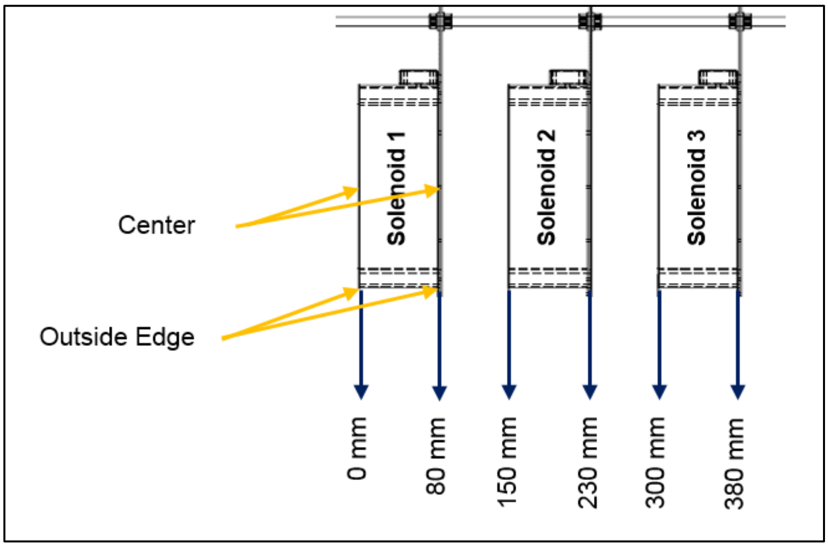

Figure 3.8: Solenoid Schematic

From Figure 3.8 it can be seen that the solenoids are 80 mm wide, and was kept 70 mm apart throughout the experiments. The inner diameter of the solenoids is 220 mm, while the outer diameter is 280 mm, thus indicating that the solenoids are 60 mm thick. Due to the conical form of the cyclone, the effect of the solenoids tapers off from Solenoid 1 to Solenoid 3 (refer to Figure 3.5). This has an influence on the effectiveness of the solenoids, and will be further discussed in Chapter 4.

The next step was to commission the solenoids.

3.5.2 Commissioning Phase

The aim of these tests were to determine at which conditions the density differentials obtained were at the optimum.

1. During these tests, a charge of fine magnetite and water was made up.
    a. The water was first added to the sump, and
    b. The main valve feeding the cyclone was closed.
    c. The bypass valve was then fully opened in order to circulate the water through the pump, bypassing the cyclone.
    d. The required mass of solids was slowly added to the sump, with the cyclone being on bypass mode in order to thoroughly mix the slurry so that it would be considered as homogenous.
    e. An amount of coarse magnetite was added.
2. After each addition, the RD was measured prior to any samples being taken.
3. Once these values were constant, the density differential, which is the difference in density between the cyclone underflow and overflow streams, were measured.
4. The RD measurement methodology is described below:
    a. A mass scale and volumetric cylinder is needed to determine the RD of the slurry.
    b. The RD of the feed was measured while the cyclone is on bypass mode.
    c. The volumetric cylinder was filled with slurry, and the mass of the filled cylinder was weighed.
    d. The mass of the volumetric cylinder was subtracted from the total mass, and this mass was divided by the volume as per the volumetric cylinder to determine the RD:

$$RD = \frac{(\text{Cylinder Mass} + M_{slurry})\text{-Cylinder Mass}}{V_{slurry}} \quad \text{(Equation 3.2)}$$

    e. This was then repeated until three consecutive RD measurements are constant.
5. Once the RD was constant, a feed sample was taken using a 5 litre bucket,
6. After this, the main valve was opened and the bypass valve was closed so that the slurry could be processed through the cyclone.

7. A potentiometer was used to adjust the cyclone to the desired pressure (25 - 50 kPa).
8. Five minutes were allowed to lapse before taking the overflow and underflow samples.
9. The RD of the overflow and underflow was then calculated as per Equation 3.2, and should again have been constant for three iterations.

During these tests, it was found that due to the excessive recirculation of the material, particle attrition took place. It was decided to discard that batch of media, and to start from scratch. A batch of 100 % coarse media was consequently made up in a similar manner as before, and fine media was added until a point was reached at which it was no longer beneficial to add any more fine media.

It is important to note that prior to making up the new batch, and while the media was coarsened up, it was determined that SpecSep™ solenoid 3 (the solenoid closest to the cyclone spigot/outlet) did not have a stabilisation effect on the magnetite, and henceforth only SpecSep™ solenoids 1 (the solenoid closest to the vortex finder/cyclone inlet) and 2 (the solenoid between solenoids 1 and 3) were used. This will be explored in more detail in Chapter 4.

3.5.3 Tracer Tests

During this phase of the test work, the constants were the number of tracers, tracer size and tracer density. The manipulated variables were the two magnetite grades, solenoid current and induced field position. The measured variables were the sample mass, cyclone stream RD, tracer distribution to each cyclone stream and cyclone density differential.

1. The system was allowed to reach steady state, and
2. Once again three relative densities of each of the feed, overflow and underflow streams were measured.
3. Once the density differentials were determined, tracers were added to the system in order to determine the cut-points and sharpness of separation.
4. Sieves were used to retain the tracers reporting to both the overflow and the underflow streams.
5. These tracers were counted and the data reported on in Chapter 4.

According to Wills and Napier-Munn (2006: 264), the following equation can be used to predict the Ep of a given set of data pertaining to a partition curve:

$$P_i = \frac{1}{1+\exp\left[\frac{\ln 3\left(\rho_{50}-\rho_i\right)}{Ep}\right]} \qquad \text{(Equation 3.3)}$$

Where

P_i = partition number (feed reporting to the sinks)

ρ_{50} = separating density

ρ_i = mean density of the density fraction

Therefore, an approximation can be made by using Equation 3.3. In Chapter 4.3, this equation will be used to demonstrate that the curve fits the data generated.

3.6 Conclusion

During these tests, a three phase approach was taken. Firstly, the SpecSep™ solenoids had to be calibrated as these are new units, secondly commissioning tests had to be run to determine the ratio of coarse to fine magnetite that was needed in order to obtain favourable density differentials. Thirdly, tracer tests had to be done at these "optimal" conditions so that cut-point and sharpness of separation data could be generated.

Chapter 4 will now focus on the results obtained from these tests and will contain discussions thereof.

CHAPTER 4: RESULTS AND DISCUSSION

Chapter 4 contains the results obtained from the experimental work as well as a discussion of said results. The outline of the chapter will follow the chronological order of the work that was done, starting with the calibration phase, moving on to the commissioning tests and finally the tracer tests.

4.1 Calibration Phase

During the calibration phase, two aspects were considered. Firstly, a relationship had to be drawn between the magnetic flux density and solenoid current. Secondly, the effect of individual solenoid current on the overall density differential was touched on.

4.1.1 Relationship between Magnetic Flux Density and Solenoid Current

During the calibration phase, the average magnetic flux densities (in millitesla) at the center of the solenoid versus the current (in Ampere) was determined, and can be seen below:

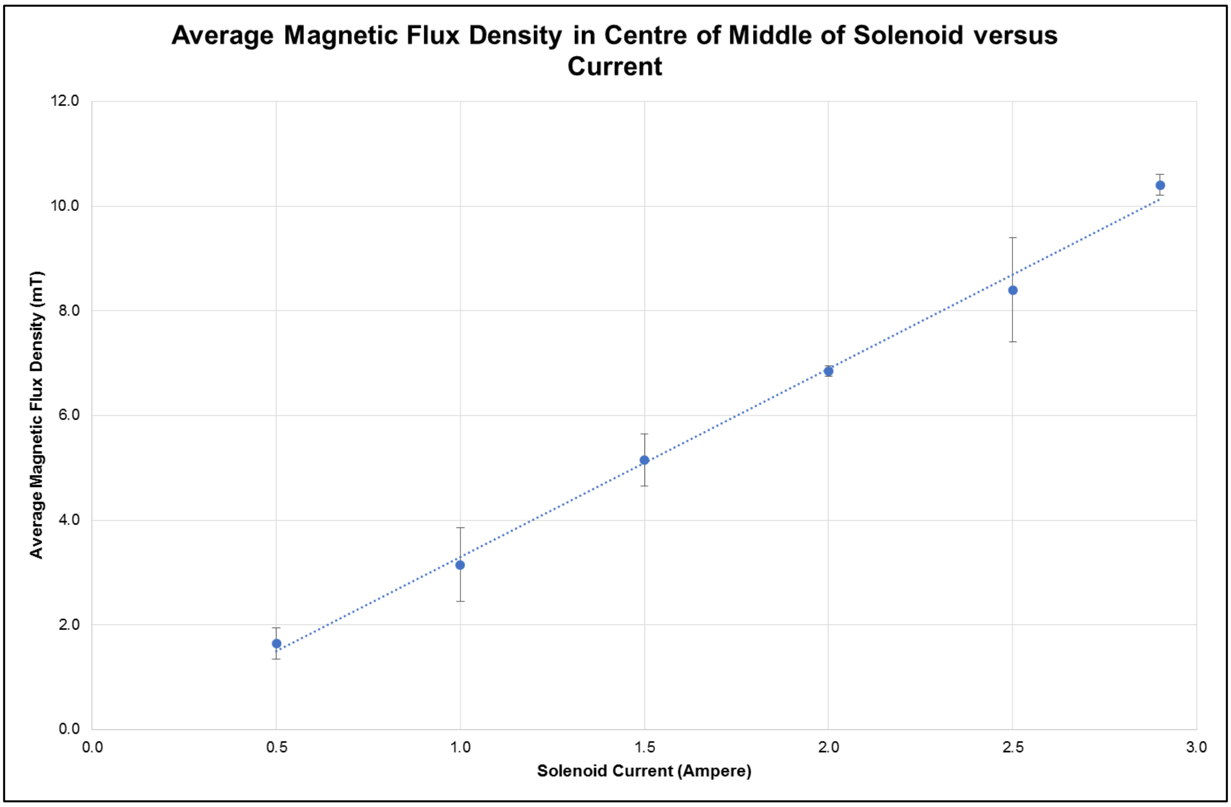

Figure 4.1: Solenoid Current versus Magnetic Flux Density

From Figure 4.1 above, it can be seen that there is an almost linear relationship between these two variables. For instance, a solenoid current of 1 A results in a magnetic intensity of 3 mT, which translates to 30 Gauss. This information will be used to couple a magnetic intensity to a specific current used, throughout this chapter.

4.2 Commissioning Phase

During these tests, a suitable mixture of fine and coarse magnetite was made up and the effect of the solenoid current on the medium stabilisation was determined. For the commissioning, two sets of tests took place, namely a test with coarse media being added to the fine media, and a test with fine media being added to the coarse media to change the ratios between coarse and fine medium. These tests formed the baseline of the tracer tests to follow.

4.2.1 Coarsening the Media

In an industrial application, fine magnetite would be present in a coal DMS plant setup. Therefore it was decided to charge the sump with fine (conventional) magnetite while gradually coarsening the media. After each addition of an amount of coarse media, the density differential was measured. This value was used to determine at which ratio the density differential would be between 0.2 and 0.5 g/cm^3, as according to literature (Campbell & Coetzee, 1997:6), this would be the optimum density differential at which to operate the system.

An initial amount of 183.8 kg of fine magnetite was mixed with water, and batches of coarse magnetite, with a mass of 18.3 kg each, was added to the fine magnetite. At a random point (17 % coarse magnetite), the effect of the solenoid current on the density differential was determined and can be seen below:

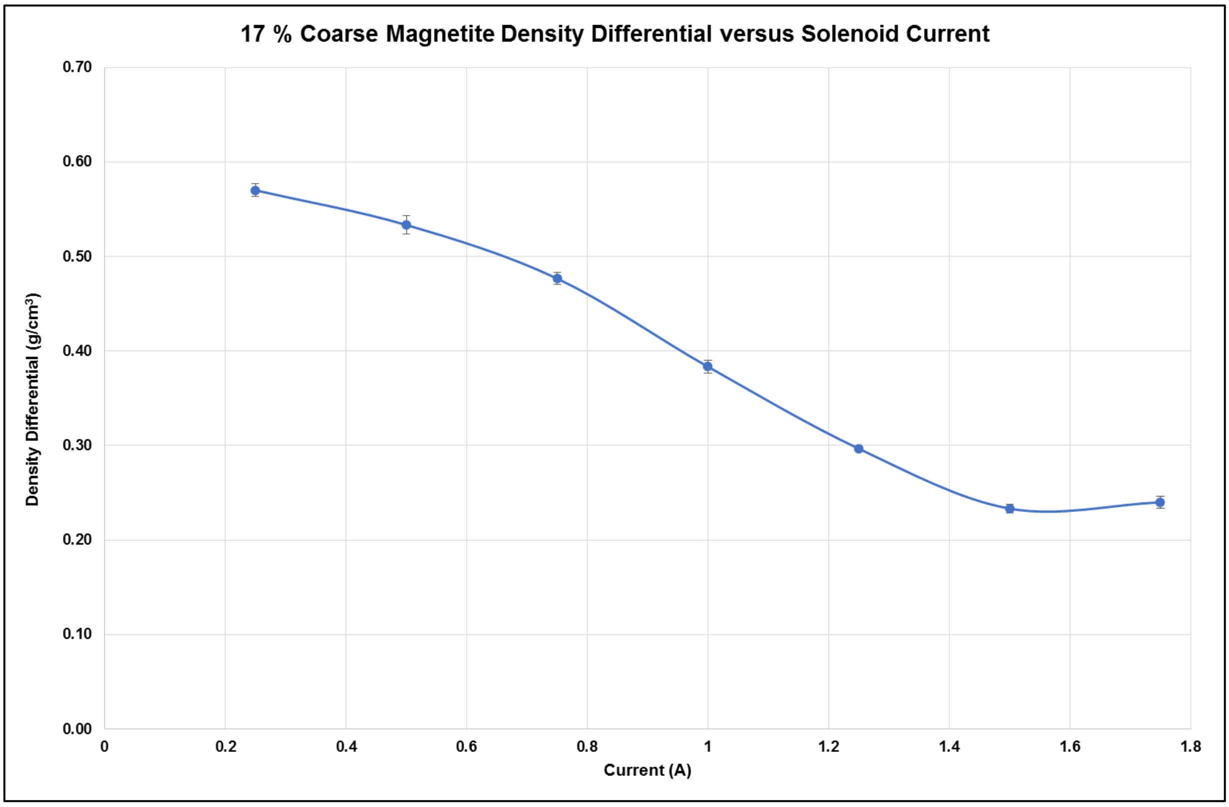

Figure 4.2: Density Differential versus Solenoid Current - 17 % Coarse Magnetite

From Figure 4.2 it can be seen that an increase in solenoid current results in a decrease in density differential. This appears to plateau after a solenoid current of 1.5 A (identical for all three solenoids).

At this coarse magnetite percentage, it was found that the density differentials could be manipulated further by operating the solenoids at different currents. These effects will be discussed before moving on to the further coarsening of the media.

4.2.2 Effect of Individual Solenoid Currents on the Density Differential

Tests were done in which the individual solenoid currents were varied in order to establish the degree to which each solenoid contributes to the stabilisation of the media. The results below refers:

Table 4.1: Effect of Differing the Individual Solenoid Current on Density Differential

Current (A)			RD (g/cm^3)		
Sol 1	**Sol 2**	**Sol 3**	**Overflow**	**Underflow**	**Differential**
0.0	0.0	0.0	1.57	2.26	0.68
2.0	0.0	0.0	1.65	1.99	0.34
0.0	**2.0**	0.0	1.64	2.04	0.40
2.0	**2.0**	**2.0**	1.67	1.97	0.30
2.0	**2.0**	0.0	1.68	1.90	0.22
2.0	**1.8**	0.0	1.67	1.91	0.24

From Table 4.1, and with a solenoid current of 0 A as a basis, the following can be seen:

- Passing a current through Solenoid 1 only has a stabilisation effect on the media;
- Passing a current through Solenoid 2 only has less of a stabilisation effect;
- Passing an identical current through all three solenoids has a greater effect than when only making use of Solenoid 1 or Solenoid 2 in isolation, however, passing an identical current through Solenoids 1 and 2 has the greatest stabilisation effect compared to all scenarios listed; and
- Passing a lower current through Solenoid 2 than Solenoid 1 also has a destabilisation effect on the media.

It can thus be concluded that the inclusion of Solenoid 3 causes a lesser stabilisation effect than when only including Solenoids 1 and 2. This might be attributed to the fact that Solenoid 3 is too low down in terms of the cyclone geometry to effectively make a positive difference in the density differential. It might also be that due to the distance of the solenoid surface from this section of the cyclone with has the smallest diameter, the solenoid does not have an effect on the material within that specific section of the cyclone. It was thus decided to not make use of Solenoid 3 for the rest of this study, unless specifically mentioned in the results which are to follow. It is also interesting to note that according to work done previously, as per Chapter 2.6, the reported optimum solenoid position is the equivalent to the position of Solenoid 1 in this study. This is compared to the positions of Solenoid 2 and Solenoid 3 in isolation. Table 4.1 echoes what was found previously, however what makes this study different is that more than one solenoid was made use of.

This adds an extra element to the research, as it has shown that a combination of solenoids has a greater effect on the density differential than when using the solenoids in isolation. The destabilisation effect of passing non-identical currents through Solenoids 1 and 2 will be discussed in the section 4.2.3.

4.2.3 Effect of Non-identical Currents for Solenoids 1 and 2 on the Density Differential

After the discovery of the results in the preceding this section, it was decided that only Solenoid 1 and Solenoid 2 would be used during the course of the experimental work, and the current passed through each of these solenoids would remain identical throughout, unless otherwise specified in the results.

It was noted during a trial run that operating Solenoid 2 at a 10 % higher current than Solenoid 1 had a slightly higher medium stability effect than when operating both these solenoids at an identical current. See the graph below for the effect that this would have:

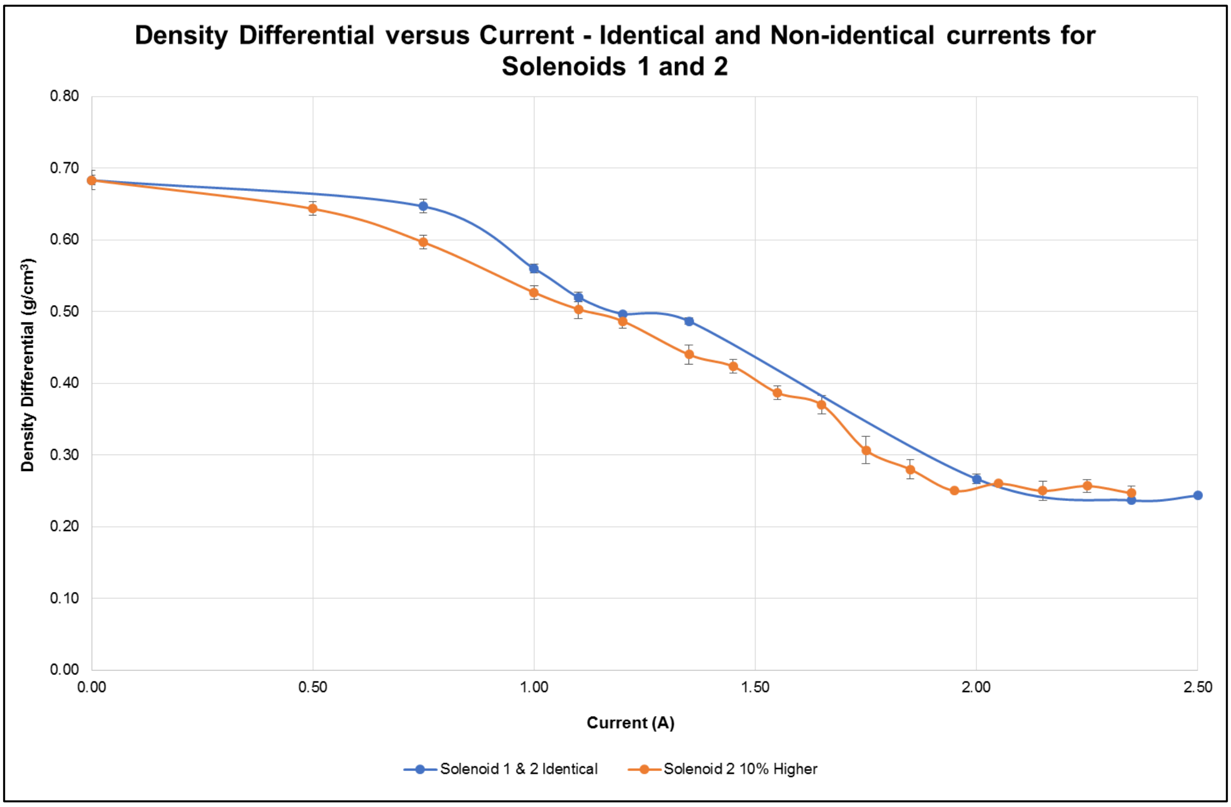

Figure 4.3: Density Differential versus Solenoid Current – Identical and non-identical currents through Solenoids 1 and 2

From the Figure 4.2 above, it can be seen that by passing a current through Solenoid 2 which is 10 % higher than that of Solenoid 1, a consistently lower density differential can be achieved than in the instance where both Solenoids 1 and 2 are operated at an identical current. This system reaches a plateau at 2 A and beyond, which in turn indicates as well that there will be a very slight benefit in operating the Solenoids at currents above 2 A.

Operating Solenoid 2 at a higher current than Solenoid 1 supplements the stabilisation effect, as the near density material is usually hung up to a certain extent in the section of the cyclone around which Solenoid 2 is positioned. The higher magnetic field intensity aids in stabilising the near density material specifically, thus favourably lowering the density differential in this solenoid configuration. It is expected that, should Solenoid 1 be operated at a higher current than Solenoid 2, no benefit would be seen as the magnetic effect in this part of the cyclone would be introduced "too early", thereby negating the effect that an increased solenoid current would have.

4.2.4 Further Coarsening of the Media

It was decided to run all further tests during the coarsening of the media. The results of the media coarsening tests are as follows:

Table 4.2: Coarsening of Media Results

Coarse Magnetite (%)	Feed RD (g/cm^3)	Overflow RD (g/cm^3)	Underflow RD (g/cm^3)	Density Differential (g/cm^3)	Solenoid Current (A)		
					1	2	3
0%	1.70	1.66	1.77	0.10	0.00	0.00	0.00
17%	1.82	1.66	1.90	0.24	1.75	1.75	1.75
17%	1.82	1.66	2.27	0.61	0.00	0.00	0.00
33%	1.97	1.89	2.11	0.22	1.75	1.75	0.00
33%	1.97	1.77	2.54	0.77	0.00	0.00	0.00
53%	2.25	2.18	2.36	0.18	1.75	1.75	0.00
53%	2.25	2.11	3.01	0.89	0.00	0.00	0.00

From the Table 4.2 above, it can be seen that with only fine magnetite and no magnetic field, the density differential amounts to 0.10 g/cm^3. As mentioned in Chapter 2, this is an indication that virtually no separation takes place. It can also be seen that with a charge of

17 % coarse magnetite (and the balance being fine magnetite) and no current passing through the solenoids, a density differential of 0.61 g/cm^3 can be obtained. At a charge of 33 % coarse magnetite and no current passing through the solenoids, a density differential of 0.77 g/cm^3 can be obtained. When the current is increased to 1.75 A however, the density differential drops to 0.22 g/cm^3. Similarly, at a coarse magnetite charge of 53 %, the density differential drops from 0.89 g/cm^3 to 0.18 g/cm^3. Two things are important to note here:

1. The density differential can be dropped quite significantly with the application of the magnetic fields from solenoid 1 and solenoid 2; and

2. An increase in coarse magnetite content causes a decrease in density differential in instances where a magnetic field is applied.

An important observation is that the feed relative density increased with an increase in coarse magnetite content, as can be expected due to the SG difference between the two grades of magnetite – the coarse magnetite has a higher SG than the fine magnetite. It was therefore not a variable that could be kept constant or manipulated. The consequence is that the two effects (coarse magnetite content and RD) could not be evaluated separately from each other.

Instability occurs at higher percentages of coarse media present, it can therefore be concluded that for the solenoids to function optimally, an amount of fine media is needed. Due to the high density differential achieved at 53 % coarse magnetite and no current running through the solenoids, it was decided that further coarsening of the media would not yield any favourable results.

Therefore, at a percentage of 53 % coarse magnetite, the following results were obtained:

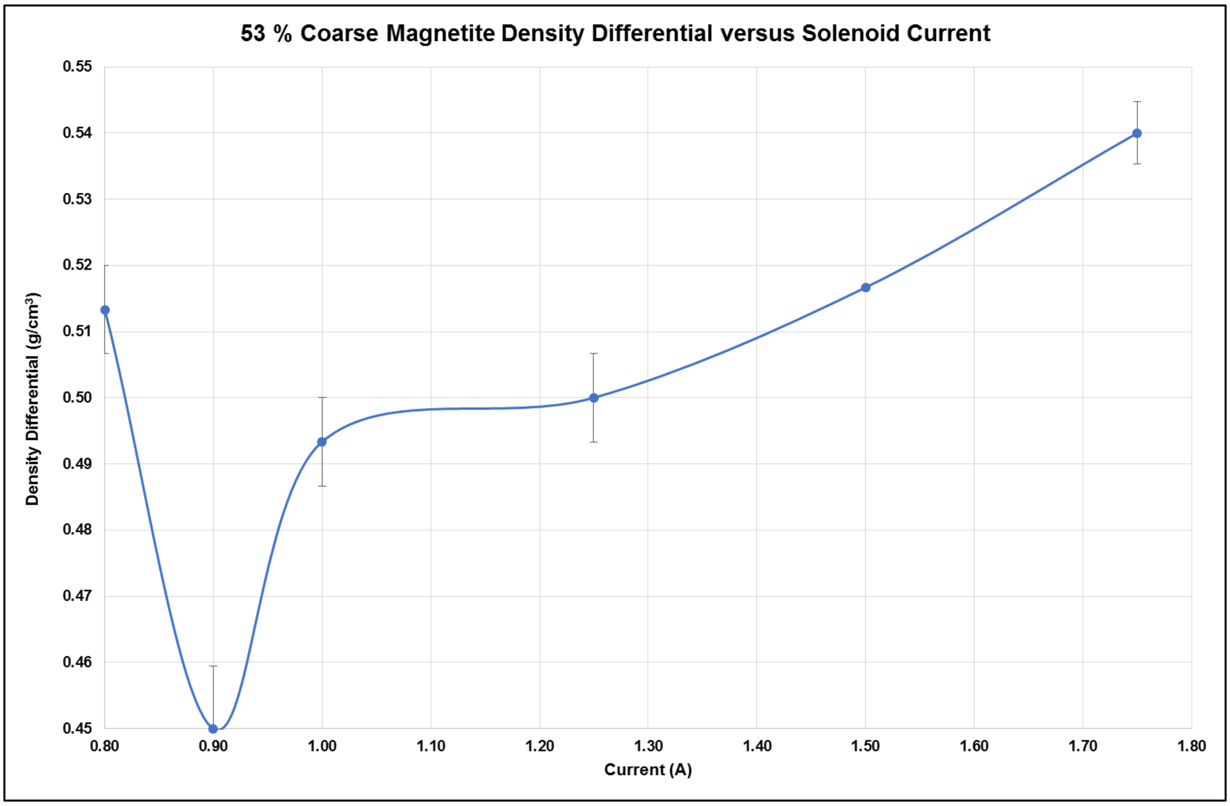

Figure 4.4: Density Differential versus Solenoid Current – 53 % Coarse Magnetite

From Figure 4.4 above, it can be seen that at a current of 0.9 A, the medium was optimally stabilised and a density differential of 0.45 g/cm^3 was achieved. This reiterates that going above 53 % coarse magnetite would lead to instability.

4.2.5 Adding Fine to Coarse Magnetite

A reverse of the coarsening of the media was done – a fresh charge of 100 % coarse media was made up to which known quantities of conventional media were added. The following results were obtained with regards to the amount of coarse magnetite present:

Table 4.3: Adding Fine to Coarse Magnetite

Coarse Magnetite (%)	Overflow RD (g/cm^3)	Underflow RD (g/cm^3)	Density Differential (g/cm^3)	Solenoid Current (A)		
				1	2	3
100%	1.31	2.68	1.38	0.00	0.00	0.00
60%	1.46	2.48	1.02	2.00	2.00	0.00
50%	1.54	2.50	0.96	2.00	2.00	0.00
43%	1.80	2.32	0.52	2.00	2.00	0.00

The density differential starts out at 1.38 g/cm^3 when the charge is fully coarse, and with no current going through the solenoids. This value decreases as more conventional magnetite is added to the system and a consistent current of 2 A is applied to Solenoids 1 and 2. At such a high current, it can be seen that at a charge of 50 % coarse magnetite can achieve a differential of only 0.96 g/cm^3. This is an indication that the media is too coarse, and that there would be no benefit in running at such a high coarse content. The amount of fine magnetite was increased, and at 43 % coarse magnetite content it can be seen that the differential can be decreased to 0.52 g/cm^3 with Solenoids 1 and 2 running at 2 A.

According to Table 4.2 however, at a coarse content of 53 %, the density differential is much lower than at 43 % in Table 4.3. This can be attributed to the fact that attrition had most certainly taken place at 53 % coarse magnetite due to excessive circulation of the material. For the tests ran at 43 % coarse magnetite, media circulation was kept to an absolute minimum, with the rig being switched off between test runs.

The results obtained by varying the solenoids' current at 43 % coarse magnetite can be seen in the graph below:

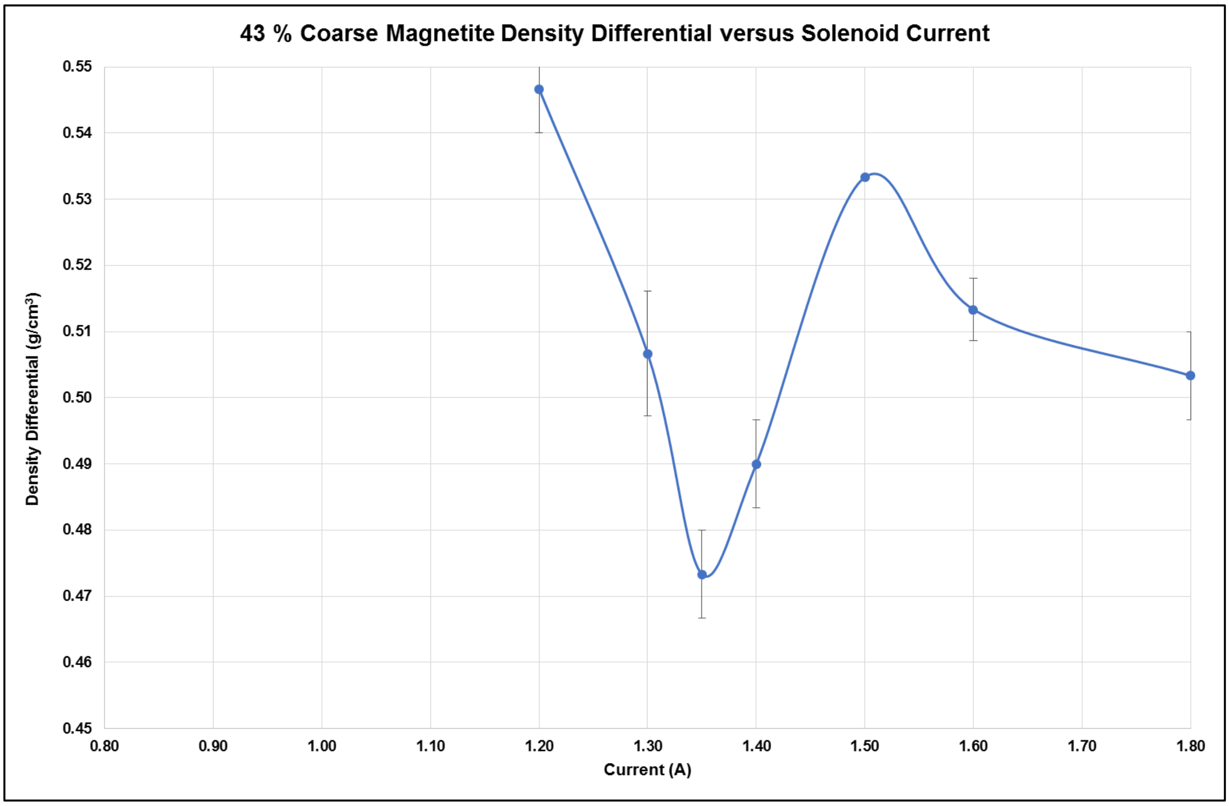

Figure 4.5: Density Differential versus Solenoid Current – 43 % Coarse Magnetite

From Figure 4.5, it can be seen that the density differential is at its lowest at a current of 1.35 A, where after it rises and then levels off.

Following these tests, tracer tests were conducted at certain conditions.

4.3 Tracer Tests

Tests were done during which tracers were added to the system in order to determine the sharpness of separation in two instances, namely where only fine magnetite was used and where coarse magnetite was used. The fine magnetite test provides another baseline for what would happen in a conventional DMS process, while the addition of coarse magnetite would provide a comparison to establish what would happen to the sharpness of separation.

The fine magnetite tracer tests were done without applying a current to the solenoids, thus mimicking what would happen in a real DMS process. The aim of this would be to compare the sharpness of separation with a scenario where coarse magnetite is processed making use of the solenoids as an aid to magnetite stabilisation. The graph below depicts the Tromp curve of the fine magnetite discussed above:

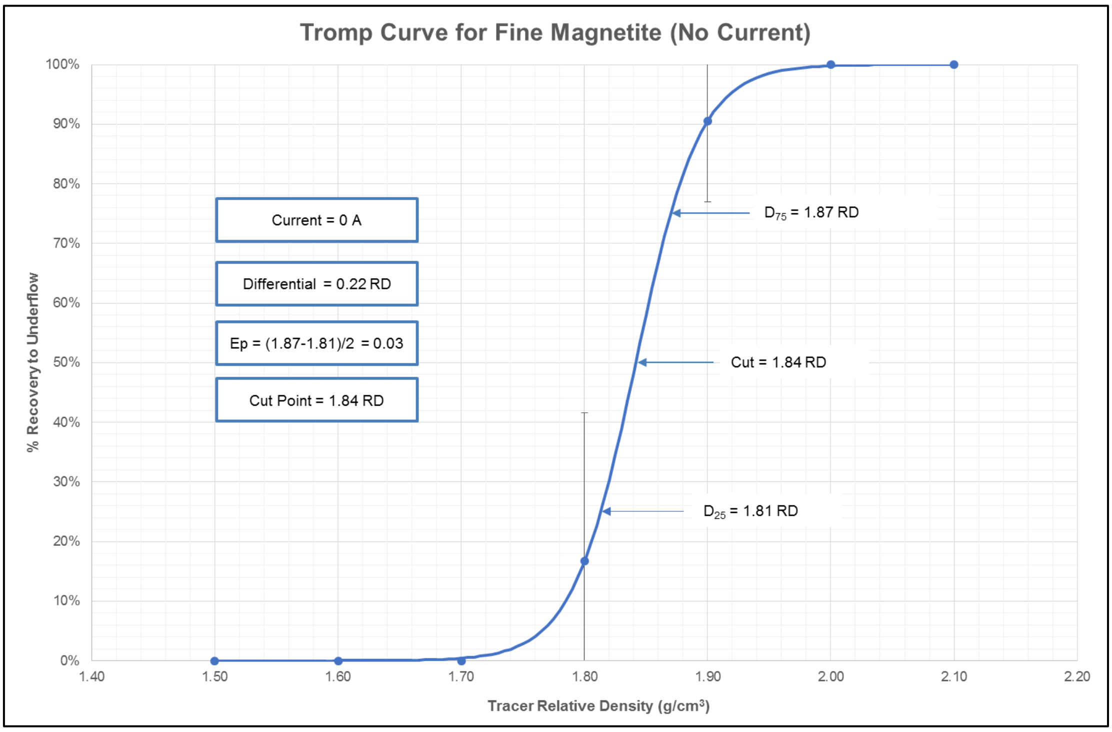

Figure 4.6: Fine Magnetite Tromp Curve (0 A)

Equation 3.3 was used to fit a predicted partition curve to the generated data. It can be seen that the data points correlate with the predicted curve. What is also important to note from this curve is that the cut-point is at 1.84 g/cm^3, with a density differential of 0.22 g/cm^3 and an Ep of 0.03.

The following graph shows the sharpness of separation where 43 % coarse magnetite has been added to the system and a current of 1.1 A passed through the solenoids.

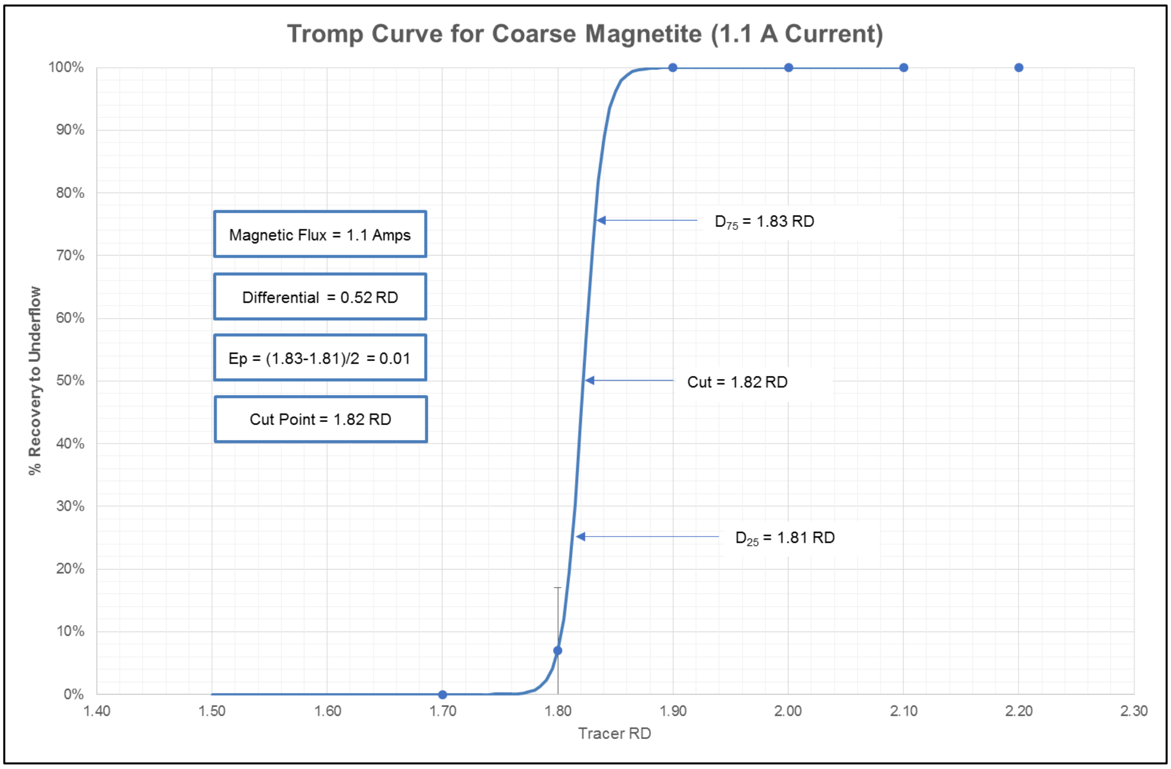

Figure 4.7: Coarse Magnetite Tromp Curve (1.1 A)

As is the case in Figure 4.6, the predicted partition curve and the actual data generated correlate. It can also be seen that the cut-point is slightly lower, however the Ep has been decreased from 0.03 in a "conventional" application to 0.01 using the SpecSep^{TM} solenoids and a coarser magnetite grade. The economic implications of this will be discussed in the next chapter. The table below summarises the data obtained from these two scenarios:

Table 4.4: Summary of Tromp Curve Results

	Unit	Fine Magnetite (0 A)	Coarse Magnetite (1.1 A)
Density Differential	g/cm^3	0.22	0.52
D_{25}	g/cm^3	1.81	1.81
D_{50}	g/cm^3	1.84	1.82
D_{75}	g/cm^3	1.87	1.83
Ep	-	0.03	0.01

From Table 4.4 it can be seen that there is a drop in cut-point when moving away from a conventional magnetite system. The implication of this is that there is room for optimization in which the cut-point could lowered even further, thereby opening up the possibility of heading towards low-cut cyclones.

The results also show that the addition of solenoids and coarser magnetite to an otherwise conventional DMS process would yield better separation efficiencies. It is thus evident that the magnetite can be stabilised in such a system.

4.4 Conclusion

From the results obtained, it can be seen that there is a clear benefit to applying a magnetic field to a cyclone dense medium separation process – coarser media can be used, and with doing so, the cut-point and sharpness of separation can be decreased, thus indicating that the process can be run more efficiently than what is the current practice in the industry.

The big question however, is what the cost implication of implementing such a system might be. Chapter 5 will touch on the high-level cost saving of using the solenoids in conjunction with coarser media in a coal application.

CHAPTER 5: ECONOMIC CONSIDERATIONS

Determining academically whether a process modification might work and applying such a modification are two vastly different aspects to any given study. A newly developed system might look fantastic on paper, however the key to implementing such a system almost always boils down to the bottom line – how much is it going to cost and will it produce a saving?

Chapter 5 aims to look into a high level economic study, to determine whether such a system is implementable in theory.

5.1 Costs, Values, Assumptions and Exclusions

Referring back to Table 4.4 in Chapter 4, it was found that the cut-point could be lowered and the separation efficiency increased when the solenoids are applied, and a ratio of 43 % coarse magnetite and 57 % conventional magnetite are mixed and used as the medium feeding a dense medium cyclone. This will form the basis of determining what the cost implication of implementing such a system would be and whether there will be a saving or not.

Two scenarios will be explored in a hypothetical coal beneficiation plant, namely a scenario where the SpecSep™ unit has been installed, and a scenario where the unit has not been installed in such a hypothetical plant.

5.1.1 SpecSep™

The cost of the SpecSep™ unit, which would be designed and manufactured to fit a cyclone with a 510 mm diameter, was given as € 14 914 (Eves, 2019). The exchange rate at 16.24 South African Rand (R) to the Euro (€), was recorded on 23/11/2019 at 08h30 AM (Morningstar, Google). The SpecSep™ unit would thus cost R 242 141.11, delivered to South Africa by ship.

5.1.2 Coal

The coal is assumed to be a typical South African number 2 seam Witbank coal (product of 4800 kcal/kg). The ash content is assumed to be equal in both scenarios.

5.1.3 Magnetite

Two grades of magnetite would be used in the hypothetical plant – coarse and conventional magnetite, as per the test work that has been done on these two grades. It is assumed that the magnetite costs the same at R 2 000 per ton, and that the magnetite losses are 0.5 kg per ton for conventional magnetite, and 0.4 kg per ton of coarse magnetite. The reasoning behind this is that it would be easier to recover the coarser magnetite in the media recovery magnetic separation circuit. It would theoretically not compact as much and get stuck in crevasses, it would also not stick to the coal as much as the conventional, fine magnetite would. The ratio of coarse-to-fine magnetite in this case would be the same as was found to be the most effective in the test work (43:57). The medium-to-ore ratio used in both scenarios is 3:1.

5.1.4 General

For this case, a 510 mm cyclone with a non-magnetic, polyurethane cone was chosen. The cost for such a cyclone is in the order of R 130 000 (Enslin, 2019). A plant feed of 250 ton per hour was chosen. The feed to the cyclone was assumed to be 80 % of the feed to the plant and the plant availability was assumed to be 85 %. Due to an increase in dense medium cyclone efficiency with the use of the solenoids and a fraction of coarser media, it can be expected that there would be an increase in yield when implementing such a system. It is therefore assumed that, at a cut-point of 1.82 as per the test work, the product yield in the SpecSep™ scenario would be 60 %, while the product yield in the conventional scenario would be less at 58 %. The cut-point for this test work was higher than what would be desired in a coal beneficiation plant, however the decrease of the cut-point should be explored in further test work. The important point is that the SpecSep™ system does show that the cut-point can be reduced, and it is based on this that the assumption is made that it brings forth an increase in product yield.

5.1.5 Exclusions

The calculations to follow are based on a "snapshot" of the direct system related to the dense medium cyclone. There are upstream and downstream cost implications that need to be considered when making a detailed economic SpecSep™ study, and it should again be emphasized that this chapter is merely a high level study to indicate whether there is a possibility of reaping financial benefits from the implementation of the SpecSep™ system. The exclusions are far too many to include, however the assumptions are mentioned clearly to compensate for the absence of information on exclusions.

5.2 Calculation of Payback Period

To calculate the payback period regarding the implementation of the SpecSep™ unit, consider Table 5.1 below, in conjunction with the details given in Chapter 5.1:

Table 5.1: Payback Period

Item	Unit	Cost	Cost (with SpecSep™)	Cost (without SpecSep™)
Plant Feed				
Feed to plant	tph	250		
DMS Cyclone feed		0.80		
DMS Cyclone feed	tph	200		
DMS cyclone product yield			0.60	0.58
DMS cyclone product	tph		120	116
Profit				
Revenue (4800 kcal/kg)[1]	per saleable ton	R 850.00		
Cost to produce product[1]	per saleable ton	R 630.00		
Profit	per saleable ton	R 220.00		
DMS cyclone product profit	per saleable ton/hr		R 26,400.00	R 25,520.00
Hours	per day	24		
Plant availability	per 24 hours	0.85		
DMS cyclone revenue	per day		R 2,080,800.00	R 2,011,440.00
DMS cyclone cost to produce product	per day		R 1,542,240.00	R 1,490,832.00
Cyclone product profit	per day		R 538,560.00	R 520,608.00
Additional profit for SpecSep™				
Additional Profit using SpecSep™	per day		R 17,952.00	
Days	per year	353		
Additional profit using SpecSep™	per year		R 6,337,056.00	
Total Capital input			R 372,141.11	
Acquisition[2] of SpecSep™			R 242,141.11	
Modified cyclone[3]			R 130,000.00	
Payback period	**days**		**21**	

[1] Enslin & Bekker (2019)
[2] Eves (2019)
[3] Enslin (2019)

From the plant feed, it is calculated that the dense medium cyclone (DMS) with a feed of 250 tph, would yield a product of 120 tph with a SpecSep^{TM} unit installed and with a fraction of coarse media added to the system, while the conventional system would yield a product of 116 tph.

According to Enslin and Bekker (20019), the revenue per saleable ton of coal is approximately R 850, while the cost to produce a saleable ton is approximately R 630. That results in a profit of R 220 per saleable ton. This gives an additional profit of R 17 952 per day when making use of SpecSep^{TM}. With an initial capital input of R 372 141.11, the payback period is then calculated as 21 days. After that, an additional profit of R 6 337 056 per year is calculated.

5.3 Magnetite Saving

Table 5.2 below shows the calculation for the cost savings of the magnetite in a SpecSep^{TM} system:

Table 5.2: Magnetite Saving per Charge

Item	Unit	Cost	Cost (with SpecSep^{TM})	Cost (without SpecSep^{TM})
Magnetite Saving				
Cost of magnetite	R/ton	R 2,000.00		
Coarse magnetite losses	R/ton		R 0.022	
Conventional Magnetite losses	R/ton			R 0.029
Saving on 43:57 ratio coarse to conventional magnetite	R/ton		R 0.004	
Magnetite feeding DMS cyclone	tph	150		
Cost of magnetite	R/hr	R 300,000.00		
Magnetite losses	R/hr		R 1,050.00	R 8,550.00
Magnetite saving per charge			**R 7,500.00**	

For this exercise, the magnetite in the dense medium cyclone equates to 150 tph (3:1 medium-to-ore ratio), and therefore 150 tons of magnetite at a cost of R 2 000 per ton is R 300 000.00. With assumed reduced magnetite losses due to the usage of coarse magnetite, the media losses on 150 tons equals to R 1 050.00 for the SpecSep^{TM} system, and R 8 550.00 for a conventional dense medium cyclone system. Therefore, a saving of approximately R 7 500.00 per charge of magnetite can be expected.

5.4 Conclusions

A high level study of the financial benefits of using a SpecSep^{TM} system versus a conventional dense medium cyclone system shows that it is possible to pay off the capital investment in 21 days, and that there are cost savings on the procurement of fresh magnetite. The next chapter will conclude the dissertation.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Chapter 6 contains the conclusions drawn based on the results obtained from this study. These conclusions address the study objectives mentioned in Chapter 1. Recommendations for further work will also be made in Chapter 6, detailing suggestions for further work that can be done to broaden the study.

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6.1 Conclusions

From this study, the following can be concluded:

1. The magnetic intensity applied to the solenoids has a linear relationship to the current (in Ampere) passed through these solenoids. Thus it makes the process of relating a magnetic intensity to a certain current value easier.

2. An increase in solenoid current (magnetic intensity) results in a decrease in density differential up to a point after which the density differential appears to level off.

3. When individually operating the solenoids in isolation from each other, the results indicate that the optimum position would be where Solenoid 1 is located close to the vortex finder. This is due to the fact that it is a turbulent zone, and the magnetic field aids in stabilising the media in a relatively short space of time. This also echoes the results of previous studies, where the effect of solenoid position was studied. Passing a current through Solenoid 2 in isolation has less of a stabilisation effect, as some separation has already occurred at this point in the cyclone. Passing a current through Solenoid 3 in isolation has little effect on the media stabilisation due to its position, once again – Solenoid 3 is positioned too close to the cyclone discharge, and it is thus "too late" to make a difference in the media stabilisation. Also, the solenoid surface is further away from the surface of the cyclone at that point, compared to the distance between Solenoids 1 and 2 and the specific respective cyclone sections around which these solenoids are positioned. The consequence of this is that the magnetic field generated by Solenoid 3 is not as effective as with the other two solenoids. Passing identical currents through Solenoids 1 and 2 has the greatest effect on the density differential, however it was found that by running

Solenoid 2 at a 10 % higher current than Solenoid 1, the media could be further stabilised. This was not further investigated.

4. During the coarsening of the media, it was found that an increase in coarse magnetite content causes a decrease in density differential in instances where a magnetic field is applied. During the these tests, it was seen that the density differential could be dropped from 0.89 g/cm^3 to 0.18 g/cm^3 at 53 % coarse magnetite and a current of 1.75 A. However, it was found that attritioning of the material had taken place due to excessive recirculation of the media during the tests.

5. A reverse of the coarsening of media was done and it was found that the density differential at a charge of 100 % coarse media yielded a density differential of 1.38 g/cm^3, while a charge of 53 % coarse media yielded a density differential of 0.96 g/cm^3 with the application of a 2 A current through Solenoids 1 and 2. Adding more fines until the media was made up of 43 % coarse magnetite caused the density differential to decrease to 0.52 g/cm^3 with Solenoids 1 and 2 running at 2 A. This shows that a there is an optimum ratio at which to blend the coarse and the fine magnetite, and that there is a definite benefit of processing material with such a blend instead of making use of only fine or only coarse magnetite.

6. From the tracer tests, it can be seen that the Ep can be dropped from 0.03 to 0.01 in the case where fine magnetite is processed with no current application to the solenoids versus a system where 43 % coarse magnetite is processed with a current of 1.1 A running through Solenoids 1 and 2. Also, the cyclone cut-point can be lowered. This is a favourable occurrence as there is a drive in the coal industry to move towards low-cut equipment.

7. With many realistic assumptions made, and with data available, it is calculated that the payback period when implementing the SpecSep™ system is a mere 21 days, and that there is a further potential profit of over R 6 million per year.

8. In a hypothetical scenario relating to magnetite losses, it was found that a cost saving of approximately R 7 500.00 is possible with the implementation of the SpecSep™ system.

The results correlate with what has been found in previous studies, as mentioned in Chapter 2: The cut-point density, density differential and cyclone efficiency could be manipulated.

The results also clearly show that it is possible to use coarse media and to manipulate the density differential thereof, and therefore the dense medium cyclone efficiency by means of the application of a weak magnetic field to such a system, and further studies are needed to optimise this process. It has also been shown on a high level that it seems economically feasible to implement such a system in a coal beneficiation plant.

6.2 Recommendations

The following is recommended:

1. Study the effects of passing non-identical currents through Solenoids 1 and 2.
2. Introduce ore to the system to accurately determine the sharpness of separation in such a process.
3. Investigate the use of a single solenoid at some optimum point between solenoid positions 1 and 2.
4. Expand the scope to include other commodities, such as iron ore.
5. Develop an automated plant control system with a closed loop feedback controller, which has the capability of manipulating the density differential by controlling the dense medium cyclone solenoid current with changing conditions in the upstream plant. The control system should feed into the plant's existing control network, interacting and adjusting parameters according to varying plant conditions.
6. A comprehensive economic study is needed to determine whether such a complete unit and system would be feasible to use on an industrial scale, and whether there truly will be a financial benefit in implementing this.

This study contains the proverbial tip of the iceberg in terms of what can be done to determine the vast effects of applying a weak magnetic field to a fine and coarse magnetite blend dense medium separation process. Implementing these recommendations in the future would assist in commercialising this system of using SpecSep™ solenoids in conjunction with a percentage of coarser media to a conventional dense medium separation cyclone process in the coal industry and beyond.

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APPENDIX A: DATA – CALIBRATION PHASE

A.1 Magnetic Flux Density Determination

Table A.1: Solenoid Current (A) and Magnetic Flux Density (mT)

Solenoid 1							
Magnetic Flux Density (mT)						Average Magnetic Flux Density (mT)	Error in Magnetic Flux Density
Position		Flux Centre	Flux Centre	Flux Edge	Flux Edge		
Distance*		0	80	0	80		
Current (A)	0.5	1.2	1.4	1.2	1.5	1.3	0.2
	1.0	2.6	3.0	2.4	3.1	2.8	0.4
	1.5	3.8	4.9	3.9	4.8	4.4	1.1
	2.0	5.1	6.7	5.4	6.3	5.9	1.6
	2.5	5.7	8.4	6.4	8.1	7.1	2.7
	2.9	7.6	9.7	7.5	9.1	8.7	2.1
Solenoid 2							
Magnetic Flux Density (mT)						Average Magnetic Flux Density (mT)	Error in Magnetic Flux Density
Position		Flux Centre	Flux Centre	Flux Edge	Flux Edge		
Distance*		150	230	150	230		
Current (A)	0.5	1.5	1.8	1.4	1.6	1.7	0.3
	1.0	2.8	3.5	3.1	3.3	3.2	0.7
	1.5	4.9	5.4	4.6	5.0	5.2	0.5
	2.0	6.9	6.8	6.2	6.7	6.9	0.1
	2.5	8.9	7.9	7.6	8.3	8.4	1.0
	2.9	10.5	10.3	8.8	9.8	10.4	0.2
Solenoid 3							
Magnetic Flux Density (mT)						Average Magnetic Flux Density (mT)	Error in Magnetic Flux Density
Position		Flux Centre	Flux Centre	Flux Edge	Flux Edge		
Distance*		300	380	300	380		
Current (A)	0.5	1.7	1.3	1.2	1.3	1.5	0.4
	1.0	2.7	2.6	3.6	2.6	2.7	0.1
	1.5	5.1	3.7	4.1	4.0	4.4	1.4
	2.0	6.2	5.3	5.6	5.6	5.8	0.9
	2.5	8.5	6.5	7.3	6.9	7.5	2.0
	2.9	8.7	8.0	8.0	7.8	8.4	0.7

***Distance from end of SpecSep™ solenoids near the cyclone inlet (mm)**
Refer to Figure 3.8 for descriptive schematic

APPENDIX B: DATA – COMMISSIONING PHASE

B.1 Coarsening of Media

Table B.1: Coarsening of Media – 17 % Coarse Magnetite

Cum. Coarse Magnetite (kg)	Initial Fine Magnetite (kg)	Feed RD (g/cm^3)	Overflow RD (g/cm^3)					Underflow RD (g/cm^3)					Differential (g/cm^3)	Solenoid Current (A)		
			Data 1	Data 2	Data 3	Avg.	Error	Data 1	Data 2	Data 3	Avg.	Error		1	2	3
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	2.27	2.28	2.27	2.27	0.0094	0.61	0.00	0.00	0.00
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	2.23	2.23	2.23	2.23	0.0000	0.57	0.25	0.25	0.25
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	2.2	2.19	2.19	2.19	0.0094	0.53	0.50	0.50	0.50
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	2.14	2.14	2.13	2.14	0.0094	0.48	0.75	0.75	0.75
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	2.04	2.05	2.04	2.04	0.0094	0.38	1.00	1.00	1.00
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	1.97	1.95	1.95	1.96	0.0189	0.30	1.25	1.25	1.25
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	1.90	1.89	1.89	1.89	0.0094	0.23	1.50	1.50	1.50
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	1.89	1.91	1.9	1.90	0.0163	0.24	1.75	1.75	1.75
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	1.88	1.88	1.88	1.88	0.0000	0.22	1.75	1.75	0.00
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	2.02	2.02	2.02	2.02	0.0000	0.36	1.75	0.00	0.00
36.6	183.8	1.82	1.66	1.66	1.66	1.66	0.000	2.14	2.14	2.14	2.14	0.0000	0.48	0.00	0.00	0.00

B.2 The Effect of Differing Solenoid Currents per Solenoid

Table B.2: Density Differential and Differing Solenoid Currents – Solenoids 1, 2 and 3

Current (A)			Overflow RD (g/cm^3)					Underflow RD (g/cm^3)					Differential (g/cm^3)	
Sol 1	**Sol 2**	**Sol 3**	**Data 1**	**Data 2**	**Data 3**	**Avg.**	**Error**	**Data 1**	**Data 2**	**Data 3**	**Avg.**	**Error**	**RD**	**Error**
0.0	0.0	0.0	1.57	1.57	1.58	1.57	0.009	2.25	2.26	2.26	2.26	0.009	0.68	0.013
2.0	0.0	0.0	1.65	1.65	1.65	1.65	0.000	1.99	1.99	2.00	1.99	0.009	0.34	0.009
0.0	**2.0**	0.0	1.64	1.64	1.65	1.64	0.009	2.04	2.05	2.04	2.04	0.009	0.40	0.013
2.0	**2.0**	**2.0**	1.67	1.67	1.67	1.67	0.000	1.97	1.97	1.97	1.97	0.000	0.30	0.000
2.0	**2.0**	0.0	1.68	1.68	1.68	1.68	0.000	1.90	1.91	1.91	1.90	0.007	0.22	0.007
2.0	**1.8**	0.0	1.67	1.67	1.68	1.67	0.009	1.91	1.91	1.91	1.91	0.000	0.24	0.009

Table B.3: Density Differential and Differing Solenoid Currents – Solenoids 1 and 2

Current (A)		Feed RD (g/cm^3)					Overflow RD (g/cm^3)					Underflow RD (g/cm^3)					Differential (g/cm^3)	
Sol 1	Sol 2	Data 1	Data 2	Data 3	Avg.	Error	Data 1	Data 2	Data 3	Avg.	Error	Data 1	Data 2	Data 3	Avg.	Error	RD	Error
0.00	0.000	1.73	1.74	1.74	1.74	0.009	1.57	1.57	1.58	1.57	0.009	2.25	2.26	2.26	2.26	0.009	0.68	0.013
0.500	0.550						1.60	1.60	1.60	1.60	0.000	2.24	2.24	2.25	2.24	0.009	0.64	0.009
0.750	0.825						1.61	1.60	1.60	1.60	0.009	2.20	2.20	2.20	2.20	0.000	0.60	0.009
1.000	1.100						1.61	1.62	1.61	1.61	0.009	2.14	2.14	2.14	2.14	0.000	0.53	0.009
1.100	1.210						1.62	1.61	1.61	1.61	0.009	2.12	2.12	2.11	2.12	0.009	0.50	0.013
1.200	1.320						1.61	1.61	1.62	1.61	0.009	2.10	2.10	2.10	2.10	0.000	0.49	0.009
1.350	1.485						1.62	1.63	1.62	1.62	0.009	2.06	2.07	2.06	2.06	0.009	0.44	0.013
1.450	1.595						1.62	1.63	1.63	1.63	0.009	2.05	2.05	2.05	2.05	0.000	0.42	0.009
1.550	1.705						1.64	1.64	1.64	1.64	0.000	2.02	2.03	2.03	2.03	0.009	0.39	0.009
1.650	1.815						1.65	1.64	1.64	1.64	0.009	2.01	2.02	2.01	2.01	0.009	0.37	0.013
1.750	1.925						1.66	1.66	1.66	1.66	0.000	1.98	1.96	1.96	1.97	0.019	0.31	0.019
1.850	2.035						1.65	1.66	1.65	1.65	0.009	1.93	1.94	1.93	1.93	0.009	0.28	0.013
1.950	2.145						1.66	1.66	1.66	1.66	0.000	1.91	1.91	1.91	1.91	0.000	0.25	0.000
2.050	2.255						1.65	1.65	1.65	1.65	0.000	1.91	1.91	1.91	1.91	0.000	0.26	0.000
2.150	2.365						1.66	1.66	1.67	1.66	0.009	1.91	1.91	1.92	1.91	0.009	0.25	0.013
2.250	2.475						1.66	1.66	1.66	1.66	0.000	1.92	1.91	1.92	1.92	0.009	0.26	0.009
2.350	2.585						1.67	1.66	1.66	1.66	0.009	1.91	1.91	1.91	1.91	0.000	0.25	0.009

Table B.4: Density Differential and Solenoid Current for Identical Solenoid Currents – Solenoids 1 and 2

Current (A)	Feed RD (g/cm^3)					Overflow RD (g/cm^3)					Underflow RD (g/cm^3)					Differential (g/cm^3)	
	Data 1	Data 2	Data 3	Avg.	Error	Data 1	Data 2	Data 3	Avg.	Error	Data 1	Data 2	Data 3	Avg.	Error	RD	Error
0.00	1.73	1.74	1.74	1.74	0.009	1.57	1.57	1.58	1.57	0.009	2.25	2.26	2.26	2.26	0.009	0.68	0.013
0.75						1.59	1.59	1.59	1.59	0.000	2.24	2.24	2.23	2.24	0.009	0.65	0.009
1.00						1.58	1.59	1.59	1.59	0.009	2.14	2.15	2.15	2.15	0.009	0.56	0.013
1.10						1.59	1.60	1.59	1.59	0.009	2.12	2.11	2.11	2.11	0.009	0.52	0.013
1.20						1.60	1.60	1.61	1.60	0.009	2.10	2.10	2.10	2.10	0.000	0.50	0.009
1.35						1.60	1.60	1.61	1.60	0.009	2.09	2.09	2.09	2.09	0.000	0.49	0.009
2.00						1.66	1.66	1.66	1.66	0.000	1.93	1.93	1.92	1.93	0.009	0.27	0.009
2.35						1.66	1.66	1.67	1.66	0.009	1.90	1.90	1.90	1.90	0.000	0.24	0.009
2.50						1.66	1.66	1.66	1.66	0.000	1.91	1.90	1.90	1.90	0.009	0.24	0.009
2.75						1.67	1.67	1.67	1.67	0.000	1.90	1.90	1.91	1.90	0.005	0.23	0.005

B.3 Further Media Coarsening

Table B.5: Density Differential and Solenoid Current at 53 % Magnetite

Current (A)	Feed RD (g/cm^3)					Overflow RD (g/cm3)					Underflow RD (g/cm3)					Differential (g/cm^3)	
	Data 1	Data 2	Data 3	Avg.	Error	Data 1	Data 2	Data 3	Avg.	Error	Data 1	Data 2	Data 3	Avg.	Error	RD	Error
0.00	2.29	2.30	2.29	2.29	0.00	2.11	2.11	2.12	2.11	0.005	3.01	3.00	3.01	3.01	0.005	0.89	0.007
0.80						2.23	2.22	2.23	2.23	0.005	2.74	2.75	2.73	2.74	0.008	0.51	0.009
0.90						2.28	2.28	2.27	2.28	0.005	2.73	2.72	2.73	2.73	0.005	0.45	0.007
1.00						2.23	2.22	2.22	2.22	0.005	2.72	2.71	2.72	2.72	0.005	0.49	0.007
1.25						2.22	2.22	2.22	2.22	0.000	2.72	2.72	2.72	2.72	0.000	0.50	0.000
1.50						2.20	2.21	2.20	2.20	0.005	2.72	2.72	2.72	2.72	0.000	0.52	0.005
1.75						2.19	2.20	2.19	2.19	0.005	2.74	2.73	2.73	2.73	0.005	0.54	0.007

B.4 Adding Fine to Coarse Media

Table B.6: Adding Fine to Coarse Media

Current (A)	Coarse Magnetite (%)	Overflow RD (g/cm^3)					Underflow RD (g/cm^3)					Differential (g/cm^3)
		Data 1	Data 2	Data 3	Avg.	Error	Data 1	Data 2	Data 3	Avg.	Error	
0.00	43%	1.67	1.68	1.66	1.67	0.0163	2.81	2.81	2.82	2.81	0.0094	1.14
1.20	43%	1.80	1.80	1.80	1.80	0.0000	2.34	2.35	2.35	2.35	0.0094	0.55
1.30	43%	1.79	1.80	1.80	1.80	0.0094	2.30	2.31	2.30	2.30	0.0094	0.51
1.35	43%	1.83	1.82	1.82	1.82	0.0094	2.30	2.30	2.29	2.30	0.0094	0.47
1.40	43%	1.81	1.81	1.80	1.81	0.0094	2.30	2.30	2.29	2.30	0.0094	0.49
1.50	43%	1.80	1.81	1.80	1.80	0.0094	2.34	2.34	2.33	2.34	0.0094	0.53
1.60	43%	1.80	1.80	1.80	1.80	0.0000	2.31	2.30	2.33	2.31	0.0249	0.51
1.80	43%	1.81	1.81	1.80	1.81	0.0094	2.31	2.31	2.31	2.31	0.0000	0.50
2.00	43%	1.80	1.80	1.79	1.80	0.0094	2.32	2.32	2.31	2.32	0.0094	0.52

APPENDIX C: DATA – TRACER TESTS

Table C.1: Fine Magnetite Tracer Test Data

Tracers	Number Overflow			Number Underflow			Tracer Loss/Recovery			% Overflow				
Density	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Avg.	Error
2.10	0	0	0	10	0	0	0	0	0	100%	100%	100%	100%	0.00
2.00	0	0	0	10	9	10	0	-1	1	100%	100%	100%	100%	0.00
1.90	0	1	1	8	6	6	0	-1	0	100%	86%	86%	90%	0.13
1.80	7	8	10	3	2	0	0	0	0	30%	20%	0%	17%	0.25
1.70	5	3	5	0	0	0	-2	-2	2	0%	0%	0%	0%	0.00
1.60	9	10	10	0	0	0	-1	1	0	0%	0%	0%	0%	0.00
1.50	10	10	10	0	0	0	0	0	0	0%	0%	0%	0%	0.00

Table C.2: Coarse Magnetite Tracer Test Data

Tracers	Number Overflow			Number Underflow			Tracer Loss/Recovery			% Overflow				
Density	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Avg.	Error
2.20	0	0	0	7	7	7	0	0	0	100%	100%	100%	100%	0.00
2.10	0	0	0	10	10	10	0	0	0	100%	100%	100%	100%	0.00
2.00	0	0	0	10	10	10	0	0	0	100%	100%	100%	100%	0.00
1.90	0	0	0	7	7	7	0	0	0	100%	100%	100%	100%	0.00
1.80	9	10	8	1	0	1	0	-1	1	10%	0%	11%	7%	0.10
1.70	6	7	7	0	0	0	-1	1	0	0%	0%	0%	0%	0.00

APPENDIX D: ERRORS AND REPEATABILITY

This appendix aims to lay out the statistical methods applied to the test data that has been generated, and will focus on standard deviations, a practical example and repeatability.

D.1 Standard Deviation

The variance of a sample is given by (Devore & Farnum, 2005:71):

$$s^2 = \frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1} \qquad \text{(Equation D.1)}$$

Where,

s^2 = sample variance;

$\sum_{i=1}^{n}(x_i-\bar{x})$ = sum of deviations; and

n = sample observations.

The standard deviation can thus be found by taking the square root of the sample variance. Thus, according to Devore and Farnum (2005:71), the following can be derived:

$$\text{Standard deviation} = s = \sqrt{s^2} \qquad \text{(Equation D.2)}$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}} \qquad \text{(Equation D.3)}$$

For this work, three sets of samples at each point in the process was taken. The standard deviation of each data set was calculated. As an example, an excerpt from the data in Appendix B was taken:

B.2 The Effect of Differing Solenoid Currents per Solenoid

Table B.2: Density Differential and Differing Solenoid Currents – Solenoids 1, 2 and 3

Current (A)			Overflow RD (g/cm^3)					Underflow RD (g/cm^3)					Differential (g/cm^3)	
Sol 1	Sol 2	Sol 3	Data 1	Data 2	Data 3	Avg.	Error	Data 1	Data 2	Data 3	Avg.	Error	RD	Error
0.0	0.0	0.0	1.57	1.57	1.58	1.57	0.009	2.25	2.26	2.26	2.26	0.009	0.68	0.013

Figure D.1: Data Excerpt for Statistical Analysis Example

From Figure D.1 it can be seen that each data set consists of three data points (Data 1, Data 2 and Data 3). The errors mentioned in the case of the overflow and underflow stream relative densities are also plotted on the graphs in Chapter 4 in the form of error bars. These errors are equal to two times the standard deviation, and can be calculated using Equation D.3 for the overflow relative density:

$$\pm 2\times\text{Standard deviation} = \pm 2s = \pm 2\times\sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}} \qquad \text{(Equation D.4)}$$

$$2s = 2\times\sqrt{\frac{(1.57-1.573)^2+(1.57-1.573)^2+(1.57-1.58)^2}{2}}$$

Thus

$\pm 2s = \pm 2(0.007681)$

This can be applied to the underflow data as well.

To calculate the error of the differential, Equation D.3 is used, with the overflow and underflow errors as the x-values, and n thus equating to two.

D.2 Repeatability

According to Devore and Farnum (2005: 183), repeatability refers to the amount of variation that can be expected when the errors have been controlled, and has to do with measurement instruments. Repeatability is important because the tests were done using measuring instruments such as density bottles, mass scales and volumetric measuring cylinders. The work of Devore and Farnum specifically state that it is preferable for the data to fall within three standard deviations from the true data, however in this case two standard deviations were used. The errors are very low and it can thus be concluded that the data is repeatable.