

**An experimental and modelling approach to
develop a winnowing pilot plant for fine dry coal
beneficiation**

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Thesis accepted in fulfilment of the requirements for the
degree *Doctor of Philosophy in Engineering with Chemical
Engineering* at the North-West University

Promoter: Prof QP Campbell

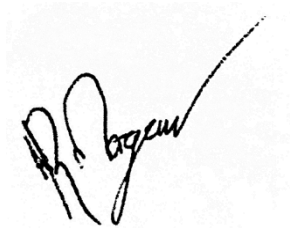
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Graduation: December 2023

I, **Lee-Roy Morgan**, hereby declare that this thesis entitled:

*An experimental and modelling approach to
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is my own work and has not been submitted to any other University before. Where publications involving co-authors were used, the necessary permission from these authors had been obtained in writing. Relative contributions by the different authors are acknowledged in the relevant chapters.



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Section 5.4.2 states that “Faculty rules may provide that full or partial compliance with the research component of a doctoral degree may take the form of one or more publishable or published research articles in a specified field, taking into account the requirements of rules 5.10 and 5.12 and specifying the minimum number of research articles required in lieu of a thesis, mini-thesis or the research component of a professional doctoral degree”.

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Format style used in this thesis.

No changes in terms of content (aside from spelling and typing errors) were made to the 5 original papers that form part of this thesis. Each paper had its own original format as requested by the individual publishers, however the format of the text, figures, tables, and references in the papers was changed to comply with the overall format of the thesis and give a single coherent formatting style to the document.

The content of all figures and tables were retained during the formatting of the papers and no data or written content was modified as the papers were already peer reviewed and published in their respective publication media.

List of Publications

The papers that form part of this thesis are listed below in the order that they are presented.

Peer reviewed papers that were published as conference proceedings.

Campbell, Q., le Roux, M., & Morgan, L., 2019. Simulation of a horizontal flow coal winnower. International Coal Preparation Congress (ICPC 2019) – New Delhi, India 13 – 15 November.

Morgan, L., Campbell, Q., & le Roux, M., 2019. Horizontal airflow fine coal winnower. South African Coal Processing Society (SACPS - 2019) – Secunda, South Africa 19 - 22 August.

Morgan, L., Campbell, Q., & le Roux, M., 2020. Horizontal airflow fine coal winnowing. International Mineral Processing Congress (IMPC - 2020) – Cape Town, South Africa 18 - 22 October.

Morgan, L., Campbell, Q., & le Roux, M., 2021. Design and mathematical behavior model for a fine coal winnowing pilot plant. South African Coal Processing Society (SACPS - 2021) – Secunda, South Africa 12 - 14 October.

Peer reviewed journal articles

Morgan, L., Campbell, Q., & le Roux, M., 2022. Evaluation of a prototype winnower for dry fine coal processing. Publication pending in 2023 with publication media still to be announced.

Statements from co-authors

The contributions made to this thesis by the following co-authors are recognized and their statements follow:

Q.P. Campbell

Page VII

M. le Roux

Page VIII

Statement of consent: Q.P. Campbell

To whom it may concern,

I, **Quentin Peter Campbell**, give my consent to **Lee-Roy Morgan**, candidate for the degree Doctor of Philosophy in Engineering with Chemical Engineering at the Potchefstroom Campus of the North-West University to include in this thesis entitled: **An experimental and modelling approach to develop a winnowing pilot plant for fine dry coal beneficiation**, the following publication of which I am co-author:

Campbell, Q., le Roux, M., & Morgan, L., 2019. Simulation of a horizontal flow coal winnower. International Coal Preparation Congress (ICPC 2019) – New Delhi, India 13 – 15 November.

Morgan, L., **Campbell, Q.**, & le Roux, M., 2019. Horizontal airflow fine coal winnower. South African Coal Processing Society (SACPS - 2019) – Secunda, South Africa 19 - 22 August.

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The relative contributions to these papers by the different authors are given on Page ix

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Q.P. Campbell

Statement of consent: M. le Roux

To whom it may concern,

I, **Marco le Roux**, give my consent to **Lee-Roy Morgan**, candidate for the degree Doctor of Philosophy in Engineering with Chemical Engineering at the Potchefstroom Campus of the North-West University to include in this thesis entitled: **An experimental and modelling approach to develop a winnowing pilot plant for fine dry coal beneficiation**, the following publication of which I am co-author:

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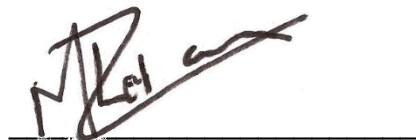
Morgan, L., Campbell, Q., & **le Roux, M.**, 2020. Horizontal airflow fine coal winnowing. International Mineral Processing Congress (IMPC - 2020) – Cape Town, South Africa 18 - 22 October.

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Signed at Potchefstroom on 22/11/2022

A handwritten signature in black ink, appearing to read 'M. le Roux', is written over a horizontal line.

M. le Roux

Relative contributions by authors

The following pertains to the contributions made by the above-mentioned authors and is applicable to all the papers presented in this thesis.

L. Morgan is a postgraduate student working on the project of an experimental and modelling approach to develop a winnowing pilot plant for fine dry coal beneficiation, under the supervision of both Q.P. Campbell and M. le Roux.

The scope of the study and planning of the parameters to be investigated experimentally, were the responsibility of Q.P. Campbell and M. le Roux, whereas the design and simulation of the experimental apparatus was the responsibility of L. Morgan.

L. Morgan performed the experiments, data recording and calculations. The conclusions and improvements made to the equipment resulted from discussions between the authors after interpreting the collected data.

The papers were presented by different authors at various conferences and added to the conference proceedings after a peer review.

The following papers were presented by Q.P. Campbell:

Campbell, Q., le Roux, M., & Morgan, L., 2019. Simulation of a horizontal flow coal winnower. International Coal Preparation Congress (ICPC 2019) – New Delhi, India 13 – 15 November.

The following papers were presented by L. Morgan:

Morgan, L., Campbell, Q., & le Roux, M., 2019. Horizontal airflow fine coal winnower. South African Coal Processing Society (SACPS - 2019) – Secunda, South Africa 19 - 22 August.

Morgan, L., Campbell, Q., & le Roux, M., 2020. Horizontal airflow fine coal winnowing. International Mineral Processing Congress (IMPC - 2020) – Cape Town, South Africa 18 - 22 October.

Morgan, L., Campbell, Q., & le Roux, M., 2021. Design and mathematical behavior model for a fine coal winnowing pilot plant. South African Coal Processing Society (SACPS - 2021) – Secunda, South Africa 12 - 14 October.

The constant increase in the amount of fine coal being generated through day-to-day mining and processing activities is unavoidable, and thus the technology used to beneficiate fine coal is constantly evolving. Environmental and economic factors such as water shortage, waste management, and processing cost motivate the research in fine coal beneficiation and even more so in dry fine coal beneficiation. One of the more recent developments in dry fine coal beneficiation over the past few years is the use of the winnowing method as a dry beneficiation technique and this method has been proven capable of beneficiating -6 mm coal. The method of winnowing has been successfully implemented in the agricultural and pharmaceutical sectors for many years with several studies showing that the method is a viable option when implemented on the coal sector for dry fine coal beneficiation. Over the past few years several studies have been done on the method, however, there is still very little data available other than lab scale experimental results.

Research done on fine coal suggests that winnowing can separate coal particles by size, shape, and density; however, previous studies have shown the system to be size sensitive, and for this reason, a 2-stage separation is needed for the beneficiation of fine coal. The equipment used for the winnowing method has also not been fully developed to suit the needs of the coal mining industry and thus an opportunity exists to design and implement a winnowing machine capable of beneficiating fine coal. This thesis investigates winnowing in general, starting with the method itself and aiming towards designing and ultimately constructing a winnowing plant that can be used to test the method in future studies.

The papers presented in this thesis will cover the basics of winnowing but mostly focus on the design of the winnowing equipment which is the aim of this study. Two pieces of equipment were designed with the aid of Computational Fluid Dynamics (CFD) and mathematical models. These prototypes were tested using density tracers and -6 mm coal. The first piece of equipment was a size separation nozzle to aid with the size sensitivity of the method, however initial tests indicated that the nozzle favoured a density separation instead of the intended size separation and further tests are needed to confirm

if the nozzle is capable of performing a density separation, or if the nozzle will work as a size separation unit as indicated and by the CFD simulations. The second piece of equipment that was designed was the density separation chamber, capable of separating particles into multiple densities ranging from 1.2 g cm^{-3} to 2.2 g cm^{-3} . The initial results did indicate that the chamber is size sensitive and that a density separation is possible given the correct size interval. Both units work on negative pressure and initial results show that both machines have the potential to work as a combined 2 stage separation plant.

The design of the winnowing plant was successful, and a working pilot plant was constructed. There is still some optimization and testing required to improve the operation of the plant as indicated by the results in the final paper of this thesis, however initial testing looks promising.

Acknowledgements

The author of this thesis would like to thank the following persons and institutions for their assistance, both financial and technical, during the Dry Fine Coal Beneficiation research project:

- Coaltech, without whom this research would not have been possible.
- South African Coal Processing society (SACPS) for their financial support.
- The management and staff of the multiple mines that supplied the coal samples for the experiments.
- Staff and students at the North-West University, in particular the undergraduate students that contributed to this research.
- My two promoters, Prof Quentin Campbell, and Prof. Marco le Roux, for investing time and effort into this research and their valuable advice and guidance throughout the project.

On a personal level, I wish to thank my parents for all their support throughout the years.

And most important to my wife Jean-Mariè, thank you for your love, patience, and motivation.

Table of contents

DECLARATION	II
LIST OF PUBLICATIONS	V
STATEMENTS FROM CO-AUTHORS	VI
ABSTRACT	X
ACKNOWLEDGEMENTS	XII
TABLE OF CONTENTS	XIII
INTRODUCTION	1
INTRODUCTION AND MOTIVATION	1
OBJECTIVES	7
SCOPE AND CONTENTS OF THIS THESIS	7
CHAPTER REFERENCES	11
SIMULATION AND DESIGN OF A FINE COAL WINNOWER	13
PAPER 1: SIMULATION OF A HORIZONTAL FLOW COAL WINNOWER	13
ADDITIONAL NOTES	28
FUNDAMENTALS OF FINE COAL WINNOWING	31
PAPER 2: HORIZONTAL AIR FLOW FINE COAL WINNOWING	31
ADDITIONAL NOTES	47

IMPROVING THE FINE COAL WINNOWING PROCESS	48
PAPER 3: HORIZONTAL AIRFLOW FINE COAL WINNOWING	48
ADDITIONAL NOTES	64
 DESIGNING A FINE COAL WINNOWING DEMO PLANT	 66
PAPER 4: DESIGN AND MATHEMATICAL BEHAVIOR MODEL FOR A FINE COAL WINNOWING PILOT PLANT	 66
ADDITIONAL NOTES	81
 THE FUTURE OF FINE COAL BENEFICIATION	 90
PAPER 5: EVALUATION OF A PROTOTYPE WINNOWER FOR DRY FINE COAL PROCESSING.....	 90
ADDITIONAL NOTES	108
 CONCLUSION	 113
GENERAL CONCLUSIONS.....	113
CONTRIBUTION OF THIS WORK.....	115
RECOMMENDATIONS AND FUTURE WORK.....	115
 APPENDIX A.....	 117

Chapter 1

Introduction

This thesis contains a collection of four conference presentations and one pending journal publication, published over the last four years on the topic of dry fine coal beneficiation using the winnowing method. These papers cover all the relevant topics related to the method of winnowing, including the fundamentals of winnowing, the design and simulation of the equipment, and the results obtained from testing the newly designed winnowing pilot plant. Chapter 1 introduces the topic of dry fine coal beneficiation and reinforces the reason why a new method for the beneficiation of -6 mm coal needs to be developed.

INTRODUCTION AND MOTIVATION

Coal has always been an important commodity in South Africa and is used in several sectors ranging from energy supply to iron production (Ratshomo & Nembahe, n.d.). Ratshomo & Nembahe further state that coal is primarily used in South Africa because it is in abundance, affordable and easier to process all of which make coal as a resource very attractive.

“The higher price of oil and gas has positioned coal as the premium source of energy.”

This statement made by P. Dikgwatlhe is currently truer than ever, especially with several geopolitical factors influencing the energy sector in 2022. This is in favor of the South African coal market because South Africa is rich in coal resources with 19 coalfields located across the country (Jeffrey, 2005). Of these coalfields the Waterberg coalfield in Limpopo (Circled in red in Figure 1.1) is currently the focus area as it is still a large coal deposit that has not yet been completely utilized, unlike the Highveld and Witbank coalfields (Ratshomo & Nembahe, n.d.).

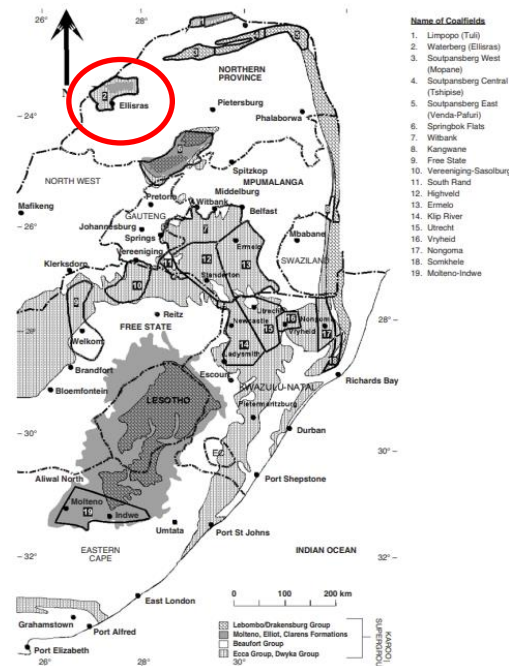


Figure 1.1: Coalfields of South Africa (Jeffrey, 2005)

The challenge that the mining industry faces in this area of South Africa is a shortage of water which makes the processing of coal especially fine coal very difficult. Limpopo receives less than 500 mm of rain per year and currently the mining industry is using 6% of the overall available water resources (Munnik, 2020) , this means that an increase in mining activity will put an even larger strain on the water scarce community.

Coal beneficiation in South Africa is dominated by water-based separation methods, such as floatation, dense medium cyclones, and spirals. These beneficiation methods require large amounts of water (de Korte, 2015) and can contribute to several other environmental problems. The alternative is to reduce water usage during the processing of coal. This can be done by implementing dry coal beneficiation processes and by doing so it can ensure the future growth of the coal industry and keep up with the demand without putting more strain on the already depleting water sources.

Aside from water scarcity South Africa faces one other large problem when it comes to coal processing and that is the beneficiation of coal fines.

In 2016 it was reported that South Africa had approximately 2.4 billion tons of fine coal that could potentially be processed for energy generation (Matrix, 2016). Coal fines are generated throughout the entire process of coal mining and processing; thus, it is an inevitable part of the coal industry and even though it is sometimes seen as a nuisance these coal fines do have economic value. Fine coal beneficiation in general is difficult but the process becomes increasingly more difficult when combined with the increasing water shortage, because fine coal beneficiation has been dominated for the past several years by the same wet beneficiation processes mentioned earlier. Similar to coarse coal processing, the alternative is to use dry fine beneficiation methods, however unlike coarser coal, dry fine coal beneficiation has not yet been successfully implemented.

Dry beneficiation of coal

Over the past few years dry beneficiation has received a lot of attention, not only in South Africa but all over the world, with several new technologies being developed in the field (Hughes, et al., 2019) and even though these new methods have been proven to work they cannot compete with the efficiency and or throughput of the wet separation methods that are currently being used. Furthermore, most of the methods that have been developed or implemented struggle to process coal particles smaller than 6 mm (Hughes, et al., 2019). So even though the new processes such as the FGX dry separator and air tables are aimed at lowering the required water usage during coal production, it still does not solve the secondary problem of processing the discarded and newly generated coal fines.

Considering the current methods and the problems that have to be addressed an opportunity arises for a new dry beneficiation method that is not only capable of processing the -6 mm coal but can also compete with the wet separation methods that are being used. If successful, the technology will not only benefit arid regions, but it will also enable other regions to beneficiate fine coal without water and thus cutting back on process costs while minimizing the environmental impact at the same time.

Coal beneficiation is based on the principle that there is a difference in density between coal particles. Coal particles can be separated from each other by exploiting this density

difference, high quality export coal for example has a very low density compared to the thermal coal used to produce electricity in South Africa (de Korte, 2015).

Density separation

Density can be defined in general as the relationship between the mass of a particle and the volume that the particle occupies (Rodríguez-Ramírez, et al., 2012). The density of a single coal particle is dependent on the amount of organic and inorganic material that it contains as this will influence the mass of a particle (Keshavarz, et al., 2018). This means that each particle will have its own unique density.

The density difference can be manipulated using various wet methods such as cyclones and spirals that have already been mentioned. Dry beneficiation uses the same principle of density difference to separate the particles, however, there are a few differences between the wet and dry methods:

- The definition of density used in the two methods are different. Dry beneficiation uses the true density of the particle, whereas wet beneficiation uses the apparent density. The difference between the densities are explained in the section below.
- The medium used to achieve the density separation in each method is different. Dry beneficiation uses air as a medium and wet beneficiation uses a combination of water and separation medium such as magnetite.
- The effectivity and amount of misplaced or near dense material differs for both methods.

Density definition and separation medium

The volume of a particle can be calculated by using or excluding factors such as particle size, shape, pores, and water content. Different combinations of these factors will yield different results when calculating the particle's volume, thus each combination of factors has a unique density definition. The different definitions of density and their characteristics are listed below as stated by Cement, 2013:

- Apparent particle density – Relationship between mass and volume where the pores and the water are included in the volume calculation.

- True density – Relationship between mass and volume where the pores are not considered when calculating the volume.

Each method uses a different density definition. When using an air-based separation method, pores are not considered since the force acting on the particle is only acting on the surface. When using a wet separation method, where particles are submerged in water and separation medium such as magnetite (Zhang, et al., 2015), then pores and water content need to be considered. This is also why the separation medium is an important factor in density separation. Adding a medium such as magnetite will improve the separation, while only using air will make the separation more complicated.

Near dense material

Aside from the definition of density and the medium in which the separation takes place, one other factor has a significant influence on the density separation of particles and that is near dense material. Near dense material can be defined as a material with a relative density that is very close to the density of the medium in which the density separation is taking place (de Korte, 2008). de Korte, 2008 further states that it is because of the near dense material that particles are “misplaced”, in this case low density material will report to the discard and high-density material will report to the product.

When using air as a medium in the dry beneficiation particle misplacement can also occur due to the shape of a particle. A small, high-density particle with an irregular shape can have the same mass as a big, low-density particle and both the particles can report to the same section. It is thus important to monitor the separation and minimize the particle displacement as much as possible to ensure an effective density separation.

Dry density separation using winnowing

One of the most popular and widely used density separation methods in the agricultural sector is winnowing (Bao, et al., 2009). This method can separate light and heavy material from one another (Figure 1.2) and in the case of this study it can separate high density coal particles from low density coal particles resulting in a discard and a product, respectively.

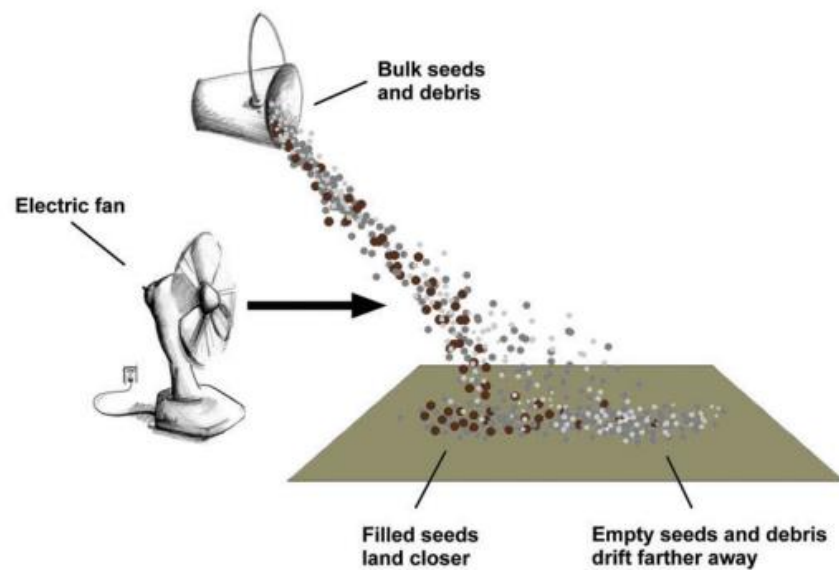


Figure 1.2: Winnowing diagram (Dumroese, et al., 2012)

As seen in Figure 1.2 the method of winnowing works by exerting a force (created by the moving air) on the particle surface. If the particle is light enough the constant force will move the particle horizontally if not, the particle will remain in the current position and thus a separation occurs.

Although the method of winnowing has been tried and tested in other sectors, it has not yet been successfully implemented in the coal mining industry. Several studies have shown that the method can be applied to the coal mining industry but a machine capable of effectively separating the -6 mm coal particles and competing with the current wet separation methods in terms of efficiency and throughput has not yet been designed.

OBJECTIVES

The main aim of this study is to design and build a working fine coal winnower. However, to accomplish this several other objectives must be achieved first. The objectives that need to be accomplished for the winnower to be built successfully are set out in each of the papers presented and briefly summarized below:

- To research and understand the basic principles and mechanisms of the winnowing method. This includes understanding the forces exerted on the particle as well as the particle movement to design a winnowing prototype.
- To investigate the current dry and wet fine coal beneficiation methods in order to establish a benchmark and understand the limitations of dry beneficiation.
- To mathematically model and simulate (using a behavioral model CFD as illustrated in Chapter 6 and the additional notes of Chapter 2 respectively) a fine coal beneficiation technique based on the winnowing method.
- To show that this method works by designing a lab scale winnowing unit for density tracer and coal tests.
- To further investigate the method, improve the design of the lab scale unit to a working demonstration scale unit.
- To build and test the final demonstration winnowing plant and test its capability on coal samples.

SCOPE AND CONTENTS OF THIS THESIS

Chapter 2 is an introduction to the concept of winnowing as a dry beneficiation method for fine coal. The paper presented in Chapter 2 explores the concept of winnowing and uses CFD (As explained in Appendix A) to design a preliminary winnowing machine that can be used to beneficiate -6 mm coal. At the time of this paper very little information and data was available on the possibility of using the winnowing method for coal (in particular fine coal) and thus the approach to testing the concept was to start from scratch and design equipment capable of using the method specifically for fine coal.

The equipment was designed based on the results from the CFD analysis and after the equipment was constructed, density tracers of different sizes and varying densities were used to validate the CFD data. The results obtained from the tracer tests and the CFD simulations were used to improve the design of the separation chamber and the most valuable result obtained from this first study was that the method of winnowing seemed capable of beneficiating -6 mm particles.

Chapter 3 builds on the results obtained by the initial test in chapter 2, the initial design for the equipment was improved using the observations and data from the CFD and tracer tests in chapter 2. The separation chamber was rebuilt taking into account the results from chapter 2 and, for the first time, coal particles were used to test the separation capability of the separation chamber. Several problems came to light as addressed by the paper of which the size and shape effect of particles on the separation were the most severe. Furthermore, the turbulent airflow that was being experienced during the particle separation tests made consistent results very difficult as particles would be misplaced when the airflow fluctuated.

To assist with the understanding of shape and size effects on the separation, the RhoVol analyzer was used because it is capable of sorting particles by size, shape, and density. Thus, by using the RhoVol as a pre-screening device some of the size and shape effects were eliminated.

When the paper in chapter 3 was completed, the winnowing method started to show promise. However, the equipment that was used to test the method still had some shortcomings and a second redesign of the separation chamber was necessary. The redesign described in this chapter would address the problem of size effects on the separation of particles, correcting the fluctuating airflow, and the possibility of having more than one product by adding separation plates to the winnowing chamber. The results obtained in this chapter did indicate that separation of fine coal by both size and density could be possible when using the winnowing method and the observations led to the penultimate design of the density separation chamber.

Chapter 4 conclusively proves that the method and equipment designed can successfully beneficiate fine coal. This chapter ends phase 1 of the design and based on the combined results from chapter 1 – 3 the paper presented in chapter 4 completely changes the winnowing method for fine coal by introducing for the first time a possible winnowing pilot plant design, as well as introducing the concept of using a negative pressure system instead of the traditional positive pressure system seen in the agricultural sector. Chapter 4 serves as a transition between the initial phase of understanding and testing the method to the secondary phase which was the deeper understanding of the separation mechanisms and the improvement of the method to get the ultimate density separation chamber design capable of separating -6 mm coal.

Chapter 5 investigates the mechanisms used by the winnowing method to separate individual particles. The objective at this point was to better understand how particles behave within the separation unit and to observe this behavior, a mathematical model was derived to model the particle movement given specific conditions. The model that was derived and set out in the paper in this chapter was further used to set up a virtual twin for the winnowing chamber which opened the possibility of virtually testing the separation of the particles and further improving the design of the separation chamber before the final design of the winnowing plant was completed.

This chapter also shows the final design for the separation chamber. The design seen in this chapter was obtained by taking into account the results and observations of all the preceding chapters as well as the results from the behavioral model. The design explained in the paper was used for the remainder of the study as it was proven to be the optimal design in terms of airflow and separation capability.

Chapter 6 is the culmination of the study in terms of design and this paper shows the results from testing the newly designed prototypes for the size separation nozzle and density separation chamber. At this stage, the study has reached its end for the given time period and although the paper has not yet been published, the results and paper are included in this chapter to serve as a benchmark for the final design before new studies are started to further improve and test the equipment and method.

The results contained in the paper in chapter 6 are surprising but promising as the separation nozzles appear to also favor a density separation, instead of a size separation as initially intended. Further investigation is needed to confirm this and to test the possibility of using the size separation nozzles as a density separation method on its own.

As for the separation chamber the results indicate that the separation is very size sensitive as predicted by previous studies, however the general operation of the chamber was very successful. Further investigation and tests are needed to optimize the density separation chamber and achieve the desired separation.

In general, the aim of the study was to have a working prototype capable of beneficiating fine coal and the papers presented in each chapter show the progress made during each phase up until the end of the study where the design was completed. There are still some improvements and additional tests that must be done on the equipment however these tests can be done on the designed equipment as part of future projects.

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Chapter 2

Simulation and Design of a Fine Coal Winnower

Simulation of a horizontal flow coal winnower

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This peer-reviewed paper was presented at the XIX International Coal Preparation Congress held in New Delhi, India from 13 - 15 November 2019, by the Coal Preparation Society of India and was published in the conference proceedings (pp. 164 - 175).

PREFACE

The paper investigated the initial concept of winnowing as a dry beneficiation method for fine coal. The application of winnowing at this stage was mostly conceptual with no equipment commercially available and very limited data available on the application of the method on fine coal. This paper demonstrated a proof of concept, initial design, and rudimentary simulation to test the feasibility of the winnowing method.

Simulation of a horizontal flow coal winnower

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ABSTRACT

Dry coal processing is an attractive beneficiation technique, especially in arid areas. Where water is abundant, dry processing still has environmental benefits regarding water pollution. There are a number of dry processing options available, but these are more suited to coarser and easy-to-beneficiate feeds. Attempts to process dry fine coal industrially are still mostly in the developmental stages with limited practical application.

Air winnowing has the potential to be used for dry fine coal processing, and it has been used for millennia in agriculture. A proof-of-concept experimental setup, consisting of a closed box through which a horizontal air stream flows, has been developed. Coal or tracer particles are dropped into the air stream and are displaced horizontally by a distance depending on the particle size and density, thus establishing separation based on these parameters.

Modelling and simulation of the system using fundamental equations of motion was done to assist in designing and optimizing the dimensions and operation of a laboratory scale test apparatus. Using tracers, the simulation results as well as the size dependency of the separation was confirmed, and the partition data for narrow size ranges were promising. After the next stage of operating on real coal samples with realistic washability characteristics, the information will be used in the scale-up towards a pilot- and full-scale prototype.

KEYWORDS: dry processing, fine coal, winnowing, simulation

INTRODUCTION AND BACKGROUND

Dry fine coal beneficiation is becoming increasingly important in South Africa due to the decline of high-quality coal resources coupled with the depletion of suitable process water sources. Fourie, et al., (1980) states that it has always been custom to either discard the coal smaller than 5 mm or blend it unwashed into a steam coal product, but it is becoming imperative, both from an environmental and financial point of view, to treat the fine material. South African coal operations are mostly beneficiating fine coal using wet separation methods such as the dense medium cyclone (van Houwelingen & de Jong, 2004), but the handling and processing of fine coal is much more water intensive. This has a significant environmental impact (de Korte, 2015).

Water scarcity and pollution is a global risk and given that South Africa is a water scarce county, the impact on coal beneficiation in future will be significant. The country is currently faced with challenges where the demand for water exceeds the availability (Kanjere, et al., 2014). Several arid and semi-arid regions in South Africa have very rich coal fields, however due to unpredictable climate changes, unforeseen droughts, and seasonal rainfall these coalfields cannot be completely utilized because of the lack of water (Jeffrey, 2005).

Thus, there is a need for research into dry processing methods, especially for fine coal. One alternative to consider is air driven separators that can be viable substitutes for wet processes, if correctly applied. Several air driven dry beneficiation methods are being investigated and even implemented, such as the FGX and X-ray sorter (de Korte, 2015), and although some have been commercialized these methods cannot in general compete with the efficiencies achieved by dense medium separation.

The agricultural sector has been using wind for hundreds of years to separate wheat from chaff by using a technique called winnowing. The concept of winnowing is based on the difference in density between particles. The method is traditionally carried out by throwing the mixture of particles up in the air and allowing the wind to blow through the particles. The lighter particles are carried away by the force of the air along the horizontal axis, while the heavy particles will stay behind or in this case fall back down.

If the principle of winnowing is applied to fine coal particles a similar approach can be taken. By allowing air to pass through a falling or suspended stream of coal particles, the lighter coal will be transported away leaving the heavier particles behind. The question remains as to whether efficient separation can be achieved for fine (say, -6 mm) particles.

Winnowing is being investigated by a number of researchers to find practical and economic ways to apply this principle to fine coal (Sakhre et al., 2018).

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Design of the winnowing box

A laboratory size horizontal winnowing box was designed using first principles to determine the dimensions, as well as the required air flow velocity to achieve a certain horizontal displacement for a range of particle sizes and densities. The design for the winnowing box started with the concept of a closed box (Figure 2.1) with a single particle inlet, an air inlet, and an air outlet sufficiently large not to have a pressure build up.

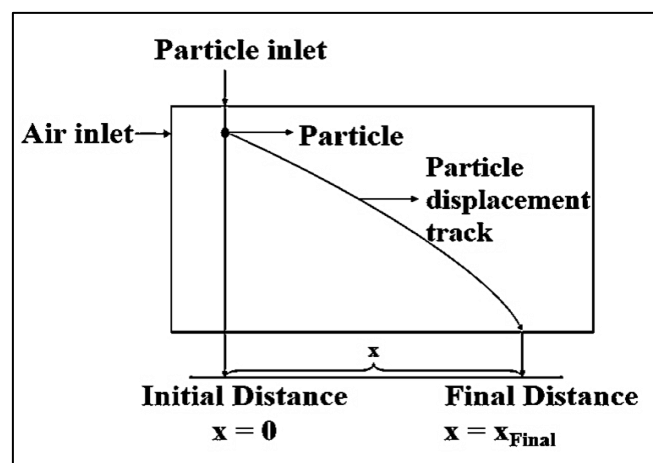


Figure 2.1: Initial design concept of the winnowing box

Fundamental laws of motion incorporating an air drag factor were used to predict the behavior of ideal particles under ideal conditions.

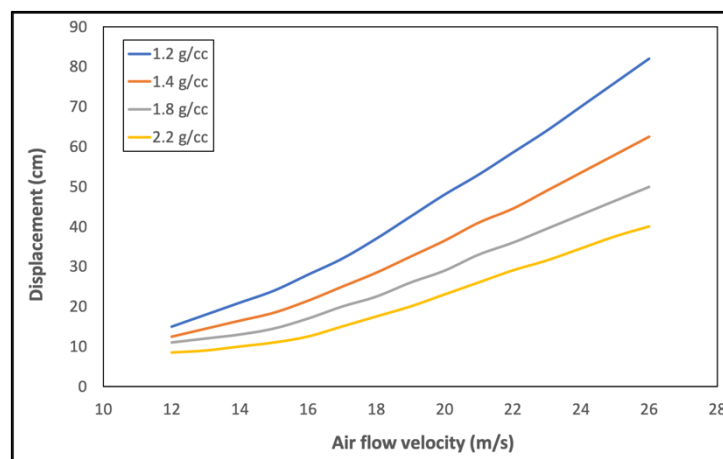


Figure 2.2: Predicted horizontal displacement of 4 mm tracer particles dropping from a height of 0.63 m above the bottom of the box.

Figure 2.2 shows the displacement of 4 mm spherical particles, for example, if introduced into a horizontally flowing air stream at a height of 0.63 m above the point of impact.

Table 2.1 lists a selection of these values (shown in red) for three particle sizes. The flow velocities to be considered in the project were chosen within the range possible with a 1.6 kW household vacuum cleaner in reverse (“blower”) mode.

Table 2.1: Horizontal displacement (cm) of particles for selected air flow velocities

Particle size	Air flow velocity (m s ⁻¹)	Particle density (g cm ⁻³)					
		1.3	1.4	1.5	1.6	1.8	2.0
6 mm	18	21	19	18	16	14	12
	20	24	22	21	19	16	14
	22	28	26	24	23	19	16
	24	34	32	30	28	24	20

Table 2.1: Horizontal displacement distances of particles for selected air flow velocities
(continued)

4 mm	18	33	29	27	26	23	20
	20	42	37	35	33	29	26
	22	52	45	42	40	36	33
	24	62	54	51	48	43	39
2 mm	18	67	55	54	53	50	45
	20	84	70	68	66	62	56
	22	101	84	82	79	75	68
	24	121	101	98	95	89	81

From this information, a flow velocity of 21 m s^{-1} was selected to use for all tests to ensure that a practically sized box length of about 1 m can accommodate the horizontal movement of any of the particles in question. The motion calculations did not consider the flow regimes, so the particle Reynolds numbers (Re_p) were used to determine whether flow was laminar or turbulent (Table 2.2).

Table 2.2: Particle Reynolds numbers for a range of velocities and particle sizes

Particle size	Air flow velocity	
	20 m s^{-1}	22 m s^{-1}
6 mm	7656	8421
4 mm	5103	5614
2 mm	2552	2807

From Table 2.2 it was found that turbulent flow existed for all cases with the very high Reynolds numbers. While it would not affect the operation of the winnower significantly, it was expected to introduce some variability in the subsequent results. The final design of the experimental winnowing box, constructed from plywood and transparent acrylic sheet, is shown in Figure 2.3.



Figure 2.3: Experimental horizontal flow winnowing box.

Moveable separating wedges were placed to create variable sized collection bins on the floor of the box. The vacuum cleaner was connected to the air feed port of the box, and the air flow velocity and patterns were measured inside the box using a FLUS Professional ET-961 hot film anemometer placed at different points in the box. The velocity just inside the feed port was correlated with the power setting on the vacuum cleaner, and it was set at 21 m s^{-1} for all tests in this experiment – a setting considered to be suitable to achieve separation for most sizes and densities within the dimensional confines of the box.

Tracer tests

To simulate the separation of coal particles by winnowing according to size and density, a series of density tracers were used. The plastic cubic tracers were color-coded according to density to facilitate the determination of partition curves after separation. The tracers were introduced one-by-one by hand via a small port in the top of the box and were collected in the collection bins at the bottom.

During phase 1 scoping tests were done to confirm the actual impact points at the bottom for single sized tracers.

The predictions were found to be adequate, considering the variability introduced by operating in the turbulent flow regime. Hence the position of the separating wedge from the datum point directly below the feed port (defined by the point $x = 0$ on Figure 1) could be established to produce target partition cut points using the data in Table 1 for each tracer size.

The main investigation (phase 2) was performed using 36 tracers of each size (2 mm, 4 mm, and 6 mm) and each density (1.3 to 2.0 g cm⁻³, in intervals of 0.1 g cm⁻³) were introduced together, giving a total of 1620 tracers. The air flow rate was set at 21 m s⁻¹. From the results obtained in phase 1, two wedges were placed at positions $x = 28$ cm and 50 cm respectively, to create three convenient product bins. The tracers reporting to each bin were counted, classified according to size and density, and partitions curves were constructed.

Finally phase 3 was done to determine the predictability of cut points using calculated wedge positions for 6 mm tracers only. A run was done for each of two cut points (1.7 g cm⁻³ and 1.5 g cm⁻³) with corresponding wedge positions at $x = 20$ cm and then $x = 23$ cm respectively at a flow velocity of 21 m s⁻¹. Again, tracers reporting to either side of the wedge, mimicking the light “product” and the heavy “discard” were collected, counted, classified and the partition data determined.

RESULTS AND DISCUSSION

Feed densimetric data

Since the same number of tracers (36) of each density was introduced in all cases, a linear feed densimetric curve was defined, resulting in a separation difficulty classification of “formidable” according to the Bird’s scale. Whilst it is acknowledged that this is unrealistic compared to real coal washability characteristics, it was decided that the effect of variations in feed washability would be considered at a later stage in the investigation. This can easily be achieved by manipulating the numbers tracers per density, or by using coal as a feedstock.

This is, by definition, not expected to influence the mechanistic operation of the winnower, but only the yield, e.p.m. and cut point of separation.

Size and density responses

The results from phase 2 confirmed, as expected, a preference to size separation rather than density. Figure 2.4 shows the number of tracers of a particular size and all densities reporting to each of the three bins, and it is evident that size separation is the primary effect. Bin 1, closest to the feed point, contained mostly 6 mm tracers, while bin 3, the furthest away, contained mostly 2 mm tracers. Bin 2 in the middle contained a mixture of sizes, but with 4 mm tracers prevalent.

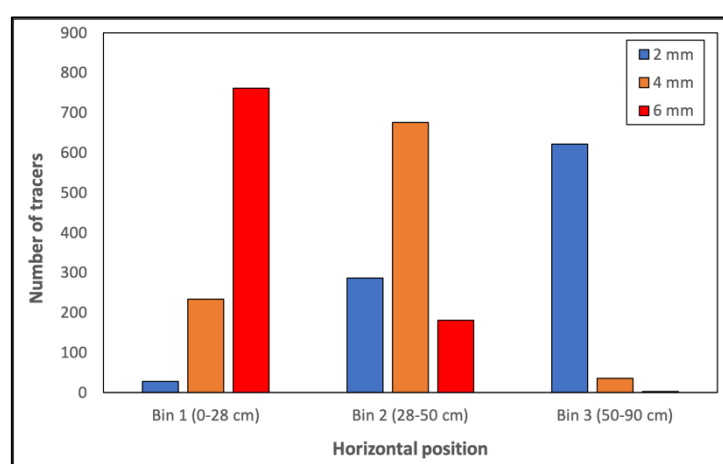


Figure 2.4: Size responses of tracers of all densities at 21 m s⁻¹ air velocity

This indicates that only very closely sized feed material can be practically separated according to density – a result completely in line with wet and dry gravity separation methods. The distribution of densities within each of the three bins for selected sizes are shown in Figures 2.5, 2.6 and 2.7. For 2 mm particles (Figure 2.5), most of the light material was concentrated in bin 3, while the central bin 2 received the heavier particles.

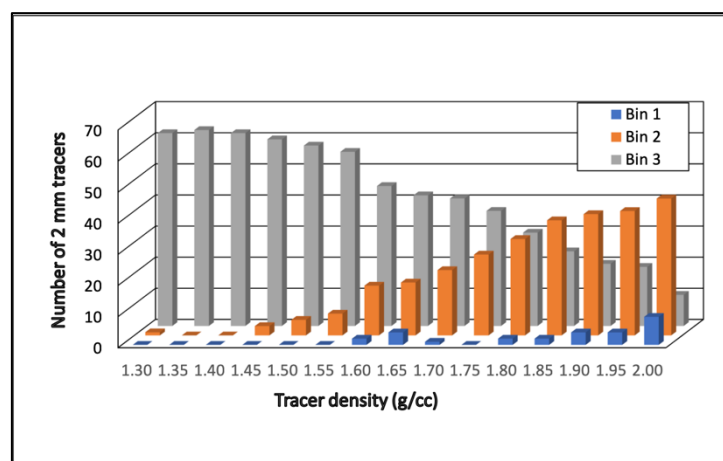


Figure 2.5: Density distribution of 2 mm tracers in the three product bins.

Very few particles reported to bin 1, since the small 2 mm tracers were easily carried to the furthest part of the box.

For 4 mm particles, most of the separation was accomplished between bins 1 and 2 (Figure 2.6). For both 2 mm and 4 mm tracers there was a significant amount of misplaced material that would translate into a low separation sharpness or *ecart probable moyen* (e.p.m.) in the practical case, but the poor densimetric characteristic of the feed population was the cause of this.

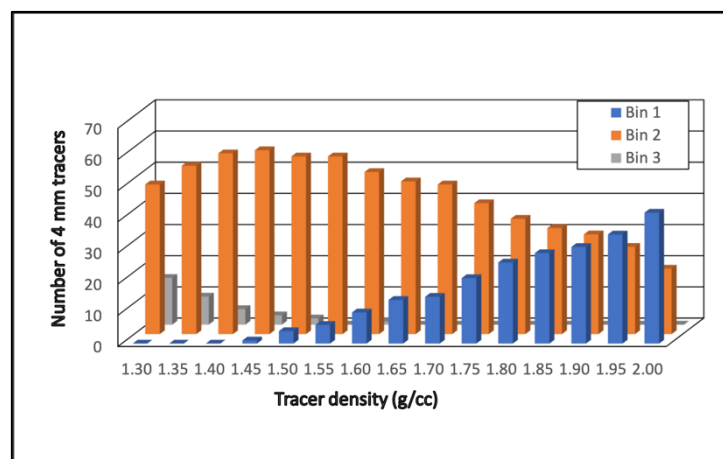


Figure 2.6: Density distribution of 4 mm tracers in the three product bins

The 6 mm particles (Figure 2.7) did not carry very far and reported mainly to bin 1, with some of the lighter fraction landing in bin 2. Again, there was a significant inefficiency for the same reason.

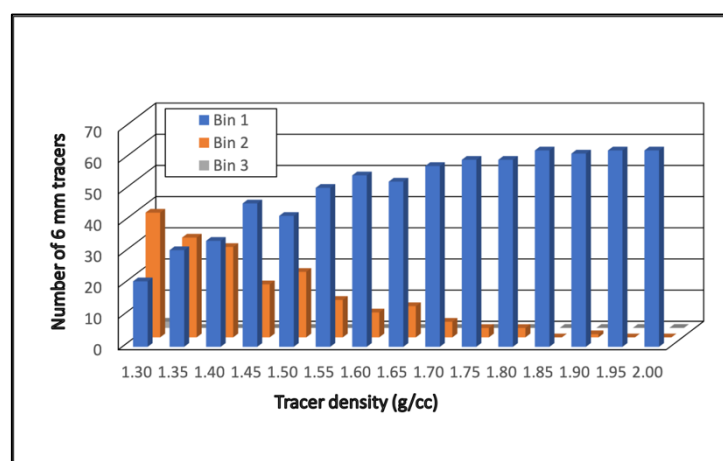


Figure 2.7: Density distribution of 6 mm tracers in the three product bins.

The size sensitivity of air winnowing is confirmed by these observations, and density separation using a wide feed size distribution is indeed problematic.

To obtain an indication of the expected yields, cut points and separation sharpness for the mixed sized feeds, partition curves were calculated for the arbitrary case where bin 1 was considered the product, while the combined bin 2 and bin 3 contents constituted the discard.

The Scott and Napier Munn (1992) theoretical partition function was fitted to the experimental points, and the e.p.m. and cut points were determined by curve fitting. Figure 2.8 shows the individual partition curves for each size, as well as the combined overall partition curve.

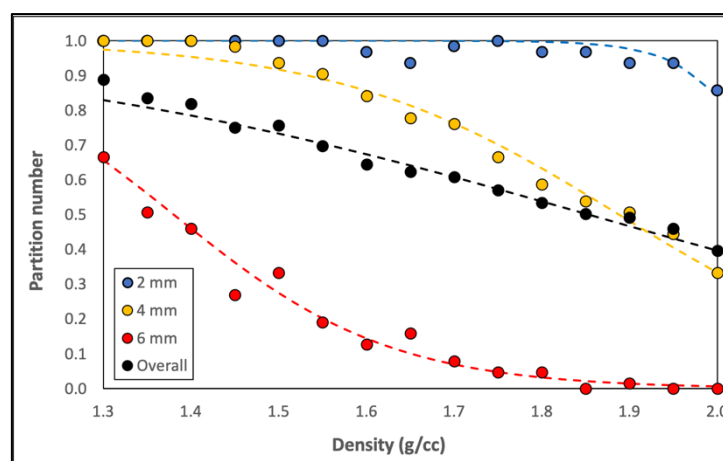


Figure 2.8: Partition curves for all sized tracers at 21 m s⁻¹. Separation at x = 23 cm.

It can be seen that there are distinct partition curves, each with a unique cut point and e.p.m. for each size. It is also evident that the overall efficiency of separation is much worse than for any single size, which again confirms the need for narrow feed sizes. The operational parameters determined from the partition data are summarized in Table 2.3.

Table 2.3: Performance data for the simultaneous separation of all sized particles at 21 ms⁻¹.

Particle size	2 mm	4 mm	6 mm	Overall
Actual cut point	2.08 g cm ⁻³	1.89 g cm ⁻³	1.38 g cm ⁻³	1.85 g cm ⁻³
Yield (by number of tracers)	97.2%	75.2%	19.4%	63.9%
E.p.m.	0.054	0.177	0.136	0.384

Partition data for 6 mm tracers

The purpose of the phase 3 tracer tests was to demonstrate that it was possible for the operator to have some predictive control over the cut point by modifying the position of the separating wedge. Yield and e.p.m. information for specifically the 6 mm tracers were generated, which gave an indication of the order of magnitude of the e.p.m. that could be expected in future applications. Obviously, the tracers had regular shapes, and a very narrow size, hence it is expected that irregularly shaped real coal particles would not perform as well. This would be the aim of the investigation in the next stage of the project.

Table 2.4 shows the results for the two cases where the target cut points were set at 1.5 g cm^{-3} and 1.7 g cm^{-3} . These cut points were selected as it was easier to achieve these high cut points on an initial test than aiming for a low-cut point on the first experiment. Figure 2.9 shows the partition curve for these target cut points.

Table 2.4: Performance data for the separation of 6 mm particles at 21 ms^{-1} .

Target cut point	1.70 g cm^{-3}	1.50 g cm^{-3}
Actual cut point	1.72 g cm^{-3}	1.58 g cm^{-3}
Wedge position	20 cm	23 cm
Yield (by number of tracers)	58.7%	42.2%
E.p.m.	0.17	0.16

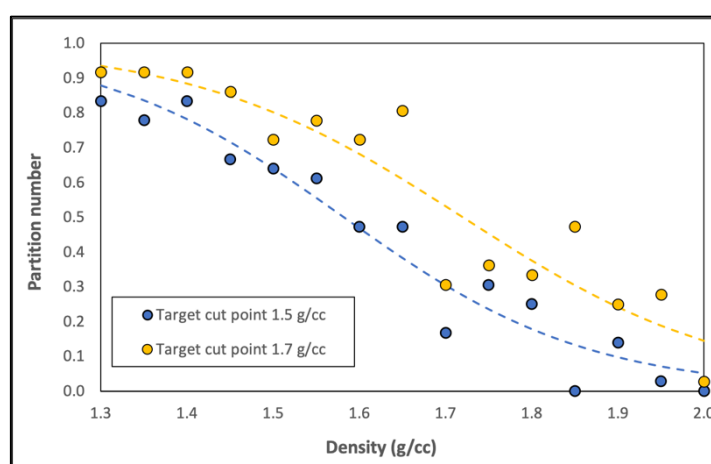


Figure 2.9: Partition curves for 6 mm tracers with the separating wedges set at 23 cm (for 1.7 g cm^{-3}) and 20 cm (for 1.5 g cm^{-3})

Again, the scatter in the partition data was due to turbulence in the winnowing box, and the fact that some tracer breakage was starting to appear after repeated use. Despite this, it was possible to show that targeted cut points were possible by an adjustment of the separating wedge, and an adjustment in the air flow velocity, even though the latter was not tested during this stage on the project.

CONCLUSIONS

Dry fine coal separation by winnowing has been shown as a feasible option that warrants further investigation. It was shown, initially by studying tracers, that the size sensitivity of this gravity process makes it imperative to use narrow size distributions for sharp separations. It was shown that with narrow distributions, good separation can be obtained (with e.p.m. values in the order of 0.16 or 0.17) but this would require very good control over the air flow velocity and flow regime inside the box. In all cases linear feed densimetric distributions were used, but efficiencies will improve significantly if more realistic washability material is used.

It was possible to accurately control the cut point by changing the position of the separating wedge to create the two product bins. The next stage of development of the winnowing process would be to introduce real coal samples, which will have realistic densimetric characteristics, irregular shapes, and non-uniform size.

The major aspect to address would be the size-density interdependency. To alleviate this effect, it is planned to have a two-stage process in the next generation of winnowing boxes, where the first stage will be used for size separation only into any number of fractions (like in Figure 2.3), followed by a second stage density separation on each of the narrow size products from the first stage. It is clear that there is a potential for density separation by the winnowing process.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial and technical contribution made by The Coaltech Research Association NPC Ltd., and the Centre of Excellence in Carbon Based Fuels, North-West University, South Africa.

This work is based on the research supported in part by the National Research Foundation of South Africa (Coal Research Chair Grant Numbers: 86880; and UID85643, UID85632). Any opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF supported research is that of the author(s) alone, and that the NRF accepts no liability whatsoever in this regard.

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ADDITIONAL NOTES

This paper's focus was oriented more towards the results obtained from the tracer tests that were conducted and less towards the initial simulation of the winnowing unit, however computational fluid dynamics (CFD) played a key role in the initial design of the winnower as will be explained shortly. With the help of CFD (as explained in Appendix A), the size of the winnowing unit, feed point and air velocity could all be simulated to see what the result would be. By further optimizing the simulation and adjusting these factors the design for the winnower (that would be used in the tracer tests) could be done with a higher level of confidence.

The setup and execution of the simulation required constantly changing the parameters stated above to ensure that the particles do not collide with the winnowers walls or blow out of the separation chamber. Furthermore, the particle track was observed to ensure that the separation chamber was high enough, allowing enough time for the particles to separate. An example of the simulation setup is shown in Figure 2.10.

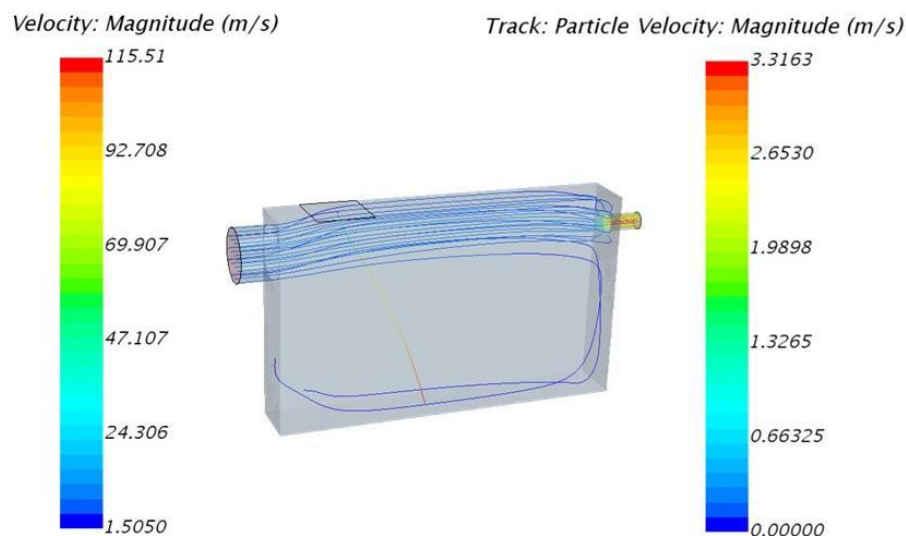


Figure 2. 10: Winnowing chamber simulation setup

As seen in Figure 2.10 a very basic and robust separation chamber was set up for the initial design to ensure enough room if improvements were needed. Figure 2.10 shows the individual factors that were crucial to the design and that had to be tested. These

factors are highlighted in Figure 2.11 which is a closer look at the setup shown in Figure 2.10.

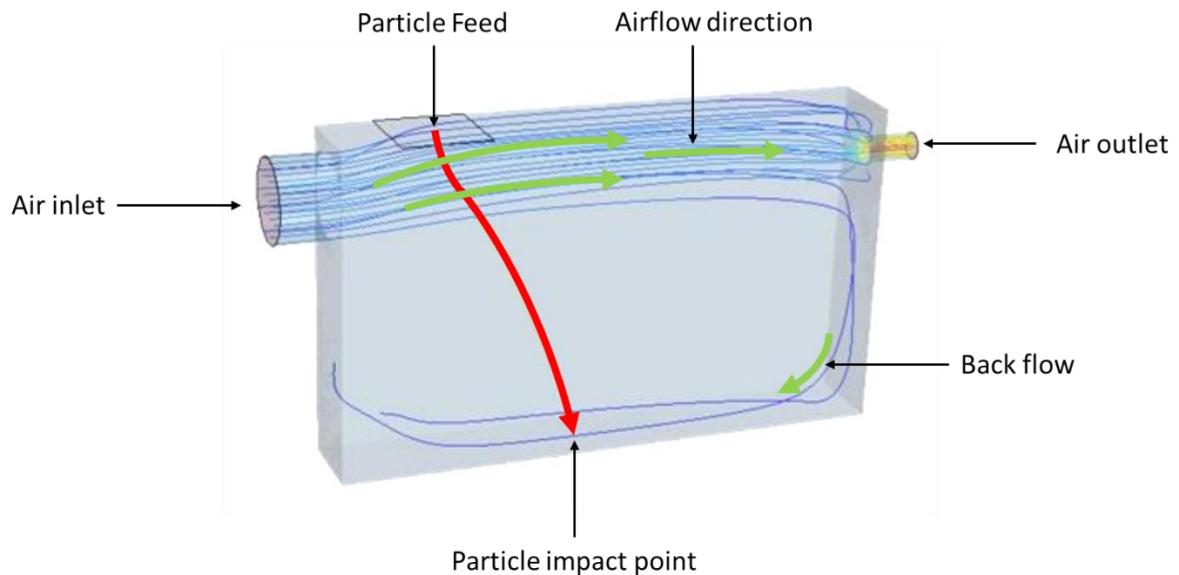


Figure 2. 11 Closeup of Figure 2.1

Figure 2.11 shows the individual components of the winnowing separation chamber, the most important of these components is the red line showing the particle's track from the feed to the impact point. This track shows how the particle interacts with the air and gives an indication of where a particle with a specific size and density will be in the winnowing unit. This was tested for all combinations of particle sizes in the range 1 mm – 6 mm with varying densities between 1.2 g cm^{-3} and 2.0 g cm^{-3} for example:

- A 1 mm particle was tested over the entire density range i.e., 1 mm with a density of 1.2 g cm^{-3} then 1 mm with a density of 1.3 g cm^{-3} etc.
- Then a 2 mm particle was tested over the entire density range i.e., 2 mm with a density of 1.2 g cm^{-3} then 2 mm with a density of 1.3 g cm^{-3} etc.

This was continued up to the 6 mm particles, and the results aided with the design of the first lab scale winnowing unit.

Although the results from the simulation are not shown in this paper a full comparison of the simulation results and the tracer test was done as part of another study and some of the findings are summarized below:

- The simulation, although helpful in the initial design, was set up using several assumptions and thus the results obtained from the simulation differed from the results obtained by the tracer tests.
- The biggest contribution made by the simulation was the ability to identify the airflow patterns in the unit and with this information the improved design will be able to address some of the issues that came forth during the initial study.
- The results obtained from both the simulation and the tracer tests confirm that separation by both size and density is possible when using the winnowing method.

Overall, the initial proof of concept study was successful, and the results indicated that the method of winnowing could possibly be used to beneficiate -6 mm coal particles. However, further investigation was needed to understand how the separation mechanism works and also to improve the design of the separation unit.

Chapter 3

Fundamentals of Fine Coal Winnowing

Horizontal air flow fine coal winnower

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This peer-reviewed paper was presented at the Southern African Coal Processing society biennial Technical Conference held in Secunda, South Africa from 19 - 22 August 2019, by the Southern African Coal Processing society and was published in the conference proceedings.

PREFACE

This paper builds on the concepts and ideas introduced by the paper in Chapter 2. After the concept of winnowing was proven to be feasible, further emphasis was put on designing and building an improved winnowing unit capable of achieving efficient separation. During this process, changes such as improved separation plates (Figure 3.2 Chapter 3) were implemented to have a multi-product density separation and control the density cut point.

Horizontal air flow fine coal winnower

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ABSTRACT

Dry coal beneficiation has been investigated on several occasions and to date most of the viable options indicate positive results on coarser coal samples. Dry fine coal beneficiation is still a very new technology and most of the methods are still in the development phase.

Horizontal air winnowing has been used in the agricultural and pharmaceutical sector for decades and the method has been proven to be effective for small particle density-based separation. To prove that this method can be used to beneficiate fine coal, a study was done that included the modelling and simulation of the method and the construction of an experimental unit, consisting of a closed rectangular box utilizing a horizontal flow of air.

During the development phase the simulations were used to establish the necessary parameters, such as the air flow velocity and box dimensions needed to achieve separation. The modelling was done using kinematic equations for projectile motion taking into account the drag force created by air resistance. During the experimental phase both tracers and coal particles were used to test the separation capability of the winnowing unit. The tracers and coal particles were also used to confirm the simulation results and size dependency as indicated by the simulation.

Although the partition data showed promising results the data also indicated that very narrow size ranges are needed in order to achieve good separation. A comparison of the results obtained by the simulation, tracers and coal particles indicate that the method is in fact viable. During the next phase, the winnowing unit will be tested on different types of coal at more controlled and non-fluctuating airflow.

KEYWORDS: dry processing, fine coal, winnowing, simulation

INTRODUCTION AND BACKGROUND

For the past several years there has been a steady increase in the importance of dry fine coal beneficiation and with the decline in suitable high-quality coal (de Korte, 2015) and the ongoing decrease in usable process water, dry fine coal beneficiation has never been more important.

Fourie, et al., (1980) states that it has been customary to either discard the -6 mm coal or blend it into a steam coal product without the fine coal being washed, however, from both a financial and environmental point of view this practice is no longer feasible. In South Africa, fine coal beneficiation is currently dominated by wet separation processes such as dense medium cyclones (van Houwelingen & de Jong, 2004). The drawbacks of these methods are that they require large amounts of process water and in some cases the discarded slurry can contribute to water pollution (de Korte, 2015).

The increasing water scarcity is not only affecting South Africa, but it is a worldwide concern (Kanjere, et al., 2014). In South Africa water scarcity is impacting the coal industry, the reason for this impact is that some of the larger coal deposits are situated in arid and semi-arid regions which makes coal beneficiation difficult (Jeffrey, 2005). The alternative and possible solution to this problem is dry beneficiation and thus the research into these methods especially for fine coal is becoming crucial. Several dry beneficiation methods such as the FGX and X-ray sorters have been proposed and tested. These methods use air instead of water to beneficiate coal. However, most of these methods are still being developed or tested and, in some cases, where these methods have been implemented, they are not able to compete with the water-based methods in terms of either separation efficiency or throughput (de Korte, 2015).

A different approach to dry beneficiation is needed and by drawing inspiration from other sectors a new method can be developed. The agricultural sector has been using a water free separation technique for decades, this technique uses only wind and gravity to separate products from waste. This method known as winnowing separates the particles based on the difference in their density, where lighter particles will be blown away by the wind and the heavy particles will be left behind. Adapting

this technique, it is possible to develop a winnowing method that can be implemented for dry fine coal beneficiation. By introducing coal particles into a horizontal air stream and allowing the force to displace the particles along the horizontal axis, separation between light and heavy particles will occur creating a density separation. Researchers have already started to investigate the method in 2008 and the investigation still continues to find the best way to implement coal winnowing (Sakhre, et al., 2018). The main question that still remains, is whether winnowing is a feasible and efficient separation method for coal particles smaller than 6 mm.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Design of the winnowing box

A laboratory scale winnowing unit was designed from first principles. Using kinematic equations for projectile motion and factoring in the drag force created by air resistance the necessary parameters such as the dimensions of the unit, air velocity needed for separation, particle displacement and the velocity of the particles were predicted. The equations derived during the design phase were entered into both Excel and Python to help predict the parameters and simulate the particle behavior. Using the concept as illustrated in Figure 3.1 several different scenarios were simulated by changing parameters such as air velocity, particle size and particle density for each case. The closed winnowing unit was designed to have a single air inlet and a single air outlet directly across one another to prevent a pressure build up within the unit. The particle inlet was placed as close to the air inlet as possible to allow the maximum force to be applied to the particle and to provide enough space in the unit for the required horizontal particle displacement. The air outlet provided the possibility for dust extraction if needed.

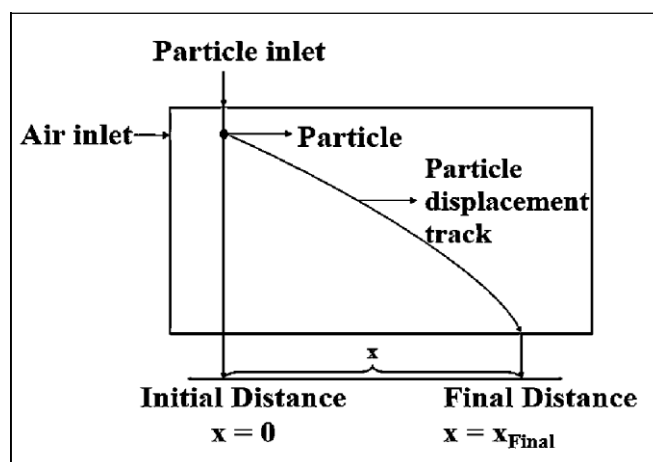


Figure 3.1: Design concept of the winnowing unit.

For the initial simulation, particles were assumed to be either spherical or cubic with three size classes (2.0 mm, 4.0 mm, and 6.0 mm). The density of the particles ranged from $1.30 - 2.20 \text{ g cm}^{-3}$ and the air velocity ranged from 12 to 26 m s^{-1} .

The data obtained from the simulations were entered into several prediction matrices similar to the one shown in Table 3.1, which was used to estimate the required velocity to achieve either size separation or density separation given certain particle properties.

The initial model indicated that separation by both size and density was possible in theory. For example, a 6 mm particle with a density of $1.5 \text{ g} \cdot \text{cm}^{-3}$ can be expected to displace 21 cm when using a velocity of $20 \text{ m} \cdot \text{s}^{-1}$ while a similar 4 mm particle will be displaced 35 cm indicating that size separation is possible.

For density separation, a 6 mm particle with a density of $1.5 \text{ g} \cdot \text{cm}^{-3}$ can be expected to displace 21 cm while a 6 mm particle with a density of $1.8 \text{ g} \cdot \text{cm}^{-3}$ will be displaced 16 cm.

Table 3.1: Simulated horizontal displacement (cm) of particles for selected air flow velocities.

Particle size	Air flow velocity (m s ⁻¹)	Particle density (g cm ⁻³)					
		1.3	1.4	1.5	1.6	1.8	2.0
6 mm	18	21	19	18	16	14	12
	20	24	22	21	19	16	14
	22	28	26	24	23	19	16
	24	34	32	30	28	24	20
4 mm	18	33	29	27	26	23	20
	20	42	37	35	33	29	26
	22	52	45	42	40	36	33
	24	62	54	51	48	43	39
2 mm	18	67	55	54	53	50	45
	20	84	70	68	66	62	56
	22	101	84	82	79	75	68
	24	121	101	98	95	89	81

Using the matrices and applying the design from Figure 3.1, the laboratory scale winnowing unit was constructed. The air flow was generated by a 1.6 kW domestic vacuum cleaner that was set to the blower function. The air velocity could be adjusted between 19 m s⁻¹ and 33 m s⁻¹ which provided a wide range of velocities.

From the matrices it was found that the best separation (for both size and density) occurs at an airflow velocity of 21 m s⁻¹. This setting was used to do all further experiments including the tracer and coal tests. The temperature and air velocity were both measured using a FLUS Professional ET-961 hot film anemometer, and these readings were taken at several different points in the winnowing unit to determine the temperature and air flow patterns within the box.

Tracer tests

To verify the computer simulated results and to mimic the separation of coal particles the laboratory scale winnowing unit was first tested using plastic cubical tracers. Three sizes were selected (2 mm, 4 mm, and 6 mm), each with a density range from 1.30 to 2.00 g cm⁻³ with 0.05 increments. The tracer tests were conducted in three stages. During stage 1 the tracers were used to confirm the displacement of the particles as predicted by the models and computer-based simulations. The tests confirmed that the predictions were accurate with small deviations which were possibly caused by the fluctuating airflow.

Stage 2 of the tracer tests tested the actual separation capability of the winnowing unit. This was done by installing several separation plates (as in Figure 3.2) at different distances along the floor of the unit. The divisions were at $x = 28$ cm and $x = 50$ cm (as these were the distances recommended by the simulation) allowing the particles to be separated into three bins. For each of the three sizes and 15 densities, nine tracers were used, resulting in a total of 405 tracers per test. Each test was repeated four times and the tracers in each of the bins were hand-sorted by size and density.

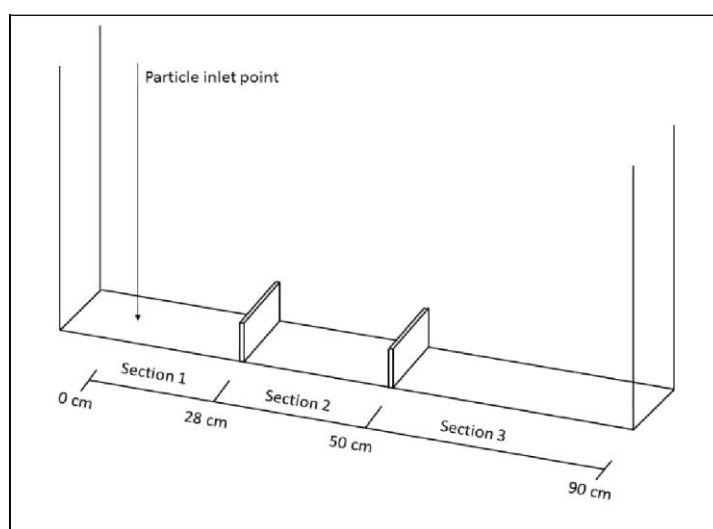


Figure 3.2: Sections for size separation.

Stage 3 was to test the winnower's capability to separate particles of a single size according to density. For this stage only the 6 mm tracers were used, and the separation plates were set at 2 different positions ($x = 20$ cm and at $x = 23$ cm) that were predicted to give two density cut points of about 1.7 g cm^{-3} and 1.5 g cm^{-3} , respectively. The data was used to construct partition curves for the two cuts, and the separation capability of the unit was examined by comparing the calculated cut points to the predicted cut points for the set positions of the separation plates.

Coal tests

Coal particles were tested in two stages. For stage 1 the initial preparation of the coal sample was done using the RhoVol BDD127SM - a separation unit owned by the De Beers Group that characterizes and separates a population of particles based on various properties, like density, shape, and size.

To prepare the coal sample, it was first physically separated in the RhoVol by shape. It uses a sphericity definition called the compactness of a particle. For this experiment a shape class with an average compactness of 0.65 was used, meaning that the extremely flat and the mostly round particles (that account for 10% of the total material) were excluded from the experiments.

The selected shape class was then physically separated using the RhoVol by size from +3.0 mm -8.0 mm with a 0.5 mm interval. Then, the final preparation step was to separate each of the size classes obtained above by density in the range of 1.30 to 2.20 g cm⁻³ with 0.1 increments. This meant that the RhoVol was used to effectively produce “coal tracer particles” of defined sizes and densities. These coal particles were introduced into the winnower at 21 m s⁻¹ one-by-one and their behavior was observed. Two size classes (+2.0 mm -4.0 mm and +4.0 mm -6.0 mm) over all densities were used and the bin into which the particle reported was recorded. The data was analyzed, and the particle sizes contained in the contents of each of the two bins were determined.

Stage 2 was to confirm that the winnowing unit was capable of separating coal particles by density, at least for narrow sizes. For this test only the +6.0 mm -6.5 mm particles were used. The estimated required cut point densities were 1.40 and 1.50 g cm⁻³ with the separation plates set at $x = 55$ cm and $x = 60$ cm (as obtained from the displacement tables), respectively. Again, particles were introduced one by one, and their behavior recorded. By counting which particle at which density reported where, partition data could be determined.

RESULTS AND DISCUSSION

Tracer size and density responses

For each size class the same number of tracers (36) was used for each density. This resulted in a linear feed densimetric curve making the separation difficulty “formidable” according to the Bird’s scale. The feed, although unrealistic, was selected in this manner to assess the separation capability of the winnowing unit even though it did not resemble the washability characteristic that are normally seen for actual coal.

During the stage 2 test (tracers of all sizes and all densities at an air velocity of 21 m s^{-1} , size separation could be largely achieved in the three bins, almost independent of density (Figure 3.3). Bin 1 was closest to the feed side, and bin 3 the furthest. Most of the 6.0 mm tracers reported to the first bin with some overlap to the second, whilst most of the 4.0 mm and 2.0 mm tracers were collected in the 2nd and 3rd bins, respectively.

This could be quantified further by examining the density distribution of particles in each bin.

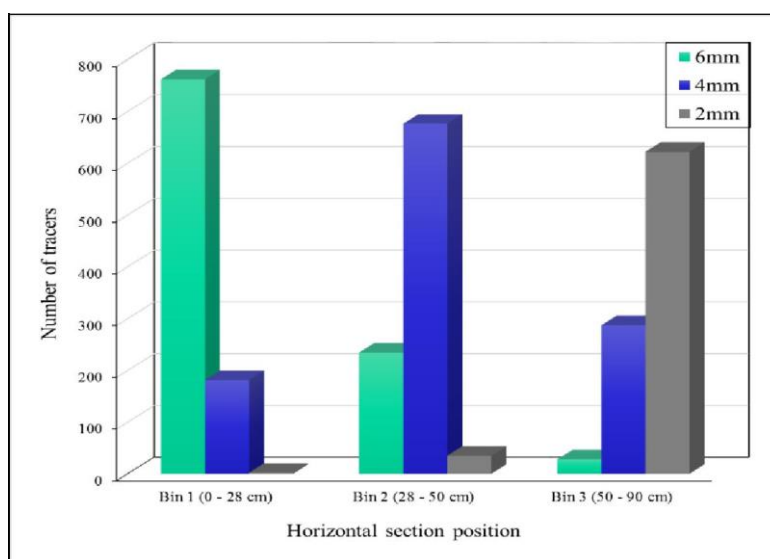


Figure 3.3: Size responses of complete density range tracers at 21 m s^{-1} air velocity.

Figure 3.4 and 3.5 shows the density distribution in each of the bins for the 6.0 mm and 2.0 mm tracers, respectively.

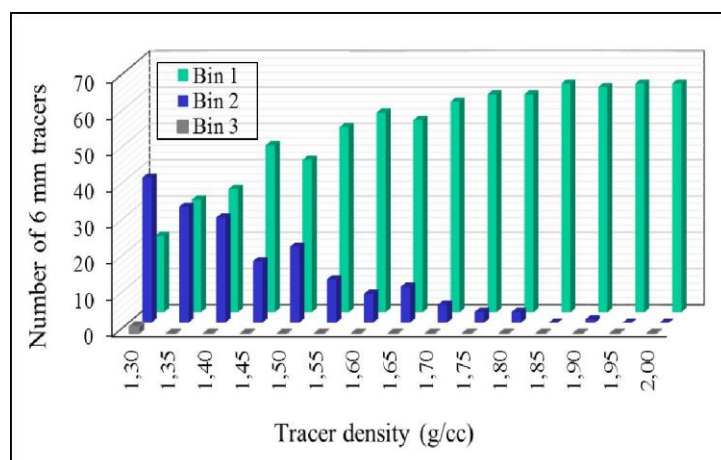


Figure 3.4: Density distribution of 6 mm tracers in the three product bins.

From Figure 3.4 it can be seen that the 6.0 mm tracers with high densities mostly reported to bin 1, with the lower density tracers displaced towards bin 2.

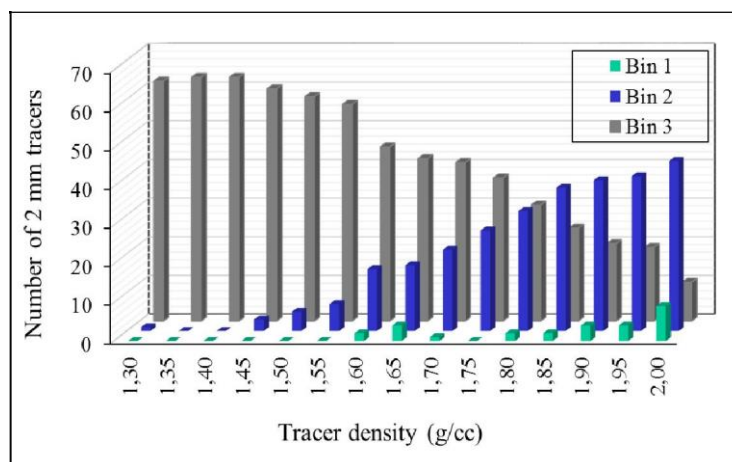


Figure 3.5: Density distribution of 2 mm tracers in the three product bins.

Figure 3.5 shows a similar but opposite result for the 2.0 mm tracers, where the lower density tracers were collected in bin 3, with an overlap into bin 2. The test showed good size separation between the 6.0 mm and 2.0 mm tracers, and the misplaced tracers that reported to Bin 2 could be contributed to the feed characteristics and fluctuating air velocity. This will of course result in a poor density separation sharpness. From this particular test the size sensitivity of the winnowing unit was confirmed, and it is noted that a density separation, using a wide size distribution, is problematic.

Partition data for 6 mm tracers

The third phase of tracer testing (done on only 6.0 mm tracers) aimed at determining the performance of the winnowing unit if certain cut point targets were set by the positions of the division plates. Table 3.2 and Figure 3.6 show the partition data obtained for these target cut points.

Table 3.2: Performance data for the separation of 6 mm tracer particles at 21 m s⁻¹.

Target cut point	1.70 g cm ⁻³	1.50 g cm ⁻³
Actual cut point	1.72 g cm ⁻³	1.58 g cm ⁻³
Plate position	20 cm	23 cm

Yield (by number of tracers)	58.7%	42.2%
E.p.m.	0.17	0.16

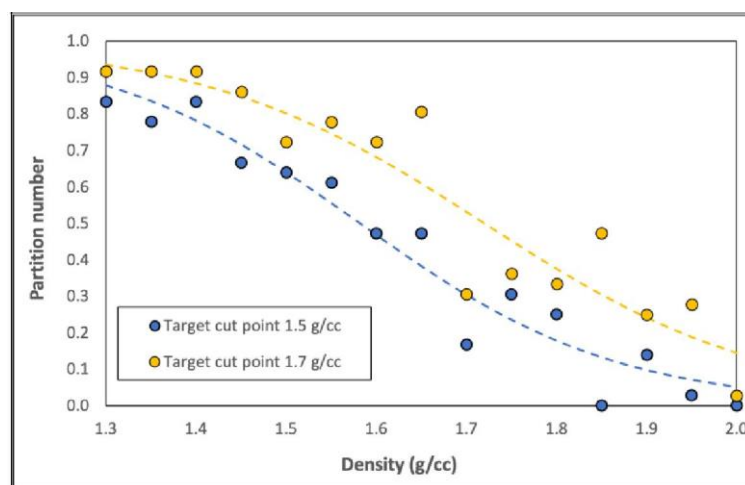


Figure 3.6: Partition curves for 6 mm tracers with the separating plates set at 23 cm (for 1.7 g cm⁻³) and 20 cm (for 1.5 g cm⁻³).

The calculated cut point (actual) and the target cut point values were similar, and the difference between the values can be attributed to the fluctuation in air flow (possibly turbulence). This can be seen by the scattered data in Figure 3.9 as well.

Nonetheless the phase 3 tests indicated that it was possible to predict a cut point with some degree of accuracy and with a non-fluctuating airflow (which was not tested in this phase) it is believed that the accuracy of the prediction will improve.

Feed data coal

The coal used for the second part of the experiments was a low density Moatize sample. The proximate analysis (air dried basis) showed that the coal had 1.60 % moisture with a feed ash and volatile content of 17.88 % and 32.20 % respectively. The densimetric curve for this sample as determined by a RhoVol analysis is shown in Figure 3.7.

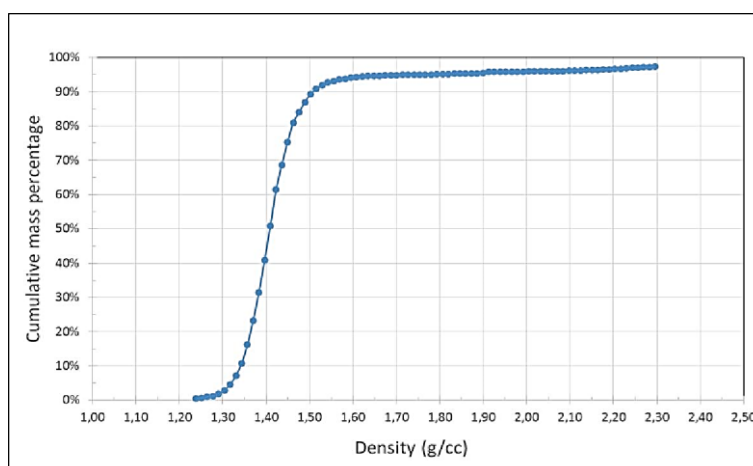


Figure 3.7: Moatize feed sample density distribution.

For this phase only one coal sample was tested and compared to the tracer results. However, different qualities of coal will be investigated at a later stage. The coal particles were prepared as described in section 2.3 and the separation capability of the winnowing unit was tested on a single particle response basis.

Size response

Stage 1 (for coal particles) tested the ability to separate coal particles by size irrespective of the density. For this test two size classes were chosen (+6.0 mm -6.5 mm and +4.0 mm -4.5 mm) and introduced one by one into the air stream. Visual observation was used to characterize the behavior of each coal particle. It indicated that the separation plate distances, as predicted by the tracer tests, were inaccurate and adjustments had to be made to the separation plate positions.

A single separation plate, resulting in only two receiving bins, was placed at 65 cm from the particle inlet and the test was restarted. Figure 3.8 shows the results of the size separation, the larger particles (+6.0 mm) were collected in the bin closest (bin 1), and the smaller (+4.0 mm) particles reported to bin 2. Some overlap occurred between the sections which was expected due to fluctuating air flow, and the wide density distribution.

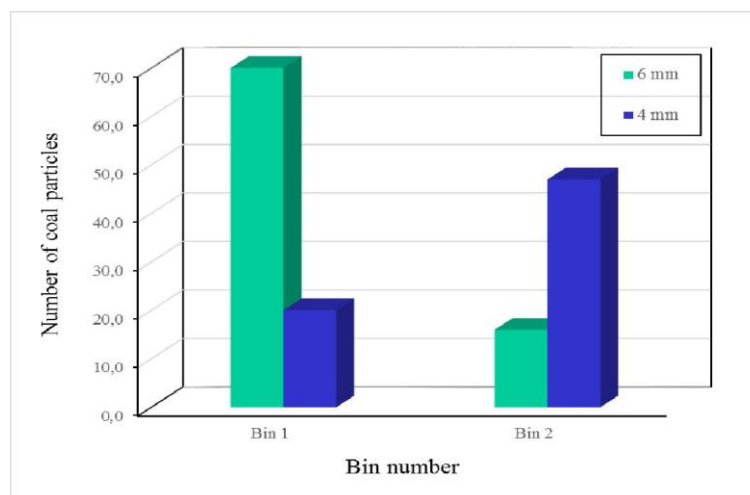


Figure 3.8: Size responses of complete density range coal particles at 21 m s⁻¹ air velocity.

Partition data coal

Stage 2 of the coal tests was to determine the density separation capability of the winnowing unit and to test the prediction control with regards to setting certain cut points. A narrow size interval (+6.0 mm -6.5 mm) was used. Figure 3.9 shows the partition curves generated for both the 1.50 g cm⁻³ and 1.40 g cm⁻³ target cut points. The yield, actual cut point and sharpness of separation were calculated and are shown in Table 3.3.

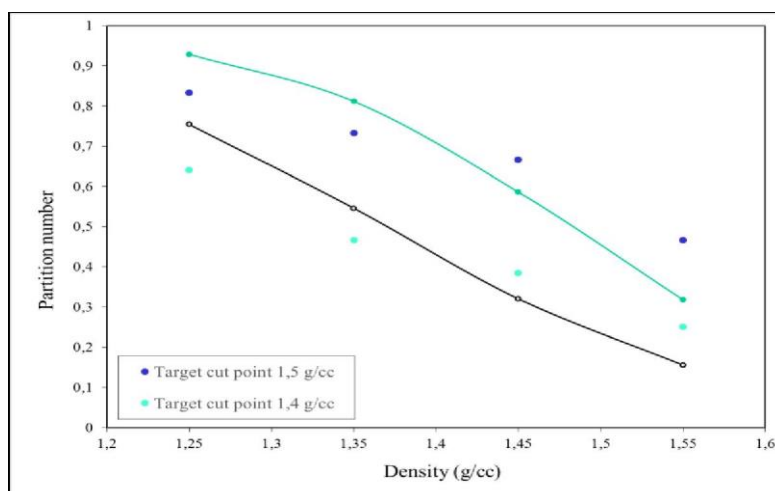


Figure 3.9: Partition curves for +6.0 mm -6.5 mm coal particles with the separating plates set at 55 cm (for 1.4 g cm⁻³) and 60 cm (for 1.5 g cm⁻³)

Table 3.3: Performance data for the separation of +6.0 mm -6.5 mm coal particles at 21 m s⁻¹.

Target cut point	1.40 gcm ⁻³	1.50 gcm ⁻³
Actual cut point	1.37 gcm ⁻³	1.48 gcm ⁻³
Plate position	60 cm	55 cm
Yield (by number of particles)	55.56%	71.74%
E.p.m.	0.117	0.099

The data shows very accurate predictions for the cut points at the pre-set plate positions. Again, it is thought that the accuracy can be improved by somehow stabilizing the air flow in the winnowing unit.

CONCLUSIONS

The results from both the tracer and coal tests prove that dry fine coal separation is feasible when using the method of winnowing. The results indicate that a narrow size distribution is indeed needed to achieve a sufficiently sharp separation, as is seen by the size sensitivity of both the tracers and the coal particle results. With this narrow distribution good separation can be achieved with coal e.p.m. values in the order of 0.117 or 0.099, however, to improve on this separation better control of the air flow must be implemented. The tests also confirmed that it was indeed possible to predict the cut points with a fair degree of accuracy using the displacement tables and mathematical model. This meant that a given sample can be separated by using a separation plate to create “clean coal” and “discard coal”.

Future testing of the winnowing unit will include testing and comparing the separation efficiency of the winnowing unit on different qualities of coal. The influence of non-fluctuating airflow and particle shape on the separation efficiency of the winnowing unit will also be further investigated.

The results show that a two-stage separation is imperative to compensate for the size-density inter-dependency. The first stage will be a size separation from where the respective size classes can be fed to a number of parallel secondary units where the density separation will occur.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial and technical contribution made by The Coaltech Research Association NPC Ltd., and the Centre of Excellence in Carbon Based Fuels, North-West University, South Africa.

This work is based on the research supported in part by the National Research Foundation of South Africa (Coal Research Chair Grant Numbers: 86880; and UID85643, UID85632). Any opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF supported research is that of the author(s) alone, and that the NRF accepts no liability whatsoever in this regard.

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ADDITIONAL NOTES

The focus of the study shifted from simulation to design and implementation. During this stage coal samples were used to test the efficiency of the winnowing unit. The problem with testing coal in a new design is that coal can be very unpredictable when doing density separation and without a sink float analysis the effectivity of the separation cannot be calculated. However, with the use of the RhoVol analyzer from De Beers (Figure 3.10) it was possible to analyze the shape, size, and density of each particle without damaging the particle. This meant that a particle of known size and density could be recirculated through the winnowing unit and the experiment could be repeated with the same particles making the optimization of the unit easier.



Figure 3.10 RhoVol Analyser

The RhoVol analyzer continued to play an important role throughout the study and the information it provided helped to solve several problems that came up during the study. The most valuable piece of information that the RhoVol provided was the shape of the particles. This gave a better understanding of the particle behavior in the winnowing unit and this feature will be used in a future study that investigates the effect of particle shape on dry separation processes such as winnowing.

From the initial concept and tests presented in Chapter 2 to the tests represented in this paper an improvement in the efficiency and design was achieved in less than a year with a lot of possible improvements that could still be made to both the winnowing unit and the process.

Chapter 4

Improving the Fine Coal Winnowing Process

Horizontal airflow fine coal winnowing

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This peer-reviewed paper was presented at the XXX International Mineral Processing Congress held in Cape Town, South Africa from 18 - 22 October 2020, by the Southern African Institute of Mining and Metallurgy and was published in the conference proceedings (pp. 931 - 940).

PREFACE

This paper was the culmination of the initial testing and design phase, it further explored and conclusively proved that the method of winnowing can be used as a dry beneficiation method for fine coal. From a design point of view this paper indicated the turning point for the design of the equipment that was used to beneficiate the fine coal. This paper introduced for the first time the concept of a 2-stage winnowing demonstration plant (Figure 4.5 Chapter 4) that would be capable of beneficiating any -6 mm coal.

Horizontal airflow fine coal winnowing

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ABSTRACT

Dry coal processing is fast becoming favored as a fine coal beneficiation technique. The decline in suitable good-quality coal, as well as the ongoing decrease in usable process water, makes dry beneficiation of the fine coal fraction even more crucial. Dry fine coal beneficiation is relatively young with most of the methods still in the developmental phase. Additionally, many of the dry processing options available are better suited for coarser (+6 mm) and easy-to-beneficiate coal. Air winnowing for fine particles has been established in both agricultural and pharmaceutical industries, which indicates that the method can be used to separate smaller particles on a density basis and therefore, may prove effective in the coal industry as well.

A proof-of-concept study was conducted using both computer-based simulations (which do not form part of this paper) and physical experiments. The initial winnowing unit consisted of a closed box with a horizontal air stream flowing through the top section. Coal particles were injected into the air stream and displaced horizontally across a distance (x), depending on the particle size and density, thus actuating a separation based on these two parameters. For this study particle sizes of 6, 4 and 2 mm were used all with a density ranging between 1200 kg m^{-3} to 2000 kg m^{-3} . The simulation in Star CCM+ confirmed the findings of the mathematic behavioral model and provided a virtual representation of the separation using streamlines and particle tracks. The coal tests prove that size separation can be achieved at an airflow velocity of $21 \text{ m}\cdot\text{s}^{-1}$ and the density cut-point can also be predicted by using the prediction matrices constructed as part of this study. The results show efficiency values (EPM) of 0.11 and 0.09 at density cut-points of 1400 kg m^{-3} and 1500 kg m^{-3} , respectively.

The data obtained from the study indicates that air winnowing can be used to separate fine coal particles based on both size and density.

However, in order to achieve an efficient density separation, a narrow size range is required. With some improvements to the model, simulation, method and design, the separation efficiency can also be improved. The next phase of testing will include the upscaling of the process to a demonstration plant, optimizing the separation unit and testing the method on different qualities of coal.

Keywords: dry processing, fine coal, winnowing, simulation, tracers, demonstration plant

INTRODUCTION

For the past several years there has been a steady increase in the importance of dry fine coal beneficiation and with the decline in suitable good-quality coal (de Korte, 2015) and the ongoing decrease in usable process water, dry fine coal beneficiation has never been more important.

Fine coal

It is possible to obtain good-quality coal from previously discarded fine coal resources (Muzenda, 2014), with millions of tons of fine coal being generated each day as a result of mechanized mining. However, fine coal and the processing thereof does not come without drawbacks.

Fine coal beneficiation

Fine coal beneficiation is possible and numerous beneficiation methods are available. Some of the most effective and well-known techniques are spiral beneficiation and dense medium cyclones (DMC). These methods work by separating the coal particles based on the difference in their individual densities, but these processes require vast amounts of water.

Water based fine coal beneficiation

Luttrell, et al., (2014) states that fine coal beneficiation is mainly dominated by wet processes, and although these processes deliver the desired products, they require copious amounts of water which may prove problematic in some cases (de Korte, 2015). Several of these methods are available to beneficiate coal smaller than 6 mm and some information on these processes is provided below.

The most popular method for fine coal beneficiation in South Africa is the dense medium cyclone. This method has been proven to work on fine coal with acceptable efficiency at several different coal plants across the world, provided that the cyclone is properly set up and operated (Klima, et al., 2012). In general, the Ecart probable (EP) values, which is an indication of the misplaced particles as well as the sharpness of separation, for a wet separation process are in the order of 0.04, if small size coal is processed (Klima, et al., 2012). This is the objective for any process aiming to be an efficient fine coal beneficiation process.

Air based (dry) fine coal beneficiation

Wet processes may set the standard for fine coal beneficiation, but the current water shortage is forcing the coal processing industry to investigate alternative methods of fine coal beneficiation (Patil & Parekh, 2011). Dry coal beneficiation has been investigated on several occasions; however, most of the equipment and processes are still in the development stage, and the processes that have been commercialized do not yet match the processing capabilities of the wet methods.

Some of the processes developed such as the Fuhe Ganfa Xuan (FGX) and the air-dense-medium fluidized bed (ADMFB) have shown promise in the dry beneficiation of coal with EP values in the range of 0.05 to 0.12 (Hughes, 2018). These methods represent the benchmark for the efficient dry beneficiation of coal; however, they need to be improved even further to match the capacity and efficiency of the wet separation methods.

Widdowing as a dry separation method for fine coal

Widdowing is an age-old technique that has been used by the agricultural and pharmaceutical sectors for decades and several versions of this method have been developed over time. The original concept of widdowing used wind to blow away the lighter material while the heavier material stayed behind. The original method was implemented by hand, using a widdowing fork to throw material into the air, this allowed the wind to blow away the lighter (unwanted) material.

Over the years the method was adapted and further improved. The agricultural and pharmaceutical sectors developed several machines to simplify the widdowing process, for example the wind was replaced with an electrical fan to make controlling the airflow easier and thereby achieving better separation. The concept of widdowing was also tested on coal in 2008 (Sakhre, et al., 2018), and although the results were promising, widdowing as a dry beneficiation method for fine coal has not yet been implemented.

Principles of widdowing

Widdowing is based on the principle of using air and gravity to separate two particles by exploiting the difference in their mass. Mass (m) can be redefined as density (ρ) multiplied by volume (V), volume can be described as a function of size (s), which means

that particles of different sizes and densities can be separated using this method. The concept described above is shown in Figure 4.1, which illustrates the basic separation mechanism of winnowing.

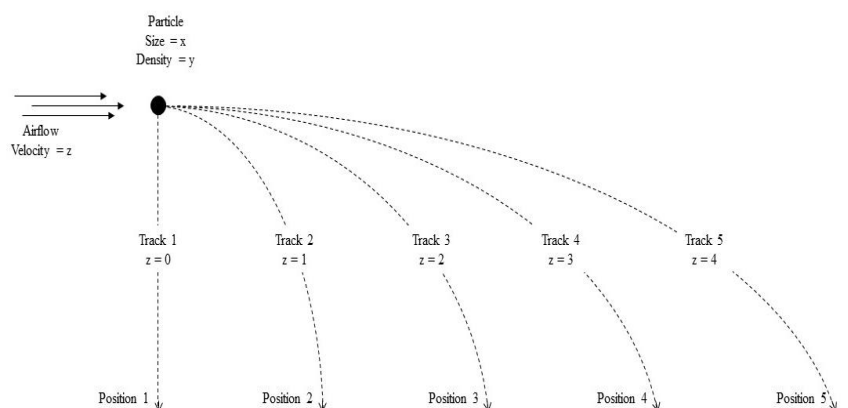


Figure 4.1. Particle trajectory diagram.

As seen in Figure 4.1 a particle with a constant size and density is placed into a crossflow airstream, the force applied to the particle by the air (depending on the airflow velocity (z)), along with the gravitational force acting upon the particle, determines the displacement of the particle. If no airflow is present the only force acting on the particle will be gravity and the particle will follow Track 1 to Position 1 as seen in Figure 4.1.

If the airflow velocity is increased $z > 0$ then the particle can follow any of the other tracks depending on the magnitude of z . Although several factors influence the particles displacement such as size, shape, density, airflow patterns and airflow velocity.

The main factors that will be investigated as part of the proof-of-concept study are the particle properties (size and density) and the airflow velocity. By changing these parameters, the displacement of each particle will be different, and this difference is what is needed to separate particles either by size or density.

EXPERIMENTAL

Laboratory-scale winnowing unit

A laboratory-scale horizontal winnowing box was designed by using a mathematical behavioral model (demonstrated and explained in Chapter 5 of this thesis) to determine the dimensions, as well as the required air flow velocity to achieve a certain horizontal displacement for a range of particle sizes and densities. The selected particle sizes for this study were 6, 4 and 2 mm with particle densities ranging from 1200 kg m^{-3} to 2000 kg m^{-3} in increments of 100 kg m^{-3} . The design for the winnowing box started with the concept of a closed box that has a single particle inlet, an air inlet and an air outlet as shown in Figure 4.2.

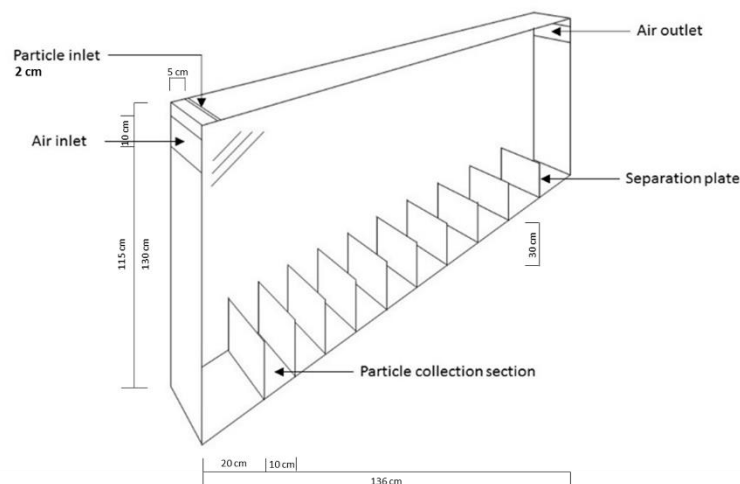


Figure 4.2. 3-Dimensional drawing of winnowing unit

As shown in Figure 4.2 particles enter the unit at the particle inlet, the air (flowing in from the air inlet) interacts with the particle and the particle is displaced into one of the collection sections. The section in which the particle lands is determined by the size and density of the particle.

EXPERIMENTAL CONDITIONS AND PROCEDURES

Widdowing operating parameters

As an initial proof of concept, several operating parameters will be selected, and the method will be tested by changing only the selected parameters. Once proof of concept has been established other additional parameters (such as shape, particle orientation and feed presentation) can be considered for further testing and optimization. The operating parameters selected for this study are selected based partly on the findings by (Sakhre, et al., 2018) combined with the general characteristics that may influence the displacement of any given particle. The selected parameters are listed in Table 4.1 below.

Table 4.1: Operating parameters for the widdowing experiment

Operating parameter	Selected range	Unit
Particle size	2, 4 and 6	mm
Particle density	1200 – 2200 with 100 kg m ⁻³ intervals	kg m ⁻³
Airflow velocity	10 – 30 with 5 m s ⁻¹ intervals	M s ⁻¹

Each one of these parameters can influence particle separation, for instance, the size and density of a particle contribute to its surface area and mass respectively, which in turn influences the displacement of the particle due to the forces of drag and gravity. The driving force behind the separation is the airflow velocity, if the velocity is too high it will cause all the particles to be blown out of the system, whereas insufficient airflow may lead to no separation.

Experimental procedure

The procedure followed for this experiment is explained using an example that is based on the actual values of the chosen operating parameters. The step-by-step procedure is described below.

1. The initial parameters are set at the lowest end of the values stipulated in Table 1 i.e., 10 m s^{-1} airflow, 2 mm particle with a density of 1200 kg m^{-3} .
2. After the experiment is completed using the above-mentioned parameters and the displacement (x) is recorded. The experiment is repeated 2 more times to ensure that the displacement data is accurate and that the experiment is repeatable.
3. After completion of step 2, the particle is changed to a 2 mm particle with a density of 1300 kg m^{-3} and the airflow is kept constant at 10 m s^{-1} . Step 2 is repeated, and the displacement data is recorded.
4. The airflow velocity and particle size are kept constant while the density is changed to the next value ranging from $1200 - 2200 \text{ kg m}^{-3}$ with increments of 100 kg m^{-3} .
5. Once all densities within the range have been tested and the displacement data has been recorded, the particle size is changed to the next size value as indicated in Table 1 and the density range is reset to start at 1200 kg m^{-3} with the airflow still set at 10 m s^{-1} .
6. Once all 3 size ranges have been completely investigated and recorded for the entire density range, the airflow velocity is changed to the next iteration in the range $10 - 30 \text{ m s}^{-1}$ and the procedure restarts with the new airflow velocity.

The procedure is completed when the data is recorded for the entire airflow velocity range, meaning that the data for the size and density ranges are recorded for each airflow velocity iteration.

RESULTS AND DISCUSSION

This section contains the results obtained from the winnowing experiment on -6 mm coal particles. The results shown here are used to demonstrate the key aspects and findings.

Coal particle displacement

Coal particles of different sizes were fed into the separation chamber and first the separation by particle size was tested. To test the method 4 mm and 6 mm particles are used for the size separation experiment at an airflow velocity of 21 m s^{-1} . Figure 4.3 illustrates the results obtained from the size separation where 2 sections are created inside the winnowing unit. Section 1 contains all particle displaced less than 0.36 m and section 2 all the particles displaced further than 0.36 m. This separation plate placement is chosen based on the results of a constructed model explained in Chapter 5 of this thesis.

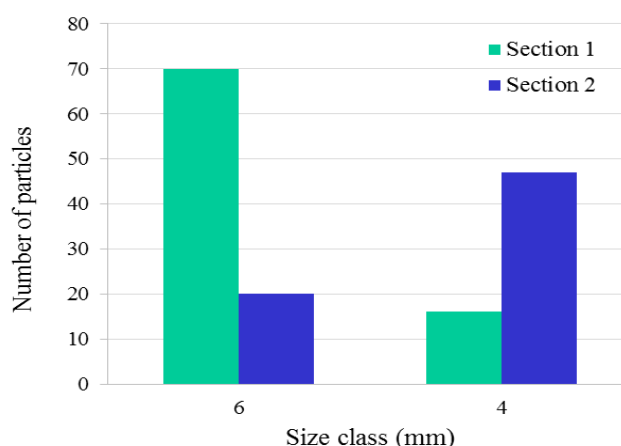


Figure 4.3. Particle size separation (multiple density)

As seen in Figure 4.3 most of the 6 mm particles reported to section 1 of the winnowing chamber ($< 0.36 \text{ m}$) with some passing over to the section 2 ($> 0.36 \text{ m}$). The 4 mm particles mostly reported to the furthest section (section 2) with some particles reporting to section 1. As seen in the figure it appears that a size separation between particles can be achieved with very little overlap between sections. The overlap observed is most likely caused by the density of the particles, where low density ($1200\text{-}1400 \text{ kg m}^{-3}$), 6 mm, particles move over to section 2 and high density ($1900\text{-}2200 \text{ kg m}^{-3}$), 4 mm,

particles fall short and report to section 1. Another possible factor causing the overlap is the fluctuating airflow or turbulence caused by backflow inside the separation chamber, which, causes the force acting on the particle to be inconsistent and as a result, the separation is affected.

The second stage of the experiment tested the density separation capability of the winnowing method. The procedure was followed, and the results were tabulated into 3 matrices (2 mm, 4 mm, and 6 mm displacement data). As an example, the 6 mm displacement matrix is shown in Table 4.2, where the displacement of each particle (in cm) is provided.

Table 4.2: 6 mm particle displacement matrix in cm

Airflow velocity (m s ⁻¹)	Density (kg m ⁻³)							
	1300	1400	1500	1600	1700	1800	1900	2000
12	31	28	25	24	23	22	21	20
13	35	31	28	26	25	24	23	21
14	39	36	33	30	28	26	25	24
15	41	38	35	33	30	28	27	25
16	45	41	38	35	33	30	28	26
17	48	44	40	38	35	33	30	28
18	51	48	44	41	38	35	33	30
19	55	51	48	44	40	38	35	33
20	60	56	51	48	44	41	38	35
21	65	60	55	51	48	44	41	38
22	70	65	60	56	53	48	44	40
23	78	73	68	63	58	53	49	45
24	85	80	75	69	64	59	54	49
25	94	88	81	76	70	65	59	54
26	105	98	91	85	79	73	66	60

The prediction matrix can be used to determine the displacement of a 6 mm coal particle if the density and airflow velocity are known. For example, at an airflow velocity of 15 m s^{-1} a 6 mm particle with a density of 1500 kg m^{-3} can be displaced 35 cm. The matrix can also be used to identify the density of a specific particle if the displacement and airflow are known.

Using the prediction matrices above a density separation experiment was conducted. The end result of the density separation experiment was to test if it is possible to predict a cut point density and achieve the prediction with the winnowing method. The results of the experiment are shown in Figure 4.4 and Table 4.3.

Figure 4.4 shows the graphical representations of the results obtained from the density separation where a density cut point was predicted (from the matrix) and tested with the winnowing unit. The theoretical cut point was calculated and the comparison between the two values are shown in Table 4.3. This curve is for a 6 mm particle at a predicted density cut-point of 1500 kg m^{-3} , and although other cut-points have been tested only this one will be used for demonstration purposes.

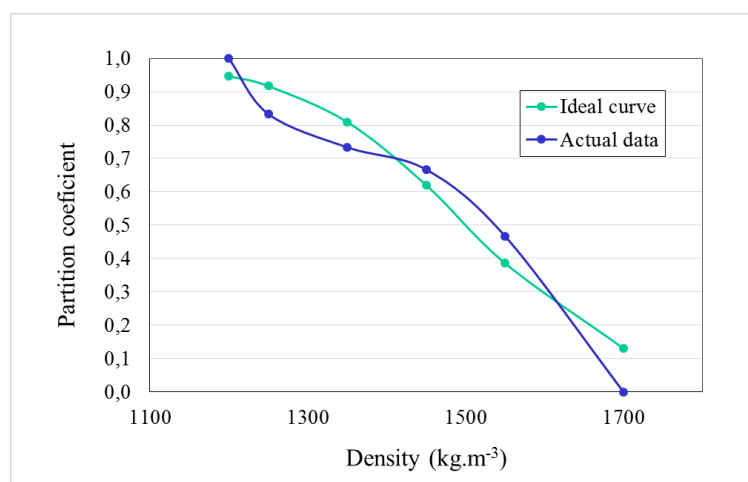


Figure 4.4. Partition curve – target density cut-point 1500 kg m^{-3}

As seen in Figure 4.4 the ideal curve is the trend line (theoretically calculated) and the actual data scattered around the ideal curve is the data obtained from the experiment. The actual data is closely scattered around the ideal curve which indicates that under

more ideal circumstances, such as a non-fluctuating laminar airflow, the data can move even closer to the ideal separation curve.

Table 4.3 shows the results for 2 separate experiments done with 6 mm particles, tested on a single particle feed basis, at low density cut-point predictions.

Table 4.3: Performance data for the density separation at predicted cut-point densities using 6 mm particles.

Target cut point	1400 kg m ⁻³	1500 kg m ⁻³
Actual cut point	1370 kg m ⁻³	1480 kg m ⁻³
Wedge position	0.60 m	0.55 m
Yield (by number of particles)	55.56 %	71.74 %
EP	0.117	0.099

The density cut-point prediction was tested based on the wedge positions indicated in the prediction matrix. The selected density cut points for the coal test were set low to determine if the method can be used to achieve separation at very low cut-points. The selected cut-points were set at 1400 kg m⁻³ (0.6 m wedge position) and 1500 kg m⁻³ (0.55 m wedge position). The 1500 kg m⁻³ cut-point reached a yield of 71.74 % at a relatively low EP value of 0.099, while the 1400 kg m⁻³ cut-point prediction shows a yield of 55.56% at a higher EP value of 0.117. The calculated EP values are relatively high compared to the EP value of 0.04 achieved by most wet separation processes. The achieved cut-point values differ slightly from the actual cut point values which indicates that the prediction can be made with a relatively high degree of accuracy.

CONCLUSIONS

When taking into account all the data obtained from the study, the separation unit and method overall showed acceptable performance and the EP values obtained (although higher than those of the wet processes) are well within the range of other existing dry beneficiation methods. The coal test was the final indicator that separation can be achieved with this method and with the data obtained it can be concluded that winnowing can be used as a dry beneficiation method for fine coal.

Herein the method of winnowing was proven to work although there are some factors that influenced the results. These factors include fluctuating airflow, dust formation, breakage of the particles and even particle shape and feed orientation. If these factors can be improved or better understood, the method could possibly deliver a better result.

Future work for the winnowing method does not only include the optimization and improvement of the current winnowing unit but also the investigation and implementation of several new concepts and designs.

The concept of winnowing has been proven to work on a single separation unit; however, the idea is to expand the method to a fully functional, pilot plant. Figure 4.5 shows the initial design concept (not to scale) for the pilot scale winnowing process.

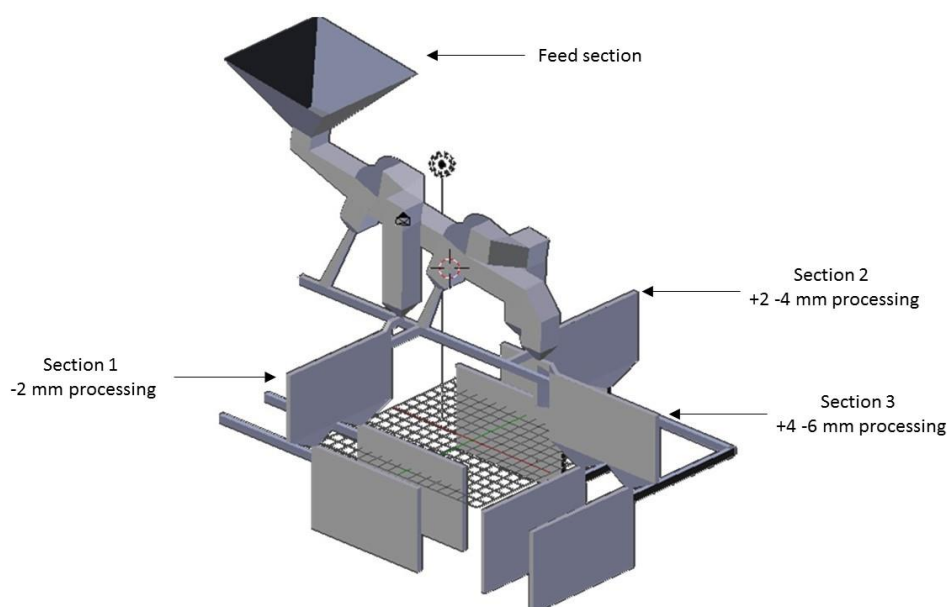


Figure 4.5. Winnowing demonstration plant

As seen from Figure 4.5 the process will consist of three sections, the first will be dust extraction to eliminate any -2 mm particles, the second will remove all +2 -4 mm particles and the final stage will consist of the +4 -6 mm particles. Within each section, a second size separation will take place, for example in the last section the +4 -6 mm particles will be sorted into two size classes. Then the sorted size classes are re-sorted according to density in the final step. This is done to obtain various products of different densities.

The pilot plant is to be constructed and commissioned to further experiment with the concept of winnowing and will be the culmination of the research that has been completed on the method of winnowing to date.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial and technical contribution made by The Coaltech Research Association NPC Ltd., and the Centre of Excellence in Carbon Based Fuels, North-West University, South Africa.

This work is based on the research supported in part by the National Research Foundation of South Africa (Coal Research Chair Grant Numbers: 86880; and UID85643, UID85632). Any opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF supported research is that of the author(s) alone, and that the NRF accepts no liability whatsoever in this regard.

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ADDITIONAL NOTES

This concept of a demonstration plant is further explored in the Chapters to follow leading up to the commissioning of the demonstration plant in the final paper (Chapter 6). Since the initial design, several changes and improvements have been made as can be seen by comparing the design sketches in the different chapters (Figure 2.3 Chapter 2, Figure 3.2 Chapter 3, and Figure 4.2 Chapter 4).

During the testing phase the results obtained indicated several issues that needed to be addressed if the method and the demonstration plant was to be successfully implemented. These results lead to a complete redesign and reconfiguration of not only the winnowing unit but the winnowing method as well. The problems outlined by the results as well as the steps implemented to solve them are listed below:

1. **Problem – Turbulent airflow leading to fluctuating forces in the winnowing unit and thus misplacing particles.** The turbulence in the airflow was caused by the air being blown into the system and forming eddies as it travels along the separation unit. The turbulence increased as the air reached the end of the separation chamber and started to hit the wall causing a backflow and thus hindering the separation.
 - Solution – converting the system from a positive pressure driven separation (blowing) to a negative pressure driven separation (suction), a system operating on the negative pressure showed to be less turbulent and would provide a more reliable separation with less misplaced particles.
2. **Problem – Conversion to suction** required higher airflow to achieve the same separation previously achieved by blowing air through the system. Although the turbulence issue was solved the suction power required was much higher than the power required by the blower, and the amount of air that had to be moved through the unit was too much for the separation to be effective.
 - Solution – Redesigning the winnowing unit and making it as narrow as possible as well as removing dead spots to improve the airflow through the unit and effectively improving the separation, this redesign is shown in Chapter 6. As part of the redesign a new behavioral model and simulation

(Chapter 5) had to be done to ensure that the changes are correctly incorporated.

3. **Problem – Dust formation** during the operation of the machine. As the particles were fed a lot of dust would be blown into the air. Since this is a dry separation method this problem was to be expected.

- **Solution** – The conversion from a positive to negative pressure system to counteract the turbulence also solved the dust formation problem as the suction would also remove all the dust from the system and collect it at a later stage, in a filter.

All these problems were addressed, and the solutions implemented as part of the new design and modeling processes that are shown and further explained in the chapters that follow.

Chapter 5

Designing a Fine Coal Winnowing Demo Plant

Design and mathematical behavior model for a fine coal winnowing pilot plant

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This peer-reviewed paper was presented at the Southern African Coal Processing society biennial Technical Conference held in Secunda, South Africa from 12 - 14 October 2021, by the Southern African Coal Processing society and was published in the conference proceedings.

PREFACE

To design the demonstration plant from the concept shown in Chapter 4, an in-depth understanding of the separation mechanism was needed. This paper outlined the equations, assumptions, and design philosophy used to ultimately design the working prototypes needed for the demonstration plant. Furthermore, a virtual environment was created using the equations in this paper to simulate the separation behavior. The virtual environment served as a pre separation test to aid with critical parameter selections such as air velocity, particle impact speeds, and particle location/behavior within the separation units.

Design and mathematical behavior model for a fine coal winnowing pilot plant

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ABSTRACT

The generation of fine coal through day-to-day mining and processing activities is unavoidable and thus the technology that is used to beneficiate fine coal is constantly evolving. Environmental factors such as water shortage and waste management, motivate the research not only in fine coal beneficiation but also in dry fine coal beneficiation. One of the more recent developments in dry fine coal beneficiation is the use of the winnowing method which has been successfully implemented in the agricultural sector for many years. Several studies have shown that the method can be used to beneficiate fine coal, however there is still very little data available on the method, other than lab scale experiments. Research suggests that the separation of coal particles (by size, shape, and density) is possible with this method; however, previous studies have shown the system to be size sensitive and that a 2-stage separation is needed to beneficiate the fine coal.

To test this a mathematical behavioral model was constructed and data was generated to prove that the method can be used for the dry beneficiation of fine coal. The data suggests that separation is possible, and it confirmed that the processes needed to be split into two stages. The first stage is a size separation with a very narrow PSD (2:1 distribution) and the second stage is a density separation to ensure that the size sensitivity of the system is counteracted. The results from the model along with the CFD simulations were used to design a pilot plant that operates on the winnowing principle; however, instead of using a blower to generate the required airflow, the plant is designed to operate completely under suction. This stabilizes the airflow and aids with the dust control in the system.

The two major components in the plant are the separation nozzle (used for size separation) and the separation chamber (used for density separation). The design is focused around these two components as they make up most of the plant. The first prototypes for these two components have been constructed and the results from these prototypes will help to further understand the method and optimize the design for the pilot plant which is to be constructed by the end of 2021.

Keywords: dry processing, fine coal, winnowing, prototype, pilot plant

INTRODUCTION AND BACKGROUND

Power generation from coal plays a key role in the economic growth and development in many countries around the world (Ramudzwagi, et al., 2020; Xie, et al., 2020; Zhao, et al., 2015), this is because coal is the largest contributor to the generation of electricity (Ritchie & Roser, 2020). Through daily mining, transport and processing activities that are needed to produce the coal several million tons of coal fines are generated annually, amounting in billions of tons of fine coal available for reprocessing globally (Ramudzwagi, et al., 2020). In the past these fines were either discarded or added to the steam coal, however; in the past several years fine coal beneficiation has increased and by using wet separation methods such as spirals and dense-medium cyclones, fine coal beneficiation was made possible (Fourie, et al., 1980; Ramudzwagi, et al., 2020; Zhao, et al., 2015). These methods do require large amounts of water and with South Africa being a water scarce country, using these methods to beneficiate the fine coal is not always possible (de Korte, 2015). The alternative, which is being considered and researched worldwide, is dry beneficiation. Dry processing of coal does not require any water and has several other economic and environmental advantages, such as being able to use these methods in arid and semi-arid regions to beneficiate the fine coal (Ghosh, et al., 2014). There are disadvantages to these dry processing methods as well, the biggest one being that these dry beneficiation methods do not match the processing capability of the wet separation methods (Hughes, et al., 2019).

This disadvantage creates an opportunity for new dry beneficiation methods to be developed, with the aim of aiding current wet separation systems or matching the separation capability of the wet systems already in place. One of the methods that has been investigated in the past several years is the method of coal winnowing. Winnowing is an agricultural technique used to separate a variety of products from unwanted stones and waste (Sakhre, et al., 2018). Recent studies have shown that winnowing can be a viable method for the beneficiation of -6 mm coal (Morgan, et al., 2019), however; there is very little data available on using this method aside from lab scale experiment results. The study did point out several problem areas that need to be further investigated if the method is to be used for fine coal. These included dust control, particle shape and

unstable airflow. All these factors influence the separation efficiency and need to be addressed for this method to work.

To better understand the mechanics behind this method it is necessary to first construct a mathematical model that will be able to predict the behavior of a particle within the winnowing system. (Lawson & Marion, 2008) states that a model is a description of how people believe the world works, they further state that those beliefs can be translated into mathematic equations. This can be done by combining what is known about a system and making certain assumptions to fill in the gaps that are too complex to model. The model is never fully complete and can be improved constantly as more facts about the system becomes known.

MATHEMATIC MODEL - THEORETICAL CALCULATION

To model and design the winnowing system as accurately as possible, it is necessary to understand the forces acting on a single particle that enters the system. Figure 5.1 shows all the forces that would act on a single spherical particle from the moment it enters the system until it reaches the density classification bin.

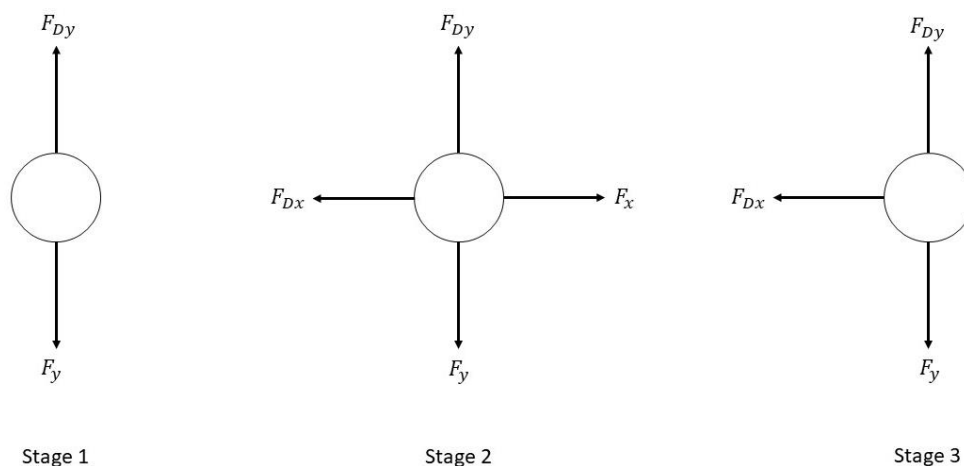


Figure 5.1: Forces acting on a single particle.

There are three main stages within the system, Stage 1 is where the particle enters the system, and it falls under the influence of gravity only. This means that there will be two

forces acting on the particle, which is gravity (F_y) and a drag force which will be in the opposite direction (F_{Dy}). Stage 2 is when the particle enters the horizontal airstream and an external force (air) acts on the particle. The force (F_x) applied by the air pushes the particle in a horizontal direction and this in return causes a drag force (F_{Dx}) in the opposite direction. For as long as the particle remains within the airstream F_x will be applied to the particle increasing the horizontal acceleration of the particle. Stage 3 is when the particle exits the airstream and it is once again falling under the influence of gravity, however; since the particle is already moving in a horizontal direction there will still be a horizontal drag force, and this will cause the particle to slow down because the force (F_x) is no longer being applied. Using these three stages the entire system can be modelled.

Starting with stage 1, and using the y direction (vertical) only, then:

$$F_{Ty} = F_y - F_{Dy} \quad [1]$$

Thus, the total force in the y direction (F_{Ty}) can be calculated by subtracting the drag force from the gravitational force.

To track the position of the particle as it passes through the system the velocity and y position of the particle can be calculated using the respective equations below.

$$v_y(t + \Delta t) = v_y(t) + a_y(t)\Delta t \quad [2]$$

v_y = vertical velocity

a_y = vertical acceleration

t = time

Δt = Selected change in time

Where $a_y = g - \frac{\frac{1}{2}\rho C_D \pi r^2 v^2}{m_{particle}}$ and $\Delta t = 0.01$ seconds

g = gravitational acceleration

ρ = Air density

C_D = drag coefficient

r = particle radius

$m_{particle}$ = particle mass

And

$$y(t + \Delta t) = y(t) + v_y(t)\Delta t \quad [3]$$

y = vertical position

v_y = vertical velocity

t = time

Δt = time interval

When converting the system to suction (meaning a particle is lifted vertically) then an external force is added to Equation 1 (F_{Air}) and the sign of the gravitational force changes because the particle is now moving in the opposite direction (Figure 5.2) and thus:

$$F_{Ty} = F_{air} - F_y - F_{Dy} \quad [4]$$

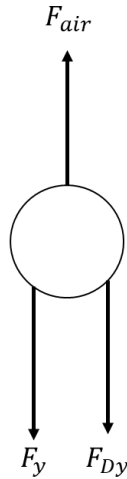


Figure 5.2: Vertical lift force diagram

The same logic applies to the movement of a particle in the x (horizontal) direction, however; in this case a particle cannot move horizontally without applying an external force. This is illustrated in stage 2 of Figure 5.1 where F_x (the external force) and F_{Dx} (the horizontal drag force) are added to the diagram.

To calculate the movement in the horizontal direction the same approach can be used as above, this means that the total force in the x direction is calculated with the equation:

$$F_{Tx} = F_x - F_{Dx} \quad [5]$$

And the velocity and x position of the particle can be calculated using equations 6 and 7, respectively.

$$v_x(t + \Delta t) = v_x(t) + a_x(t)\Delta t \quad [6]$$

Where $a_x = \frac{m_{air}a_{air}}{m_{particle}} - \frac{\frac{1}{2}\rho C_D \pi r^2 v^2}{m_{particle}}$ and $\Delta t = 0.01$ seconds

$m_{air} = \text{air mass}$

$a_{air} = \text{air acceleration}$

And

$$x(t + \Delta t) = x(t) + v_x(t)\Delta t \quad [7]$$

Combining the movement in the x and y directions will create a two-dimensional plot of how the particle behaves within the system. The movement of the particle is dependent on the particle properties such as shape, size, and density and by changing one of these properties the behavior of the particle will change as well, this is illustrated in Figure 5.3.

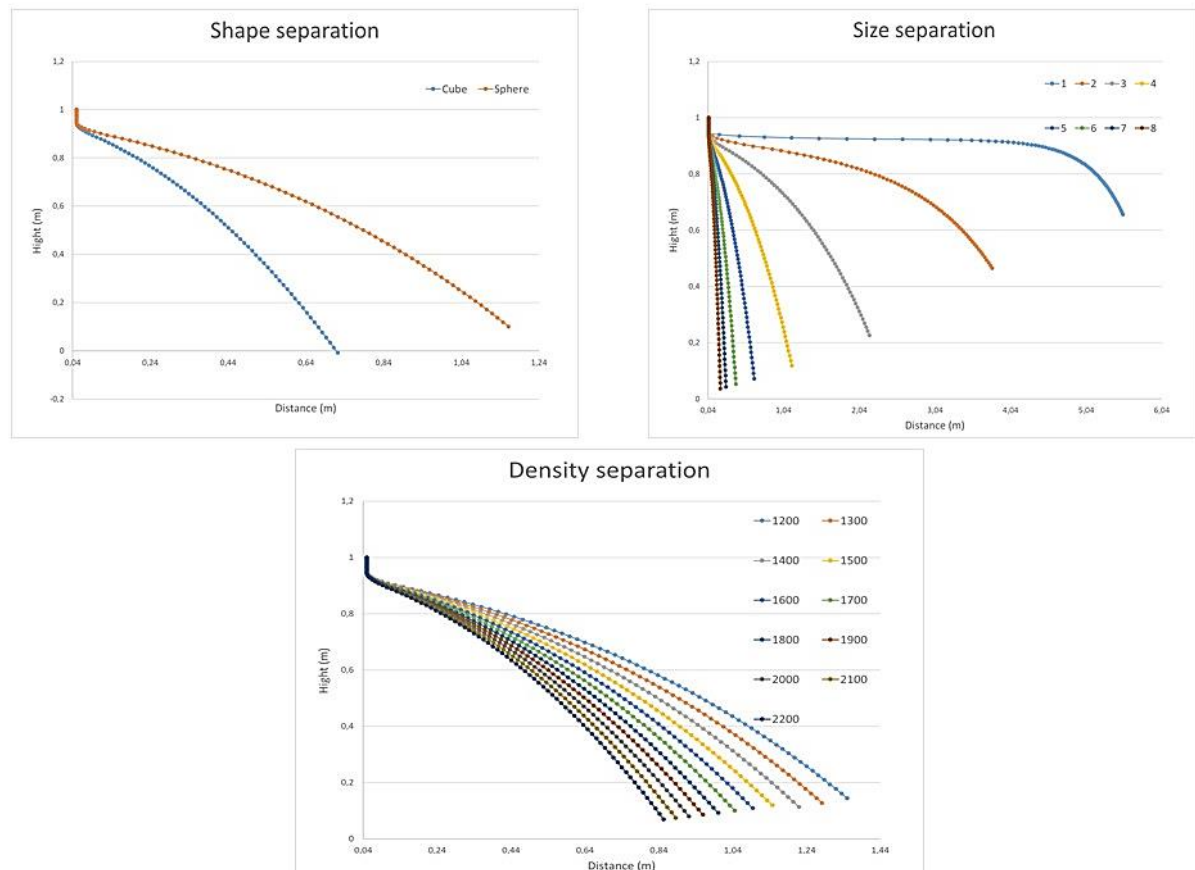


Figure 5.3: Separation of particles based on physical properties.

As seen in Figure 5.3, a change in either shape (top left), size (1 mm to 8mm on the top right) or density (bottom) will result in a change in the particles trajectory and directly influence the displacement. The properties with the largest influence on the displacement are the particle shape and size as can be seen in Figure 5.3. The displacement in the x direction can also be larger or smaller for a particle with constant physical properties, depending on the airflow velocity of the external force as shown in Figure 5.4.

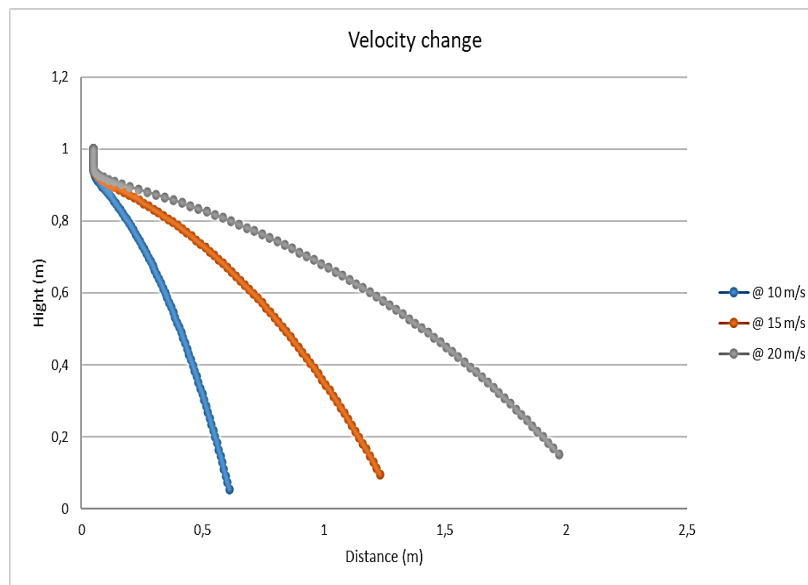


Figure 5.4: change in particle displacement with respect to airflow velocity change

The external force increases or decreases depending on the airflow velocity and thus a larger airflow velocity means a greater force acting on the particle and this leads to a larger displacement.

DESIGN RESULTS

The previous study used a basic design for the winnowing unit and when converting the original winnowing system to suction several problems were detected.

- The dimensions of the winnowing unit had to be changed to accommodate the suction. The original box was too wide and slowed down the airflow to a point where the force acting on the particle was so small that no displacement occurred and thus the width of the box was decreased to 20% of the original width.
- The box was also not high enough to allow for adequate fall time of particles. The fall time after initial separation allows particles to spread out. If the fall time is too short the particles do not separate sufficiently, if the fall time is too long then the particles have the risk of breaking on impact due to a high gravitational acceleration.

- The original design also had several dead spots where air would get trapped or start to tumble causing updrafts that would affect the separation efficiency of the winnowing unit. To eliminate this a large section of the box was removed and the suction inlet was moved closer to the particle inlet allowing air to be sucked out of the system immediately before too much turbulence occurs.

The new design can be seen Figure 5.5, with the suction attachment on the left-hand side and the particle inlet located on the right. The particles are fed to the chamber with an automated feeder to ensure an even and constant flow to the unit.

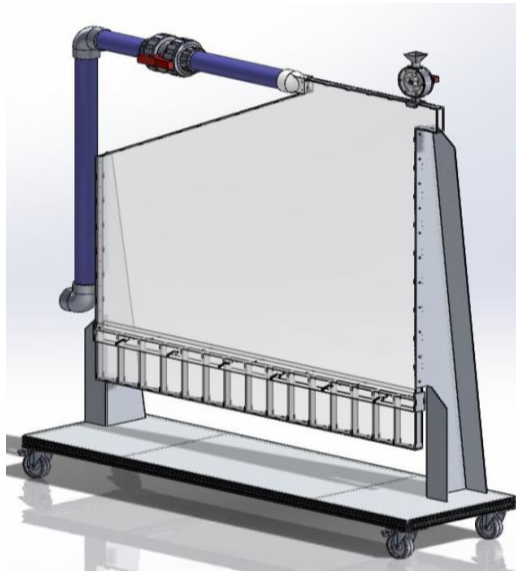


Figure 5.5: Redesigned winnowing unit

The previous study also indicated that a 2-stage separation was necessary for the system to be effective. This means that two winnowing units would have to be placed on top of one another, where the first unit will do a size separation and the second will do the density separation. This would have been necessary if the blower were still used to generate the airflow, however since the system has been converted to suction the option is available to use the suction with a nozzle to pick up the particles based on their size and then send the different size classes to individual winnowing units for density separation. The suction head needs a consistent airflow to ensure that the correct particles are picked up.

Several designs were considered for this application ranging from regular vacuum cleaner attachments to a single small PVC pipe. Airflow simulations were conducted on all the different designs to see which one fit the design specification, and after completing all the simulations, one design (Figure 5.6) was selected.

The selected particles are lifted through the small tubes of the nozzle (labeled A in Figure 5.6) and transferred to the collection bin (B in Figure 5.6). The blue pipe is connected to the suction fan and a y strainer is used to separate the particles from the air stream at point C. The size of the particle that is lifted can be determined by adjusting the airflow to the nozzle using the valve (on the right) that has been installed on the suction line.

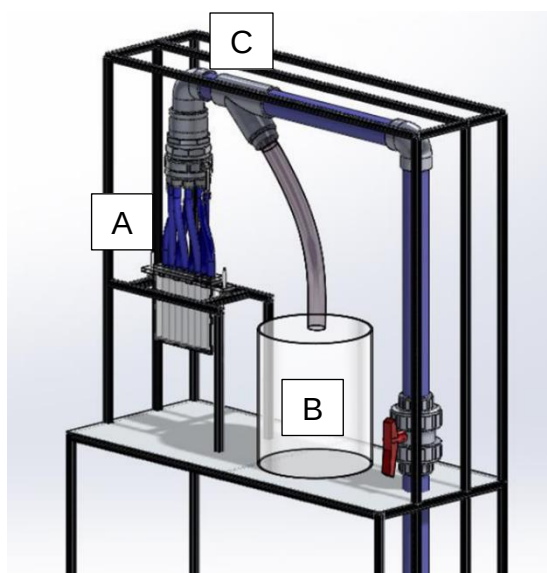


Figure 5.6: Size separation nozzle

By combining the two units in a single 2-stage separation system a dry beneficiation plant can be created. The pilot plant design is shown in Figure 5.7. The nozzles sort the particles according to size and transfer the different size classes to the winnowing units. The Winnowing units then further process the size classes and sort the particles by density (according to the users set density cut point).

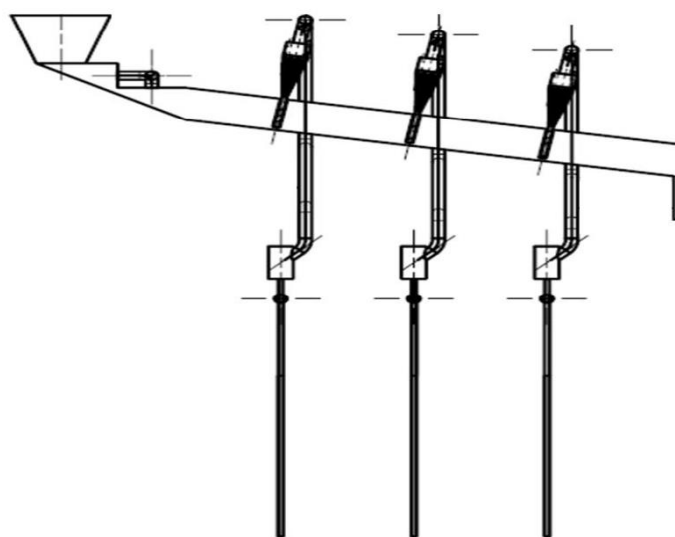


Figure 5.7: Dry beneficiation pilot plant

CONCLUSION

Using the particle behavior from the mathematical model as well as several CFD simulations (As shown in the additional Notes of this chapter) to confirm the results, the final designs for both the winnowing unit and the separation nozzle were completed. The nozzle sorts the particles into a 2:1 size ratio over the range of 1 – 6 mm and the product is then used in the winnowing unit. The winnowing unit separates the size class by density with the density cut points set by the user, these cut points can range from 1400 to 1800 kg m⁻³. From the model it was also noted that a shape separation can be achieved using the winnowing method and if needed an additional “shape sort” will be added to the pilot plant as a preparation step before the particles undergo the first size separation.

The first prototypes (Figures 5.5 and 5.6) have been constructed, and the first coal tests are underway to further optimize and improve the current designs before the construction of the final pilot plant which is scheduled for completion in early 2022. The preliminary results from both the nozzle and winnowing unit indicate an effective separation.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions made by the following organizations, financially and technically.

- The Coaltech Research Association NPC Ltd.,
- The Southern African Coal Processing Society
- The Centre of Excellence in Carbon Based Fuels, North-West University, South Africa.

This work is based on the research supported in part by the National Research Foundation of South Africa (Coal Research Chair Grant Numbers: 86880; and UID85643, UID85632). Any opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF supported research is that of the author(s) alone, and that the NRF accepts no liability whatsoever in this regard.

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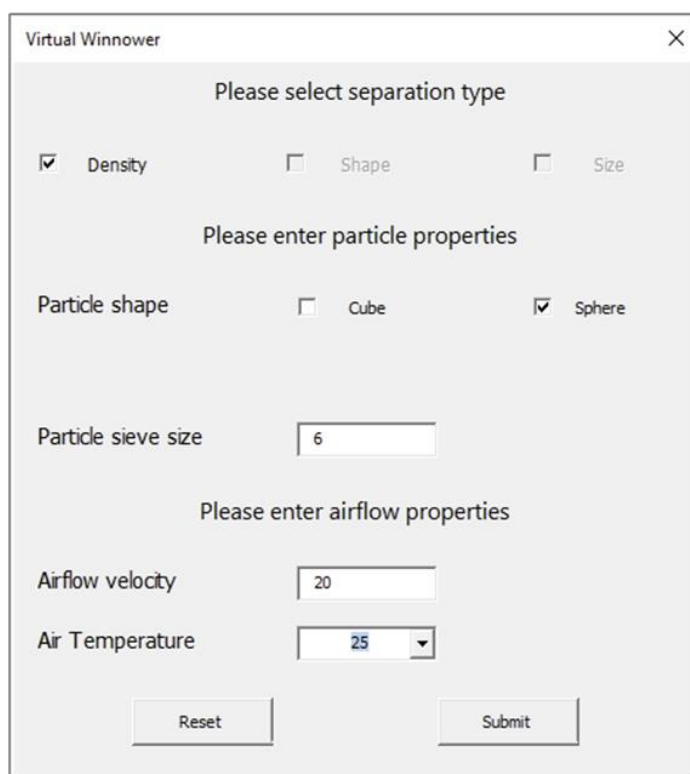
ADDITIONAL NOTES

As part of this paper, the equations derived during this study were used in Microsoft Excel to set up a virtual winnowing program that was used to generate the graphs seen in Figures 5.3 and 5.4 in Chapter 5. The program's user interface (Figure 5.8 below) allows the operator to select the separation parameters and simulate the separation to get an idea of what the outcome would be if the actual separation were to be done in the winnowing unit.

The figure shows the user interface for the 'Virtual Winnower' program. It consists of two main parts. On the left, there is a vertical panel with two buttons: 'Start Virtual Winnower' and 'Reset Virtual Winnower'. On the right, there is a larger window titled 'Virtual Winnower' with a close button (X) in the top right corner. This window is divided into three sections. The first section, 'Please select separation type', has three radio buttons: 'Density' (which is selected), 'Shape', and 'Size'. The second section, 'Please enter particle properties', includes 'Particle shape' with two radio buttons 'Cube' and 'Sphere', 'Particle density' with a text input field, and 'Particle sieve size' with a text input field. The third section, 'Please enter airflow properties', includes 'Airflow velocity' with a text input field and 'Air Temperature' with a dropdown menu. At the bottom of the window are two buttons: 'Reset' and 'Submit'.

Figure 5.8 Virtual winnower user interface

The user interface allows the operator to choose 1 of 3 separation types, either a density, shape, or size separation. Depending on the separation type selection, the input parameters for the particle properties will differ as shown in Figure 5.9. Furthermore, the user is asked to enter the air properties to complete the separation parameters. After clicking the submit button the program does the necessary calculations based on the user input and provides a graphical representation of the expected separation as demonstrated in Figure 5.10.



The screenshot shows a web-based application window titled "Virtual Winnower". It contains three main sections for user input:

- Please select separation type:** Three radio buttons are present. "Density" is selected (checked), while "Shape" and "Size" are unselected.
- Please enter particle properties:**
 - Particle shape:** Two radio buttons are present. "Sphere" is selected (checked), while "Cube" is unselected.
 - Particle sieve size:** A text input field containing the value "6".
- Please enter airflow properties:**
 - Airflow velocity:** A text input field containing the value "20".
 - Air Temperature:** A dropdown menu with "25" selected.

At the bottom of the form, there are two buttons: "Reset" and "Submit".

Figure 5.9 Demonstration of user input.

To demonstrate the virtual winnower a density separation is selected, the particle shape for the demonstration was chosen to be spherical with a sieve size of 6 mm. As for the air velocity it was selected as 20 m s⁻¹ at an air temperature of 25°C. With all the parameters filled, the submit button is clicked and the following result is returned.

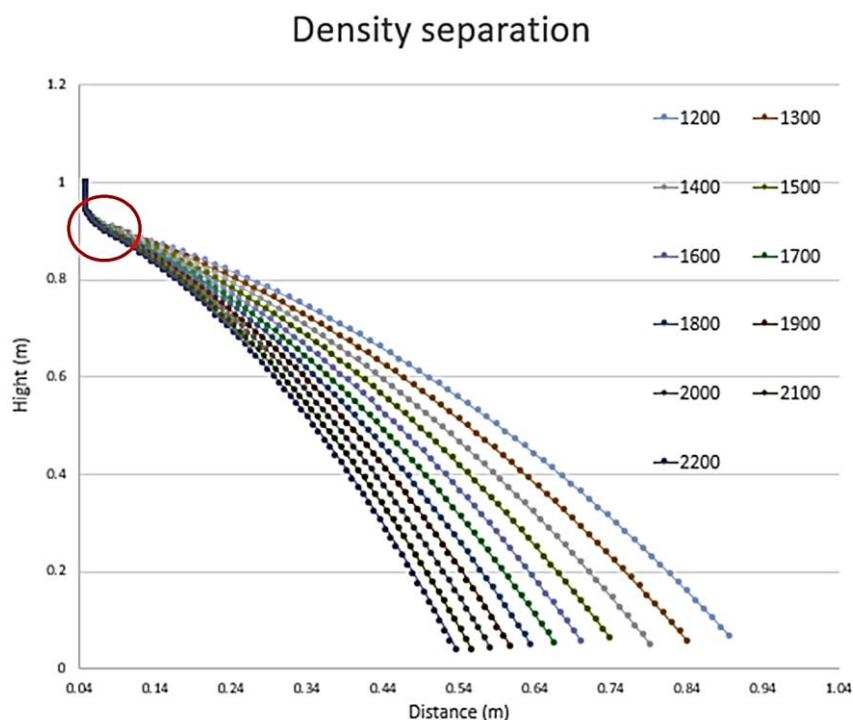


Figure 5.10 virtual density separation result

The density separation results show the particle tracks and impact points for all the 6 mm particles in the density range 1.2 to 2.2 g cm⁻³ when an air velocity of 20 m s⁻¹ is used (note that the air velocity is dependent on the air inlet geometry and area and can differ if the design is changed). As seen from Figure 5.10 the current parameters can be used to achieve some separation based on the density of the particles, however the separation distance (displayed on the x axis) is very narrow and thus a precise separation with a 0.1 g cm⁻³ density interval would be difficult. If a larger interval is selected for example a 0.3 g cm⁻³, then separation becomes easier and multiple products can be obtained. The alternative would be to increase the air velocity and redo the simulation to increase the separation distance between particles of different densities. The above-mentioned observations regarding the separability of particles are why the virtual winnower was created, it allows the user to see potential problems before hand and correct them before attempting the separation in the actual winnowing unit.

The virtual winnower has one other added feature that aides with the design and understanding of the winnowing method in general and that is the ability to show the influence of the air on the particles as they enter the separation unit (circled in red on Figure 5.10 and zoomed in on Figure 5.11).

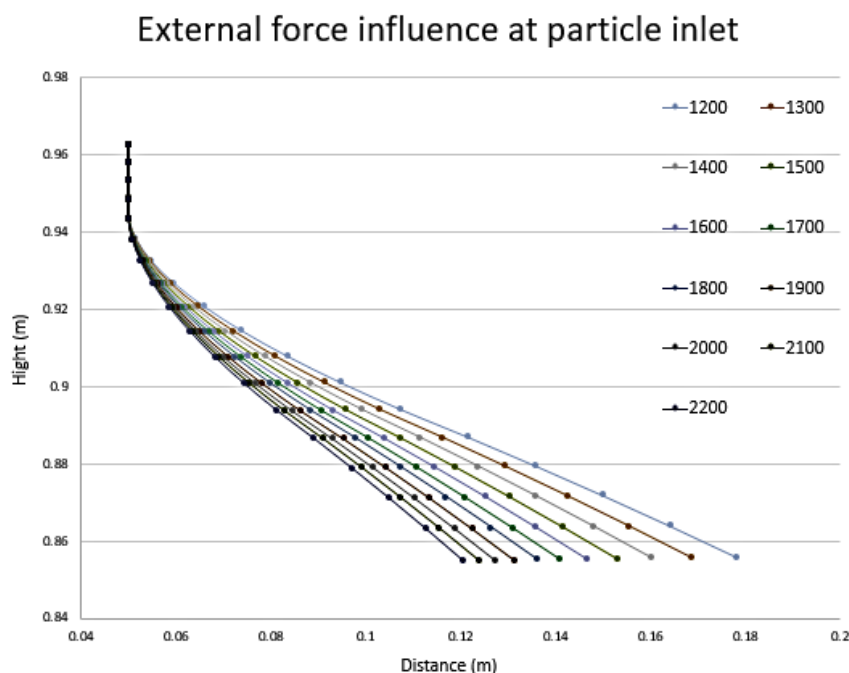


Figure 5.11 Influence of air on entering particles.

As the particles enter the system the force generated by the air influences the particles movement and the external force exerted by the air on the particles will cause the particles to move in a horizontal direction. Figure 5.11 shows the exact moment where the separation of particles takes place and as shown in the figure, higher density particles are less effected by the air than the lower density particles and thus the displacement of the higher density particles is much less. Similarly, the separation of particles by size and shape can be tested using the virtual winnower and the results from these tests were ultimately used to design the prototypes and the demonstration plant.

The prototypes shown in Figures 5.5 and 5.6 were initially simulated using CFD to ensure that the dimensions and airflow of the units were correct before constructing the prototypes. Figures 5.12 and 5.13 show the results from the airflow analysis done with the CFD software.

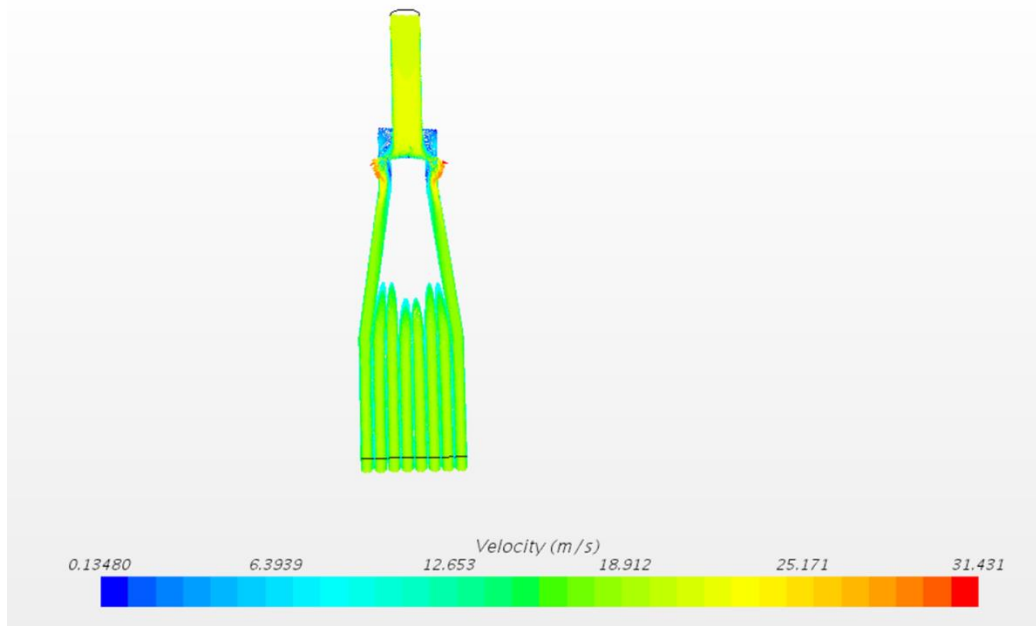


Figure 5.12: Airflow simulation of size separation nozzle

As seen in Figure 5.12 the airflow is very uniform through each one of the nozzles, indicating that the air velocity is constant as it moves through the nozzle. This is important as a constant velocity is crucial when using the nozzle to ensure that only certain size particles are lifted. By controlling the airflow to the nozzle, the air velocity can be increased or decreased. An increase in velocity means larger particles can be lifted while a decrease would have the opposite effect leaving the larger particles behind and in effect creating a size separation.

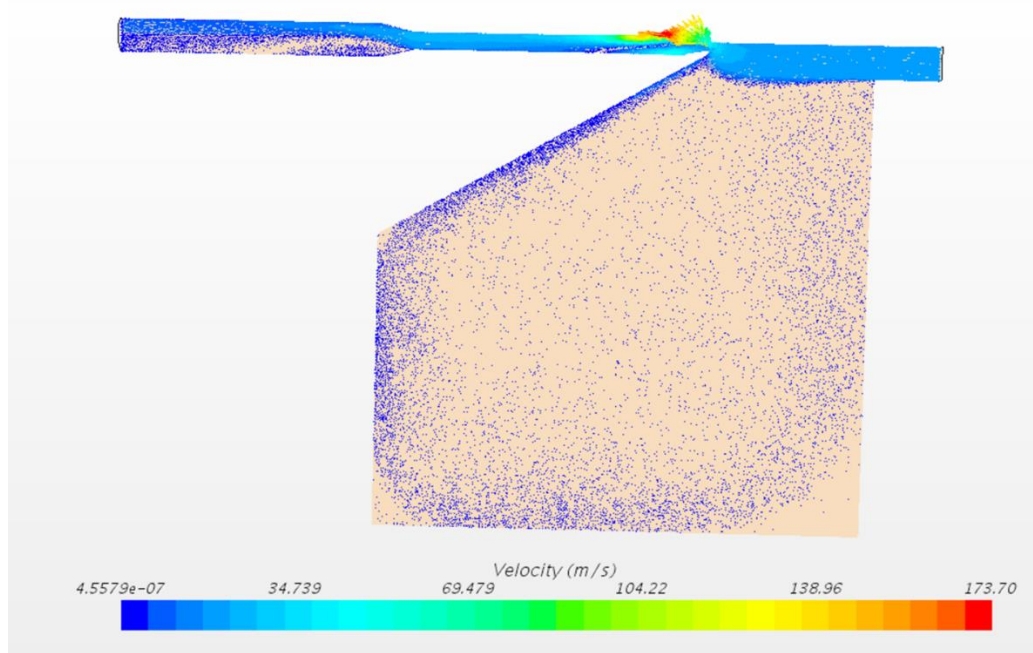


Figure 5.13: Airflow simulation of density separation chamber

The airflow simulation that was performed on the density separation chamber shown in Figure 5.13 indicated that the negative pressure system was indeed eliminating the turbulence experienced with the first separation units. As seen in the figure very little air is circulated to the bottom section, meaning that there is a decreased chance of interference caused by an updraft or potential backflow. As for the separation section at the top the air that enters, and is pulled through the unit, shows very uniform flow. The air velocity appears to be stable which is important when using this method to separate particles, because a constant air velocity means that a constant external force is applied to all the particles and thus the only factor influencing the separation is the particle properties.

These prototypes were used during the testing phase and after completion of the study some alterations were made to the prototypes in preparation for the final plant assembly. The altered units are shown in Figures 5.14, 5.15 and 5.16 and the results obtained from testing the units are presented in the following chapter.

Construction of the pilot plant was completed in 2022 and Figure 5.14 shows the completed winnowing plant that was used for the tests in Chapter 6.

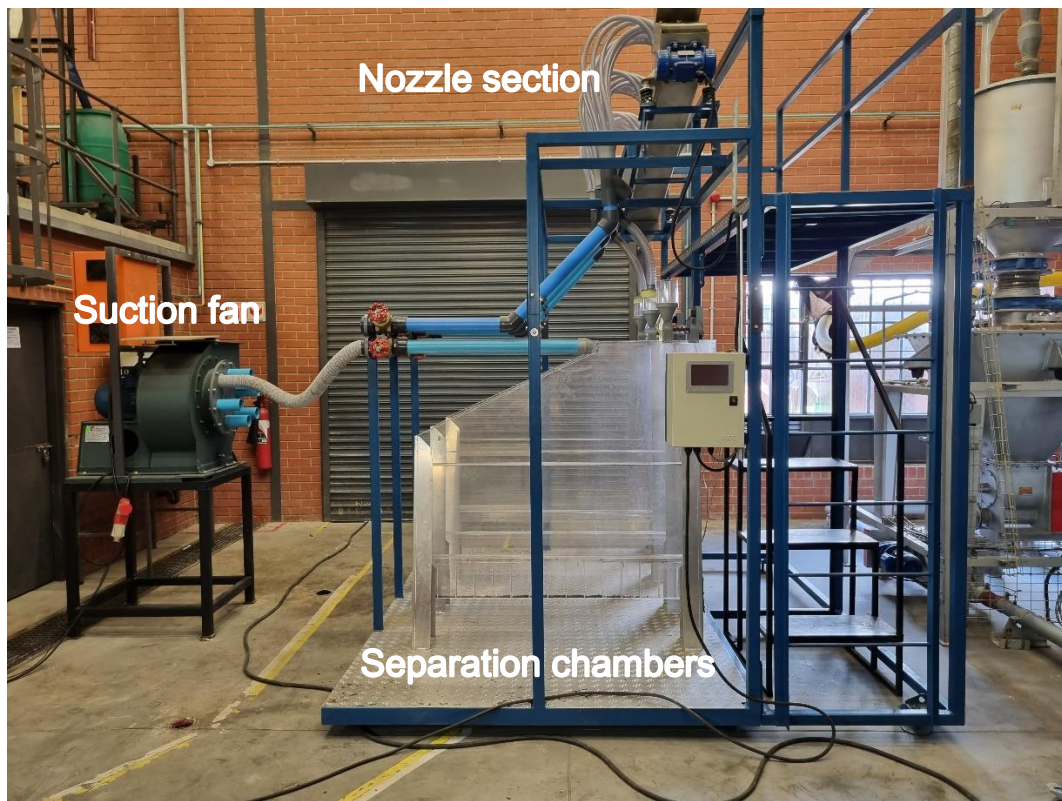


Figure 5.14: Winnowing pilot plant

As seen in the figure the suction fan (on the left) is attached to the winnowing plant using a flexible pipe. The airflow is controlled by setting the fan speed and then adjusting the valve at the end where the flexible pipe connects. The top section is where the size separation nozzles are placed, and the nozzles feed down to the density separation chambers at the bottom. A close up of each one of the described pieces of equipment is shown in Figures 5.15 and 5.16.

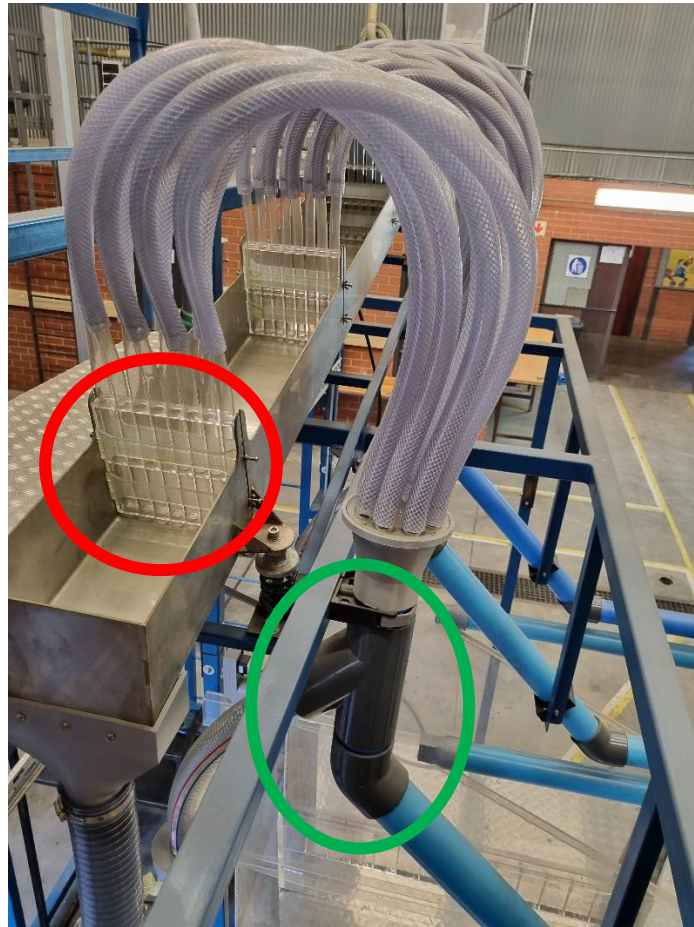


Figure 5.15 Size separation nozzle close-up

Figure 5.15 shows the different components of the size separation nozzle. The bottom transparent section located inside the feeding shoot (circled in red) is the particle pickup. From there the particles are transported through the small tubes to the dark gray section (circled in green) that has a y strainer to keep particles from entering the fan. The particles are then further transported to the feeder section of the density separation chamber shown in Figure 5.16.



Figure 5.16 Density separation chamber close-up

The particles from the nozzles are transported to the feeder (circled in red). The feeder ensures that the particles enter the density separation chamber at a consistent and evenly distributed pace. Once the particles enter the density separation chamber and the separation starts, the air displaces the particles based on their density difference. The particles that have been separated are collected in the removable bin section at the bottom.

The pilot plant shown in Figure 5.14 is the culmination of the study and is a combination of all the design, tests, and simulations that have been completed throughout the study. The detailed pilot plant design and initial test results are shown and discussed further in the next chapter.

Chapter 6

The Future of Fine Coal Beneficiation

Evaluation of a prototype winnower for dry fine coal processing

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This paper will be submitted for publication in 2023 with the publication media still to be decided.

This paper describes the results obtained from combining and operating the two previously described prototypes as a single fine coal winnowing demonstration plant. The paper contains some unexpected but promising results that could lead to some exiting changes when further testing the winnowing plant in the future.

Evaluation of a prototype winnower for dry fine coal processing

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ABSTRACT

One of the most pressing priorities in coal processing is the efficient beneficiation of fines, either as current arisings, or recovered from previously dumped discards. To be able to do this using dry methods, would be even more advantageous due to mounting water supply and pollution issues. The paper describes the development of a dry beneficiation method for -6mm material, including the proof-of-concept research, and the design as well as commissioning of a 15 kg per hour demonstration prototype, using horizontal flow winnowing as a density separation mechanism. Winnowing has successfully been used in traditional agriculture, and more recently in the pharmaceutical sectors. Several studies have shown the possible application in coal but there is still very little data available, other than lab scale experiments. Winnowing has the potential to separate coal particles by size and density; however, the interaction between the two properties is high, with poor resolution of density on wider size ranges. Hence, a 2-stage separation was suggested for the beneficiation of -6 mm coal. The first stage is a size separation producing streams with a very narrow PSD (2:1), and the second stage is density separation on each of these streams. Using the successful proof-of-concept information from previous studies on the method, a demonstration prototype was designed for the dry beneficiation of -6 mm coal. This paper describes the design philosophy, the commissioning, as well as the results obtained. It was shown that, with the correct design of the two major components (the size separation nozzle and the density separation chamber) efficient upgrading was possible. The prototype also demonstrated that low density cut points could be achieved at reasonable product yield.

KEYWORDS: fine coal, winnowing, demonstration prototype

INTRODUCTION

The processing of fine coal is becoming increasingly important in countries worldwide, with millions of tons of fine coal being produced each year (Ramudzwagi, et al., 2020). These coal fines are produced as a by-product of general mining and coal processing activities. Historically these fines were discarded and placed on stockpiles or in slurry dams; however, this is no longer the case (Energy, 2001). According to Dwari & Hanumantha Rao (2007), these previously stockpiled fines and the newly generated coal fines are predominantly processed using wet beneficiation methods. Dwari & Hanumantha Rao (2007) further states that these wet methods, such as water only cyclones, spirals, and froth flotation, are favoured around the world because of their ability to produce high-quality products with a reasonable recovery.

The industry faces an obstacle with the wet methods because they require large amounts of water, making it difficult to use them in arid or semi-arid regions (Zhao, et al., 2014). Ramudzwagi, et al., (2020) and Ghosh et al., (2014) both state that this is one of the reasons why countries around the world are leaning towards dry beneficiation. Not only does dry beneficiation require no water, but it has a lower overall cost and has several added benefits to the downstream process. Dry beneficiation is not new and has been around for several decades (Ghosh et al., 2014), with air jigs and air-dense medium fluidized beds as some well-known dry beneficiation methods (Sakhre, et al., 2018). The problem with dry separation is that the methods that have been implemented do not match the processing capabilities of the wet separation methods either in terms of product quality or throughput (Hughes et al., 2019). Over the past several years, a new development in dry beneficiation was the implementation of a well-established agricultural density separation method known as winnowing.

Winnowing has been used in the agricultural and pharmaceutical sectors for decades and works by separating the products from discard using a stream of air. However, the method has not been successfully implemented in the mining sector. Several studies by Sakhre et al. (2018) and Morgan et al. (2019) show that winnowing can be used to beneficiate - 6 mm coal. The study by the North-West University that was concluded in 2019 indicated that the winnowing method could work for fine coal, but several factors need to be

considered, such as the effect of particle shape, size, and nonlinear airflow (Morgan et al., 2019).

Working with the information gathered from the study, a new two stage dry beneficiation method was developed. The study found that the winnowing method was very size sensitive, and thus the 2-stage separation was implemented. This 2-stage method will sort particles into different size classes first, using a newly designed separation nozzle and a very narrow PSD (2:1). Each size class will be beneficiated in a separation chamber according to the desired density cut point. The size separation nozzle and density separation chamber will be combined into a single coal winnowing plant capable of beneficiating -6 mm coal.

DESIGN

The design for both the nozzle and separation chamber was based on the results obtained by (Morgan et al., 2019) and the calculations performed in a separate study titled **"Design and mathematical behaviour model for a fine coal winnowing pilot plant"**. Two prototypes were constructed and tested to validate and further optimize the design before constructing the winnowing pilot plant.

Size separation nozzle

The size separation nozzle works on the same principle as a vacuum cleaner; particles are placed on a flat surface just below the nozzle inlet, and then depending on the air velocity moving through the nozzle, selected particle sizes are picked up while other sizes are left behind on the surface. This principle is shown in Figure 6.1.

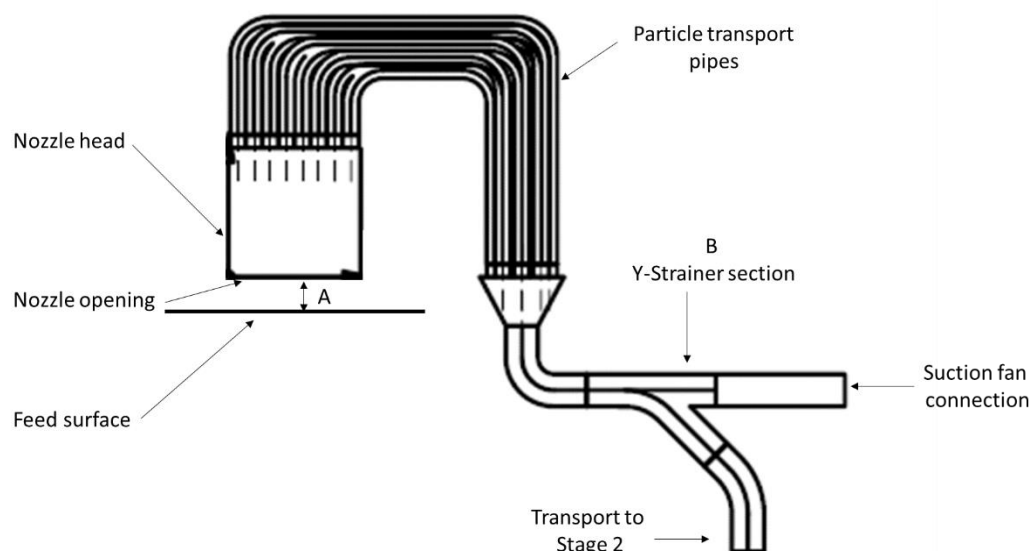


Figure 6.1 - Suction nozzle components.

Several factors were considered when designing the separation nozzle, such as the shape and orientation of the nozzle to allow for maximum air velocity control, the distance between the nozzle opening and the surface (A in Figure 6.1) and the y strainer section (B on Figure 6.1) to ensure no particles are pulled into the suction fan. The prototype for the separation nozzle was constructed according to these specifications, and this prototype was used to test the size separation capability of the nozzle and help improve the final design.

Density separation chamber

The density separation chamber works on the traditional principle of winnowing, except that the airstream used to separate the particles is generated by suction instead of a blower. Particles that enter the separation chamber experience an external force from the moving air, and based on the individual density of each particle, it is displaced a certain distance through the length of the chamber. The design is shown in Figure 6.2.

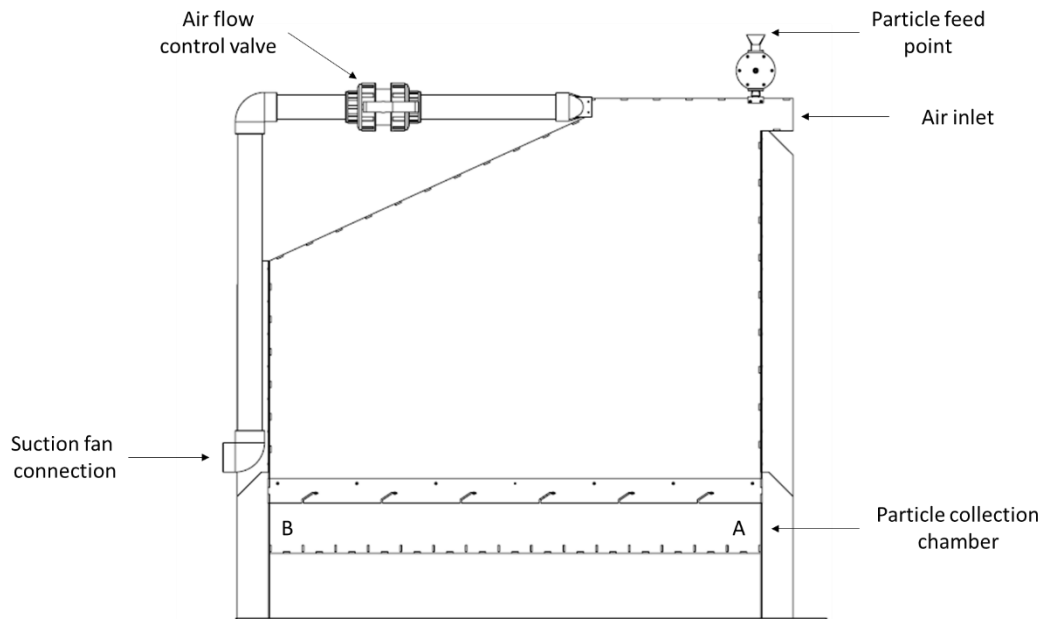


Figure 6.2 - Separation chamber components.

As the particles enter the chamber, shown in Figure 6.2, through the particle feed point, the air acts on the particle pulling it away from the air inlet and over towards the left. Less dense particles will have a greater displacement and will be collected closer to the point labelled B in Figure 6.2, while particles with a higher density will be collected in the bin closer to the point labelled A in Figure 6.2. A prototype of the density separation chamber was constructed using the concept in Figure 6.2, and the density separation capability of the design was tested.

Pilot plant

Using the results from both the studies, the design for a winnowing pilot plant was created. As seen in Figure 6.3, the design uses both the nozzle and the separation chamber in a single separation setup.

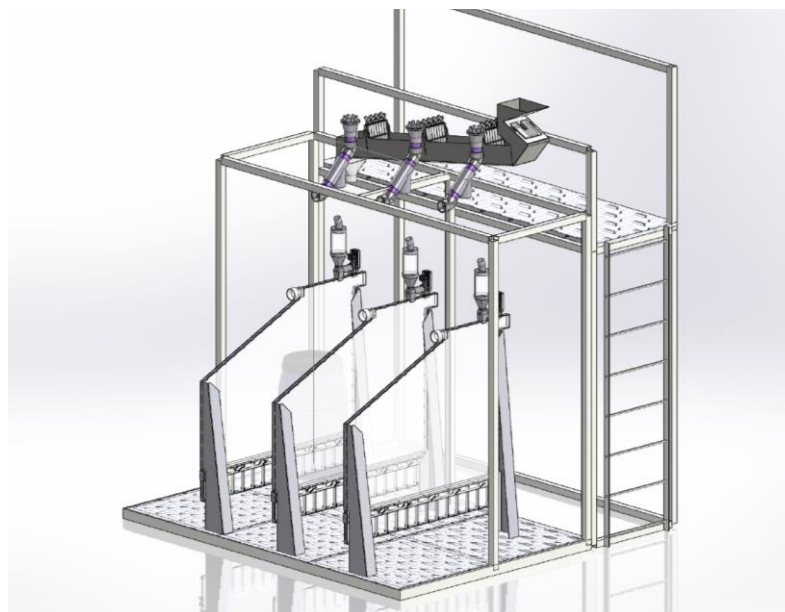


Figure 6.3 - Pilot plant design

As seen in Figure 6.3, the pilot plant design has a single feed point that transfers the coal particles to the 1st stage, which is the size sort with the nozzles. Each nozzle picks up a selected size range of particles and transfers that size range to stage 2, the density separation chamber. The products and discards from the different density separation chambers can be re-combined to give one product over the complete -6 mm to +1 mm size range.

RESULTS AND DISCUSSION

The pilot plant was operated as a batch system feeding 1 kg of -6 mm +1 mm coal per batch run. The size separation nozzles in the first section were set to pick up 3 distinct size ranges, +1 mm to -2 mm, +2 mm to -4 mm, and +4 mm to -6 mm. This is done by setting the air velocity of each nozzle at a specific value. The initial results indicated that a size separation does not occur in the first section and that the separation nozzles might favour a density separation rather than a size separation, because of this observation the two sections were evaluated individually and the results for the nozzle and the separation chamber are discussed separately.

Size separation nozzle

The size separation nozzles were set up at 3 different air velocities to ensure that 3 distinct size ranges are picked up. The setup for the nozzles is shown in Table 6.1.

Table 6.1: Nozzle setup

Nozzle #	Air velocity (m s^{-1})	Expected size range to be lifted (mm)
1	7	1 – 2
2	8	2 – 4
3	9	4 - 6

As shown in Table 6.1 it was expected that the nozzles would sort the particles from small to big as the air velocity increased. However, after running the first few batches through the system it was observed that the nozzles did not perform as expected, even after increasing the air velocity of each nozzle there was still no distinct size separation. Figure 6.4 and Figure 6.5 show the results obtained after a PSD was done on the particles that were lifted by the nozzles in 2 separate runs.

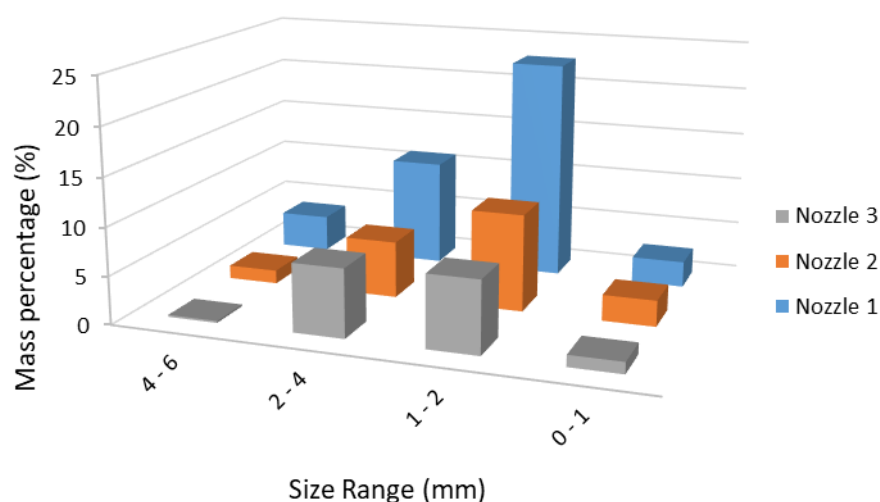


Figure 6.4: PSD of particles lifted by the size separation nozzles.

The Nozzles were set at the parameters shown in Table 6.1 and as can be seen in Figure 6.4; each nozzle picked up particles of different sizes with all 3 nozzles lifting particles from all size ranges instead of lifting the particles as predicted in Table 6.1. To test this further the air velocity was increased, and the same sample was put through the system. The results obtained by the increased air velocity run are shown in Figure 6.5.

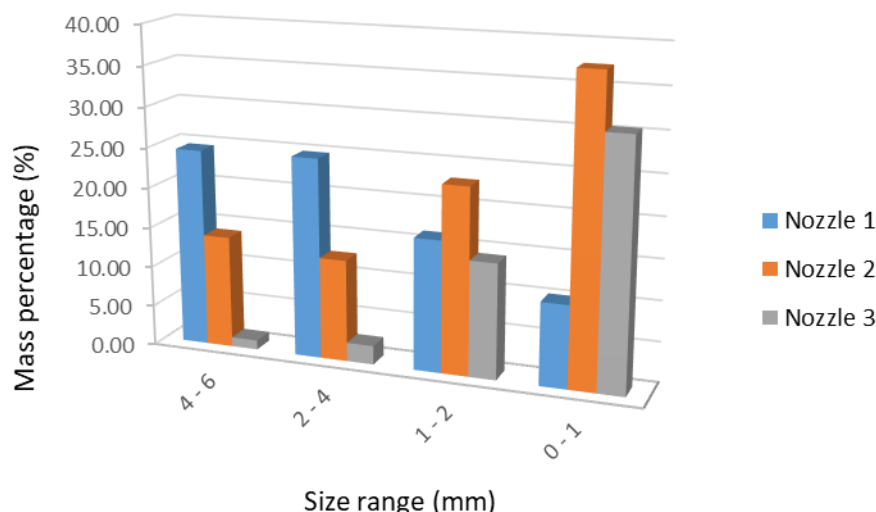


Figure 6.5: PSD of particles lifted by the size separation nozzles.

With the increased air velocity, a small separation started to become visible between the 3 nozzles, however, the result showed the exact opposite of what was expected from the nozzles. Nozzle 1 (which was expected to lift particles in the range of 1 mm – 2 mm) lifted more particles from the higher size ranges (4 mm – 6 mm and 2 mm – 4 mm), and nozzles 2 and 3 lifted more particles from the lower size ranges as shown in Figure 6.5.

The overall results shown that there is very little to no size separation when using the nozzles however when the density of the lifted particles (products) and the leftover particles (discard) were tested the following results were obtained:

Table 6.2: Average density of nozzle products.

Nozzle #	Air velocity (m s^{-1})	Average Density (g cm^{-3})
1	7	1.61
2	8	1.68
3	9	1.80
Discard	9	2.24

As shown in Table 6.2 even though the nozzles do not separate the particles by size the lifted particles from each nozzle indicate a density separation regardless of the particle size.

Density separation chamber

The feed to the chambers come directly from the separation nozzles and since the nozzles did not do the size split as predicted, the separation chamber was tested for its density separation capability over the full-size range (-6 mm to 1 mm) of particles. For this test, a high-quality coal with a very low density was used to confirm that the separation chamber can reach low density cut points. The coal sample was fed in batches of 1 kg and the separation chamber was set up as shown in Table 6.3.

Table 6.3: separation chamber setup

Density separation setup	
Air velocity (m s^{-1})	9
Particle size range (mm)	+1 to - 6
Batch size (kg)	1

A separate study showed that the best separation was achieved at an air velocity of 9 m s^{-1} and thus that was the air velocity used for the setup as shown in Table 6.3. After the 1 kg sample was fed through the chamber, a helium pycnometer was used to determine the average density of each of the 15 separation bins at the bottom of the chamber (illustrated in Figure 6.2). The density distribution within the separation chamber is shown in Figure 6.6.

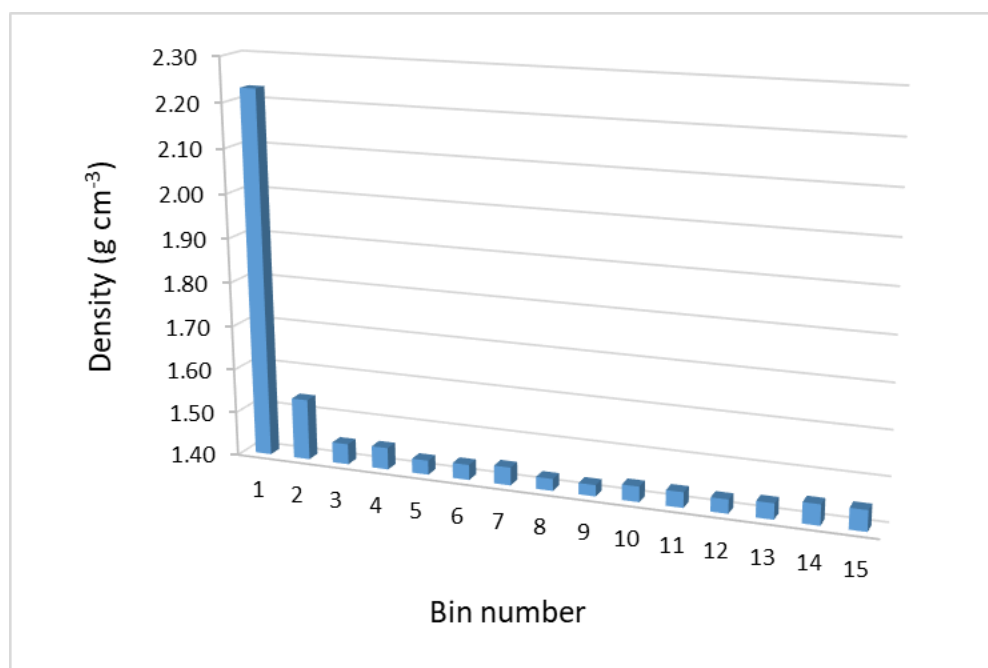


Figure 6.6: Density distribution in separation chamber over 15 bins for all particle size ranges.

Bin 1 is the closest to the inlet and thus as predicted it will have the highest density, as the bin number increases the density is expected to decrease as shown by the results in Figure 6.6. The results obtained indicate that a density separation can be achieved at densities as low as 1.45 g cm^{-3} and at first glance it would seem that a density separation is achievable without doing a size separation first. Looking at the densimetric curve for this specific coal (Figure 6.7) it is clear the separation achieved is no surprise as the coal is very easy to separate.

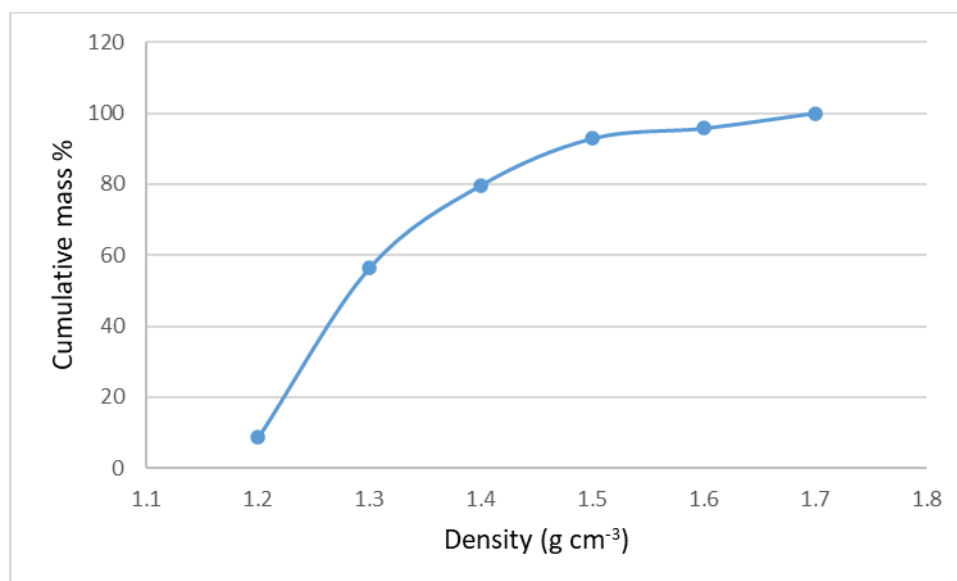


Figure 6.7: Densimetric curve for coal test.

As seen in Figure 6.7, 80% of the mass is already below the 1.4 g cm⁻³ mark, thus making the separation seen in Figure 6.6 possible with very little effort. Further evaluation of the content in each bin indicated that most of the sample accumulated in the bins 2 to 6 as shown in Figure 6.8.

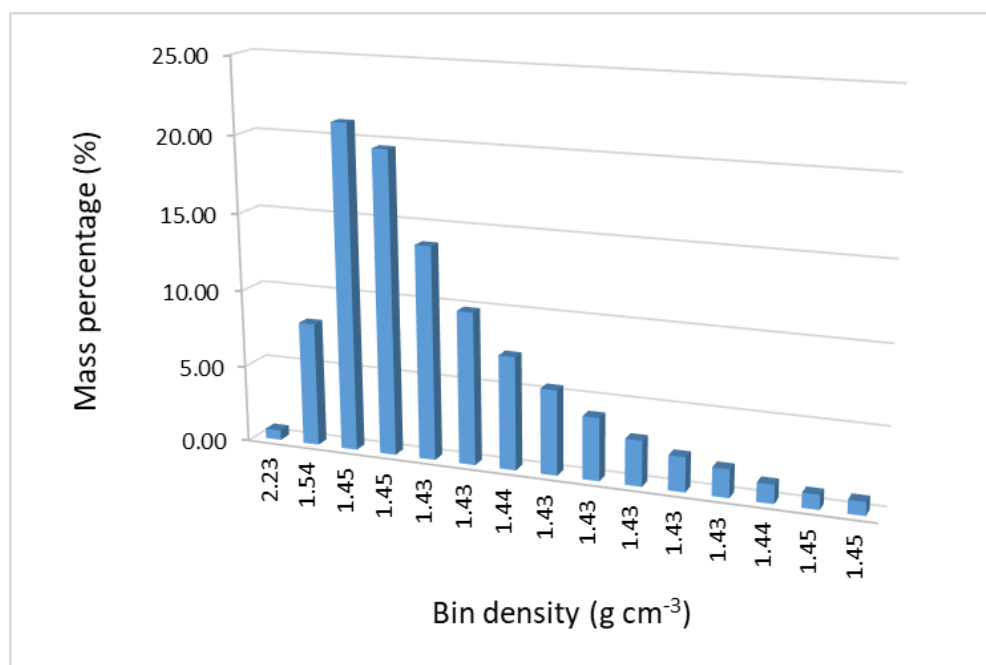


Figure 6.8 Mass distribution over the average density in each bin.

As seen from Figure 6.8, bin 1 has a very low mass percentage of the total 1 kg that was fed to the chamber whereas bins 3, 4 and 5 have the most particles, all at a relatively low density. The data in Figure 6.8 also confirms that separation of particles at a low density is possible. Apart from the density separation the size effect of the separation needed to be tested (due to the lack of size separation in the first stage) and to do this a PSD was done on each individual bin.

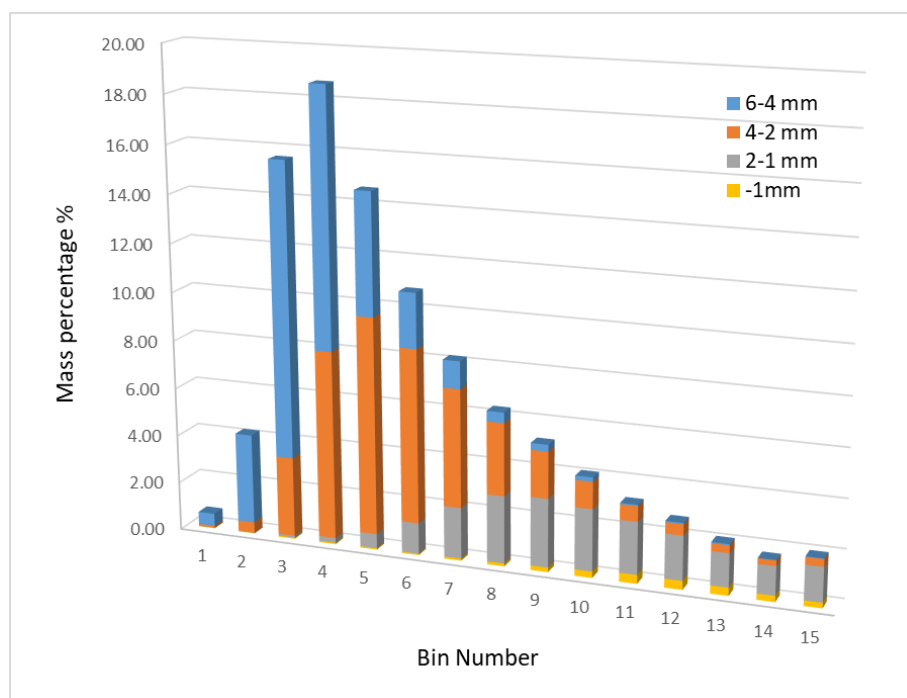


Figure 6.9: PSD in individual bins

The PSD on the bins did reveal a size discrimination taking place during the separation with most of the larger particles reporting to the first 6 bins (Figure 6.9), while most of the small particles are collected in bins 8 to 15. The overlap between particle size ranges however is still very big and this does confirm that a 2-stage separation is necessary with the initial stage separating the particles by size first. This is further confirmed by the decrease in the average particle size as the bin number increases as shown in Figure 6.10.

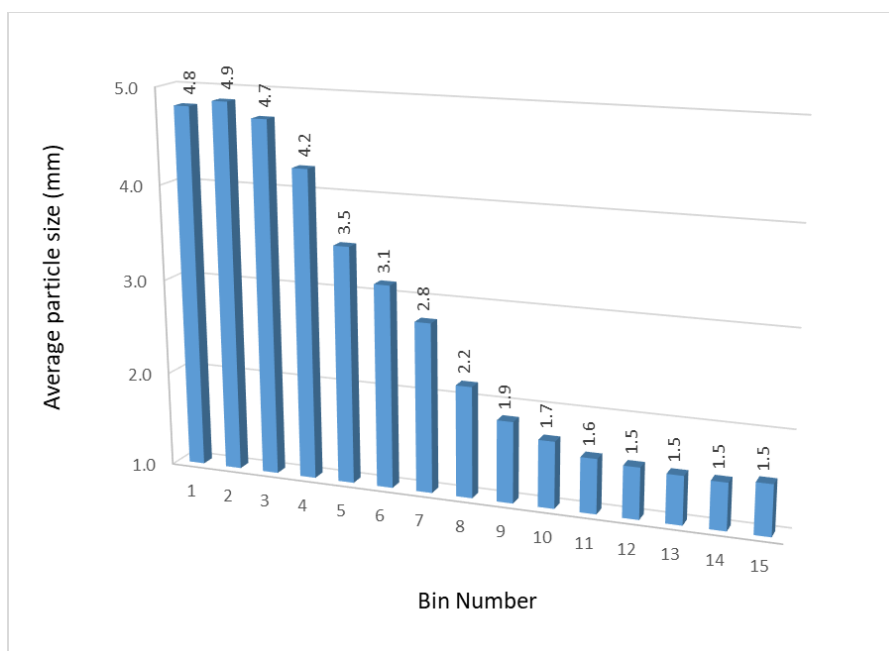


Figure 6.10: Average particle size per bin

The average particle size gradually decreases as the bin number increases indicating that smaller particles have a larger displacement, which is consistent with the initial hypothesis that a size separation might be needed before the density separation stage. Further testing is required to confirm the size effect on the system as well as the consistency of the method on other coal types. Overall, the separation data is very promising with relatively high yields being achieved at low bin densities as shown in Figure 6.11.

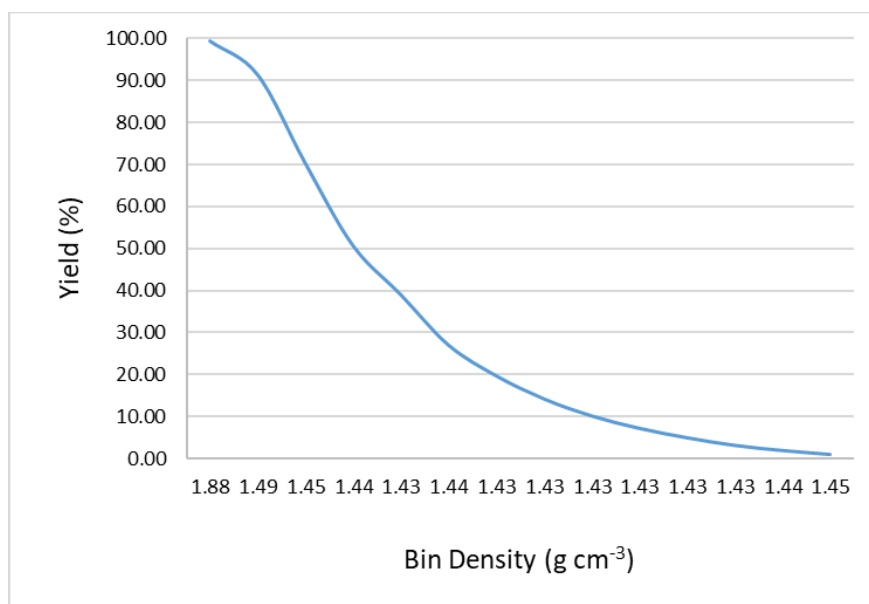


Figure 6.11: Yield vs bin density.

Bins 2 to 15 are all below the average bin density of 1.50 g cm^{-3} , thus if the desired density is set to be 1.50 g cm^{-3} the yield would be around 95% in this case with the good quality coal. If the desired bin density is set to be 1.45 g cm^{-3} the yield would be around 80% which is still relatively good for the dry separation process operating on a single stage over a wide size range.

The bin densities and size analysis do show that the equipment is capable of separating fine coal to a certain extent, however further investigation and testing will be needed to optimise the process as shown by the partition curves in Figure 6.12.

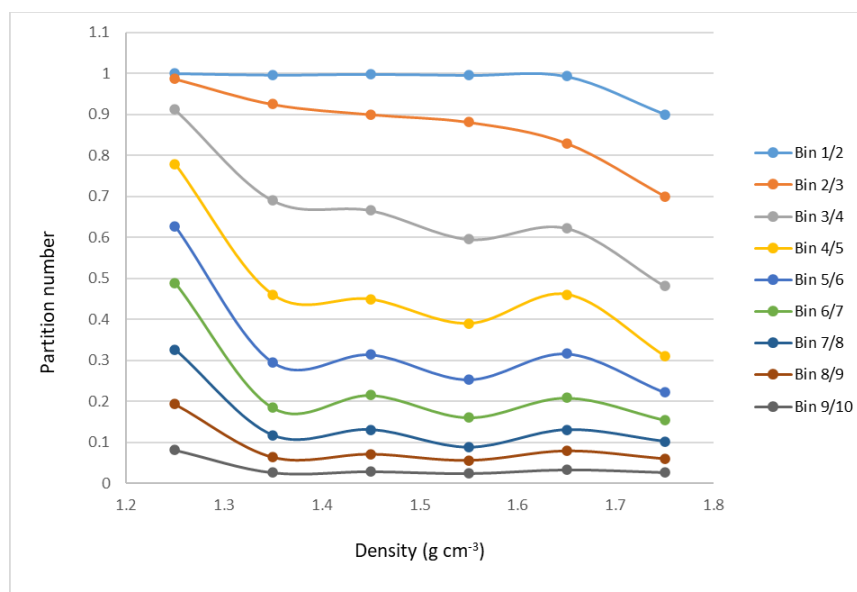


Figure 6.12: Partition curves for different combinations of bins

The partition curves in Figure 6.12 were set up by combining several bins to create a product and a discard. For example, Bin 1/2 indicates the bin cut and thus bin 1 will be the discard and bins 2 to 15 will be the product, similar for Bin 2/3 with bins 1 and 2 being the discard and bins 3 to 15 forming the product. For each combination, a partition curve was constructed (Figure 6.12) and as seen from the curve the separation (although adequate) is not yet very efficient and thus further investigation and testing is needed to optimise the density separation unit.

CONCLUSION

The results from this study were unexpected but promising and although the pilot plant did not perform as expected the results did indicate that both of the pieces of equipment that were designed are capable of separating -6 mm coal. However, further investigation is required to confirm that this is the case and other coal types will have to be tested as well to ensure that it is consistent on any -6 mm coal.

The results also open the possibility of using the separation nozzles and separation chambers as 2 separate dry beneficiation processes or combining them in a different manner to achieve an even cleaner product. This will be investigated going forward while still looking at achieving a size separation with the nozzles as initially intended to test the influence on the overall separation.

In general, the study was a success proving that the separation chamber can beneficiate dry fine coal with a very low density while maintaining a high product yield. The main reason for this is because bins can be combined or removed to create the desired product and discard.

Other future studies that will be done on the winnowing system that came as a result of this study will be:

- The effect of particle shape on the separation.
- Converting the batch system to continuous to increase the throughput.
- Increasing the size range to test the separation limits of the winnowing chamber.

Winnowing as a dry beneficiation method for fine coal is showing promise and the results that are being obtained from the studies prove that the method is feasible. With further investigation and some optimization, this method can be implemented on any -6 mm coal.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial and technical contribution made by The Coaltech Research Association NPC Ltd. and the Centre of Excellence in Carbon Based Fuels, North-West University, South Africa.

Furthermore, the authors wish to acknowledge H. Brink for his contributions and efforts in testing the equipment. As well as Devos laboratories for the construction of the equipment.

This work is based on the research supported in part by the National Research Foundation of South Africa (Coal Research Chair Grant Numbers: 86880; and UID85643, UID85632). Any opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF supported research are that of the author(s) alone, and the NRF accepts no liability whatsoever in this regard.

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ADDITIONAL NOTES

As indicated in the paper a separate study was conducted to find the best air velocity setting at which to operate the winnowing chamber. This was done by testing a size separation and density separation of the same sample at high and low air velocities. The air velocity to the unit is controlled in 2 ways:

1. The fan setting in (Hz) – The suction fan uses a frequency controller and thus the fan speed was controlled by increasing or decreasing the Hz reading from 0 Hz to 50 Hz.
2. The valve placed between the fan inlet and the suction inlet of the separation unit – the valve serves as a throttle for the air. When the fan is set to a constant speed the valve can be used to further reduce the air velocity if needed.

The different combinations were tested, and an anemometer was used to relate each frequency and valve setting to an air velocity (m s^{-1}). The resulting fan air velocities are given in Table 6.4.

Table 6.4 Air velocity correlations

Frequency setting (Hz)	Valve setting (number of full rotations from closed position)	Air velocity at winnowing chamber inlet (m s^{-1})
20	3	5
	4	6
	5	7
	6	8
	7+	9
30	3	8
	4	9
	5	10
	6	12
	7+	13

Frequency setting (Hz)	Valve setting (number of full rotations from closed position)	Air velocity at winnowing chamber inlet (m s^{-1})
40	3	10
	4	13
	5	15
	6+	17
50	3	14
	4	17
	5	20
	6+	23

To test the separation effectiveness of each combination several tests were done varying the valve setting at a set frequency. This increased or decreased the air flow to the separation unit. An example of the results for the size separation test is shown in Figure 6.13 to Figure 6.16.

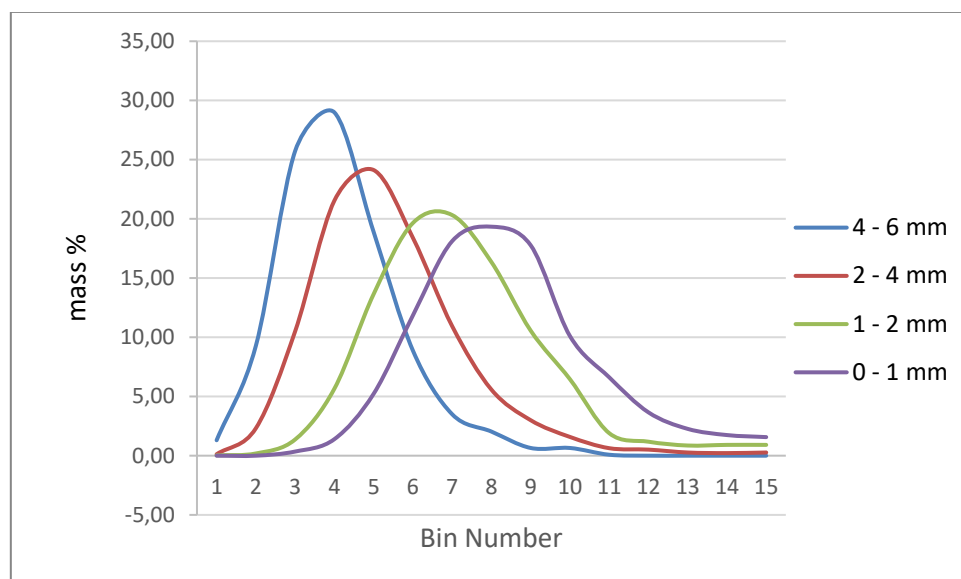


Figure 6.13 Mass distribution per particle size in each bin at 40 Hz and valve setting 4 (13 m s^{-1}).

Figure 6.13 represents the data of an attempted size separation at a frequency of 40 Hz and a valve setting of 4, this (according to table 6.4) is an air velocity of 13 m/s.

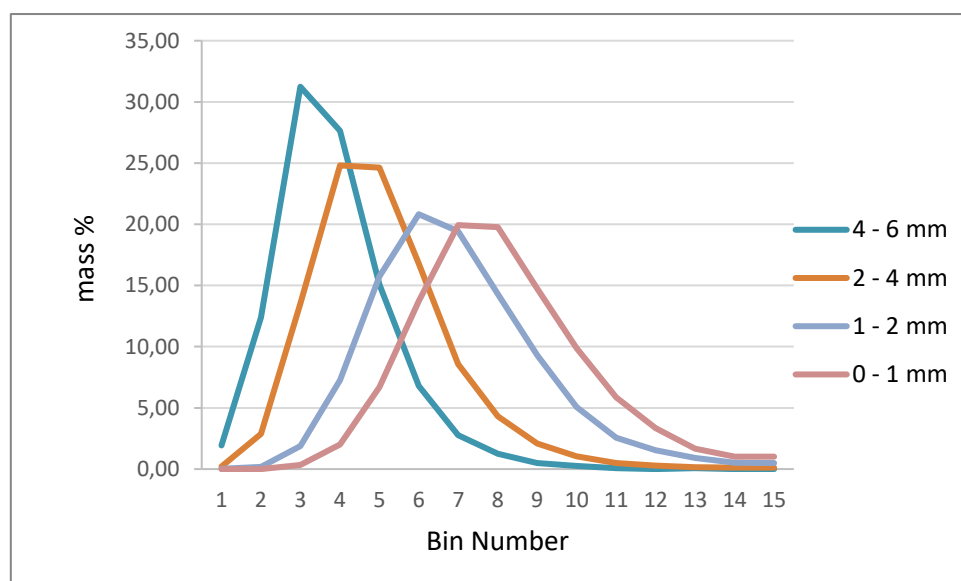


Figure 6.14 Mass distribution per particle size in each bin at 40 Hz and valve setting 5 (15 m s^{-1}).

Figure 6.14 represents the data of an attempted size separation at a frequency of 40 Hz and a valve setting of 5, this (according to table 6.4) is an air velocity of 15 m/s.

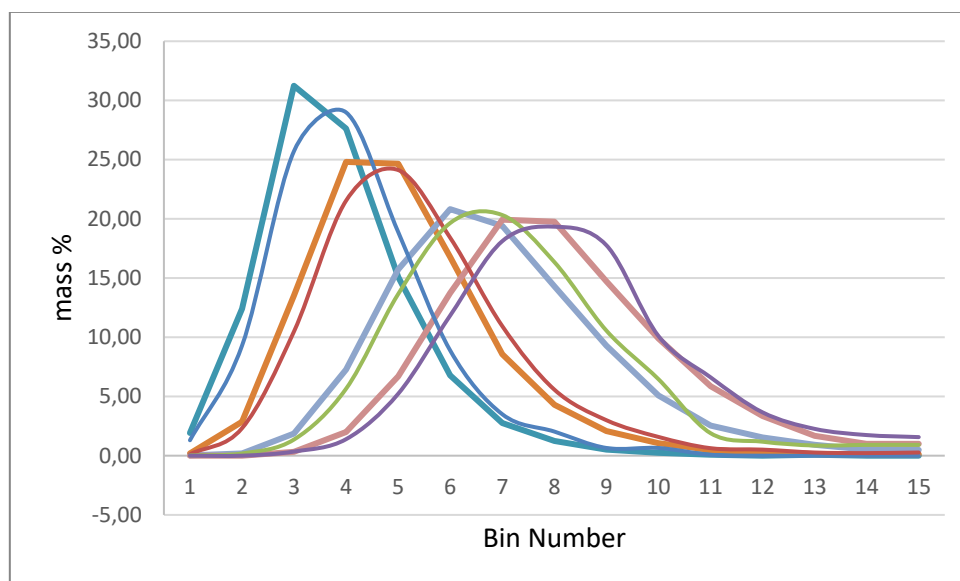


Figure 6.15 Combined comparison of Figure 6.13 and Figure 6.14

When combining the data, the results show that although there is a shift to the right, meaning that particles are displaced further, the shift is almost constant across the entire range. Thus, the increased air velocity by opening the valve further does not influence the effectiveness of the separation.

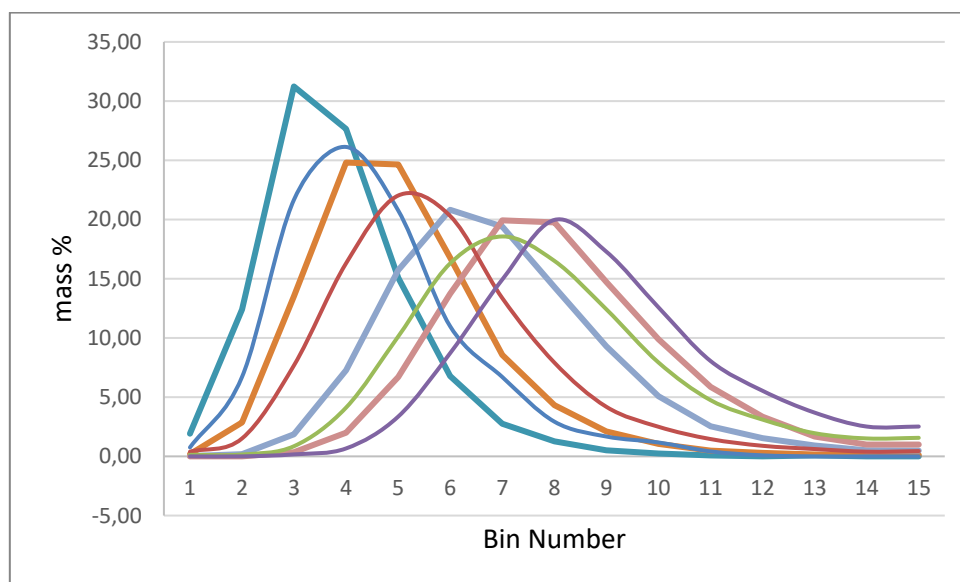


Figure 6.16 Combined comparison of increased frequency from 40 Hz to 50Hz at constant valve setting 4 (13 m s^{-1} to 17 m s^{-1}).

When comparing the data obtained from doing a similar combination on the results from a 40 Hz – 4 valve setting test and a 50 Hz – 4 valve setting test (an increase from 13 m s⁻¹ to 17 m s⁻¹) it also shows a shift to the right. However, in this case the separation was even less effective as indicated by the overlap in the sharp edge lines in Figure 6.16. Aside from the conclusion that a size separation cannot be achieved it also indicates that increased air velocity does not lead to a more effective separation.

This paper serves as the first proof that a low density cut point can be set when using the winnowing method on fine coal, and although the plant did not perform as expected a lot of valuable information and data was obtained from testing the combined separation units. The focus of the study during the testing was shifted primarily towards the separation chamber as this was the initial density separation unit and the nozzles were added afterwards as a potential size separation step. Overall, the density separation within the separation chamber was adequate and the results are promising. However, further investigation will be needed to determine if it is consistent on any type of coal and the efficiency of the separation will need to be tested.

Chapter 7

Conclusion

This Chapter summarizes and concludes the arguments made throughout the study and recommends the work that still needs to be done on the project in the near future based on the results obtained and presented in the papers.

GENERAL CONCLUSIONS

Winnowing as a dry beneficiation method for -6 mm coal has been shown to work during the course of this study and although it was not the aim of the thesis, the feasibility of the method was confirmed. The aim of this study, as stated in Chapter 1 of this thesis, was to develop equipment capable of beneficiating fine coal using the winnowing method, and the development process was shown with the completion of the initial objectives in each chapter.

The objectives as stated in Chapter 1 were accomplished and discussed in each of the chapters that followed and any additional objectives that were added throughout the course of the study that helped improve the overall design of the equipment were stated and addressed in the conclusions of the papers. The following breakdown summarizes the conclusions as pertained to the aim and objectives in Chapter 1.

The research of the winnowing method forms part of Chapters 2 and 3, and these chapters investigate the mechanisms and basic function of the winnowing method. This research was used to design the initial positive pressure winnowing unit. This unit served as a baseline testing unit and was used to generate the data needed to improve and refine the winnowing equipment.

In Chapter 4 the redesign of the equipment was discussed after the initial prototypes were tested and the results obtained in this chapter lead to the initial concept of using negative

pressure winnowing prototypes. These negative pressure prototypes corrected several problems related to the winnowing of coal, such as dust formation and turbulent airflow. Chapter 4 was the turning point of the design process and the start of the idea to have a multistage winnowing plant capable of beneficiating fine coal.

The mathematical model in Chapter 5 described the movement of the particles within the winnowing unit. This helped to develop the virtual program that was used to complete the design for the first negative pressure prototypes of both the size separation nozzle and the improved density separation chamber. The model successfully described the particle behaviour and highlighted important design factors that needed to be considered, such as the impact speed and impact points of the particles, the dimensions of the density separation chamber, and the required air velocity to achieve separation. In general, the mathematical model deepened the understanding of the mechanisms and forces that are used during the winnowing processes and by understanding these components the design of the equipment could be refined and optimized. The lab scale winnowing prototypes that were designed and built provided the first insight into the application of the equipment on actual coal.

The final paper in Chapter 6 was the culmination of the design where the prototypes were integrated into a single pilot plant design and the pilot plant was tested for the first time on a single coal type to assess the separation capability. The results from this test were surprising but positive and indicated that the pilot plant was working. However further optimization is needed for the winnowing pilot plant to work as intended.

From a design perspective the equipment produced during this study was successful in further understanding the winnowing method and the application thereof on fine coal. With further investigation and testing the equipment can be further optimized and more data can be generated to improve the efficiency of the separation. However, the aim of having equipment capable of using this method was achieved and the process itself can be further developed using the now completed pilot plant.

CONTRIBUTION OF THIS WORK

The data available on the application of the winnowing method on coal in general is very limited with one other study being done on this work and published by Sakhre, et al., in 2018. As for the equipment used to beneficiate fine coal with the winnowing method, there is currently no product that is commercially available. The original design that uses the positive pressure blower system (used in the agricultural sector) was proven to be unsuccessful due to the turbulent air and dust formation.

In this thesis both of those problems were addressed, and the study attempted to solve both of these issues. By designing a negative pressure winnowing pilot plant the need for a traditional blower driven winnowing unit was eliminated and the additional problems that came with the positive pressure were solved. Ultimately the designed equipment (once further optimised) can become the standard for fine coal beneficiation. The pilot plant that was designed and constructed in this study can be used to further investigate and test the winnowing method, which means more data on the method and its applicability to fine coal can be generated without having to first develop new equipment.

RECOMMENDATIONS AND FUTURE WORK

After completion of this study, it is recommended that future research on this topic should include:

- The optimization of both the size separation nozzle and the density separation chamber – the combination of the 2 individual parts can improve the separation as originally designed. However, further testing is needed to achieve the correct size separation with the nozzle and improve the overall density separation of the winnowing chamber.
- The possibility of using the size separation nozzle as a separate dry fine coal beneficiation method – the results indicated that the size separation nozzle is capable of separating particles by density and thus a study is needed to determine the effectiveness of using the nozzle as a separate process.

- Improved control of the airflow and conversion to a continuous process – currently the airflow is controlled manually, however, automating the controls eliminate additional human error and will improve the separation efficiency. By converting the process from batch to continuous the throughput and true capability of the equipment can be tested. This would save time and increase the amount of data generated in a single run.
- A full moisture analysis is needed to determine the effects of moisture on the separation efficiency, as the coal used for the experiments were all airdried before being fed to the plant. The moisture limit must be determined and a possible solution to the feed moisture limit must be considered.
- The pilot plant and method must be tested on different types of coal – currently the non-optimized pilot plant was only tested on a single type of coal. It is recommended that different types of coal be tested once the process is optimized to ensure that the method works on any type of coal and not just a single type.

Appendix A

This Chapter Serves as a supplementary chapter explaining the mechanics and processes involved in the CFD simulations that formed part of the papers.

As an initial proof of concept, the separation process was simulated using Star CCM+. The input parameters and layout of the separation unit were specified according to the results obtained from a model that was constructed as part of a master's study at the North-West University (Similar to the model in Chapter 5 of this thesis) Figure A 1 shows the geometric layout of the separation unit before any processing has commenced.

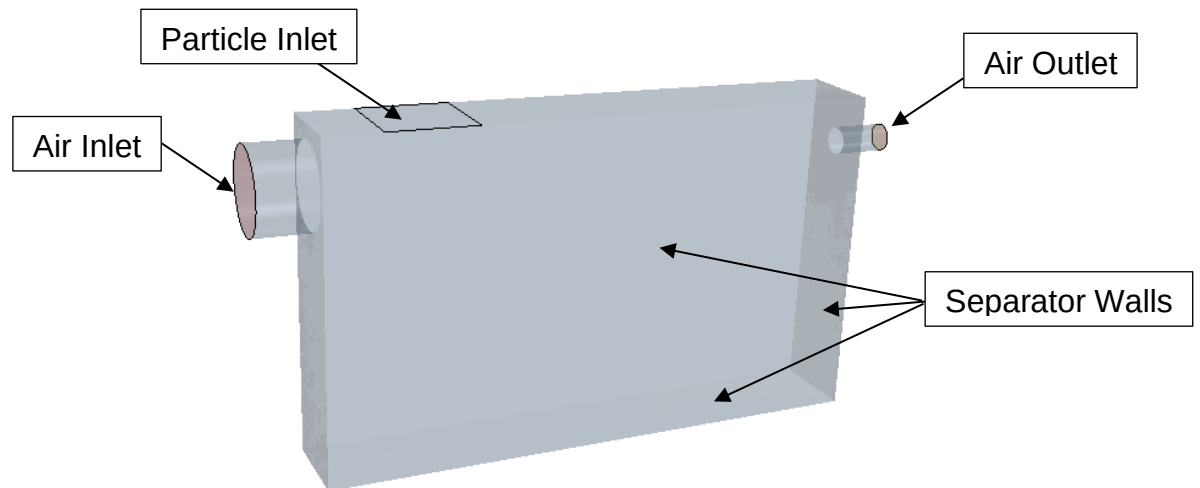


Figure A 1: Geometric layout of the original winnowing chamber

The digital construction of the geometry is the first and most important step, an incorrect geometry can lead to inaccurate results. For example, if the air inlet size is incorrect it can produce an incorrect flow pattern. There are different methods for setting up the geometry; however, the basic concept is to use a CAD program such as Siemens NX 12, AutoCAD or even the built-in CAD software in Star CCM+ to construct an accurate and spatially correct geometry for the simulation.

The spatial correctness refers to either a three-dimensional or two-dimensional space that must be selected. The geometry for this study is selected as a three-dimensional space as it allows for changes in all three planes (x, y, and z).

The first processing step after the geometry has been completed is to define the separate regions and clearly distinguish between the properties of each region. For this study, four regions are defined i.e., an air inlet, particle inlet, air outlet and the separator walls. The regions are shown in Figure A 1 and each region is assigned specific properties according to the function that it serves, the properties for each region are shown in Table A 1.

Table A 1: Region assignment and properties.

Region name	Property	Value	Units
Air Inlet	Velocity Inlet	Adjustable	m s ⁻¹
Particle Inlet	Wall with an injector	Adjustable	mm & kg m ⁻³
Air Outlet	Pressure Outlet	0	
Separator Wall	Wall		

The adjustable values are the values that can After the regions and their properties have been defined the volume and surface mesh must be generated. The meshing is done to get an adequate division of the entire unit which will serve as individual data points when tracking airflow velocities and particles. Figure A 2 shows the volume mesh as generated by the Star CCM+ software.

The meshing is done by selecting the Polyhedral mesher and a Prism layer mesher in the Star CCM + environment. These selections determine the shape that will be used when dividing the geometry up into thousands of small surfaces. The Surface Remesher is also selected to ensure that the surface mesh quality is suitable for the CFD simulation. Along with the model selection a base size must be set to determine how fine the generated mesh should be. The base size selection can range from micrometres to kilometres, depending on the size of the geometry used in the simulation. However, smaller base sizes increase the time needed for the mesh to be generated. For the geometry setup in this study, a base size of 5 mm was selected.

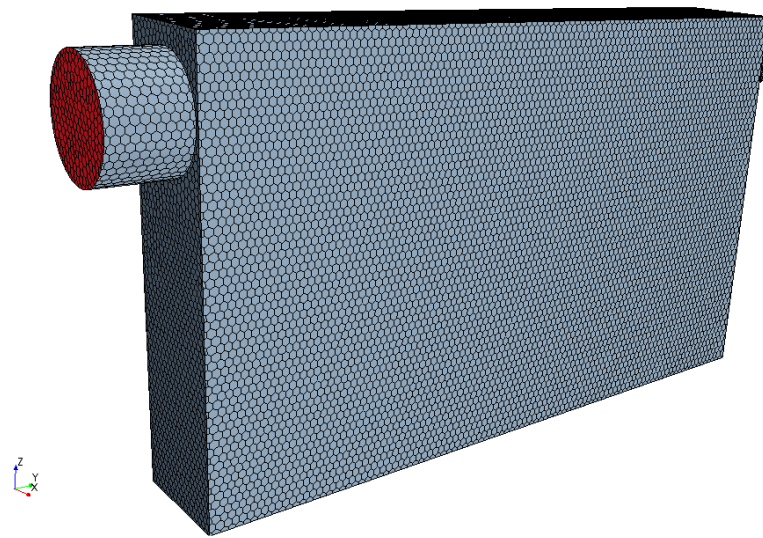


Figure A 2: Winnowing chamber with meshed geometry.

Once the meshing is done the “physics” is set (in the physics tab) in order for the program to know which models to use so as to complete the necessary calculations. The models and constants selected for this step are chosen from a master list that forms part of the Star CCM + database. Matching the description of the properties to the need at hand, the models, properties, and constants used for the simulation are listed in Table A 2 below.

Table A 2: Selected models, properties, and constants for the simulation.

Property / Model Name	Sub Model	Property Selected	Value	Units
Constant Density				
Exact Wall Distance		Minimum Allowable	1.0×10^{-6}	m
Gas		Air Density	1.18415	kg m ⁻³
		Air Viscosity	1.85508×10^{-5}	Pa s
Gradients				
Gravity			9.81	m s ⁻²
High y+ Wall Treatment				
K-Epsilon				

Lagrangian Multiphase	Constant Density Drag Force Material Particles Pressure Gradient Force Residence Time Solid Spherical Particles Track File	Drag Coefficient Coal Density	Schiller-Naumann Adjusted	 kg m ⁻³
Proximity Interpolation				
Reynolds-Average Navier-Stokes				
Segregated Flow				
Standard K-Epsilon				
Steady				
Three Dimensional				
Turbulent				
Reference Pressure		Pressure	101325	Pa

After the “physics” have been set the simulation is initiated and run to completion. Once the simulation converges several scenes can be generated to view the behaviour of both the particle and the airflow within the system. Figures A 3 and A 4 show examples of the generated scenes from this simulation.

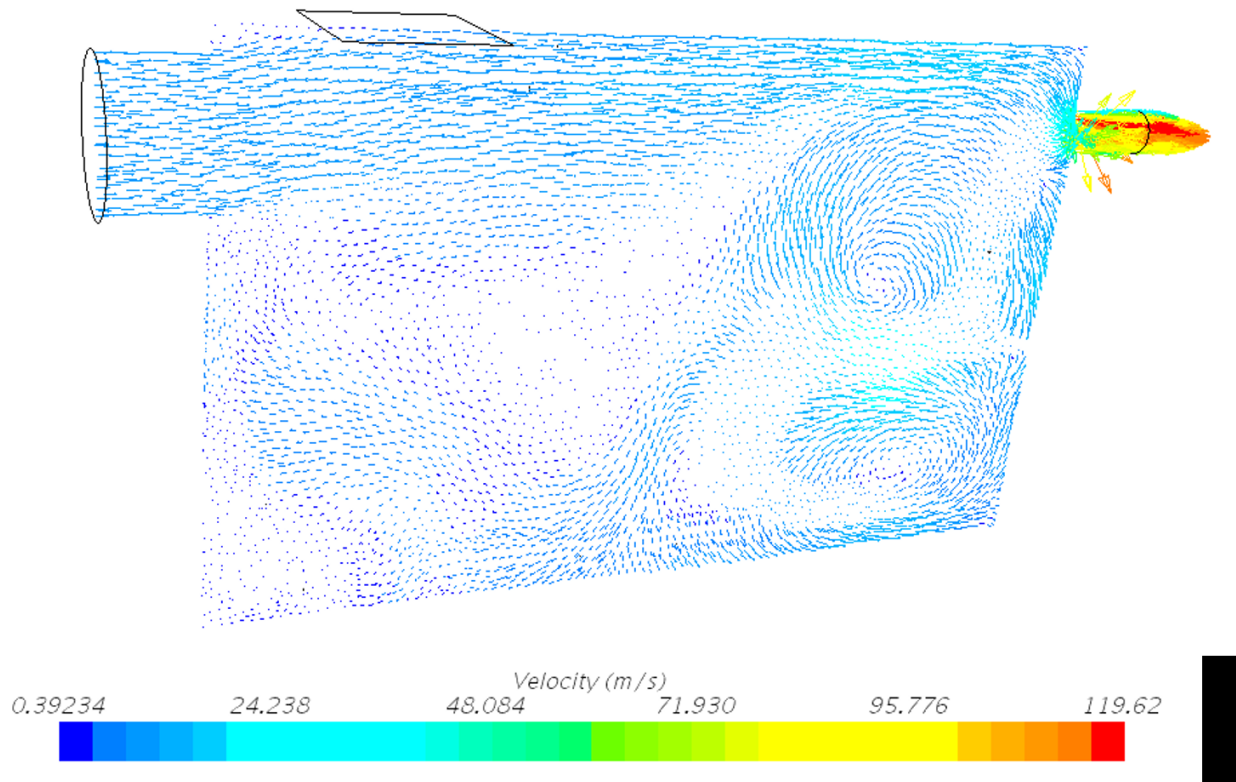


Figure A 3: Cross sectional airflow scene of the winnowing chamber.

The vector scene in Figure A 3 shows the velocity profile of the air flowing from left to right through the separation unit. This scene is generated by adding a plane that cuts through the centre of the separation unit. The velocity (m·s⁻¹) of the air is indicated by the colour difference, and the small arrows indicate the direction of flow.

The geometry scene is combined with several streamlines to produce the scene shown in Figure A 4. This figure serves as both an airflow and particle velocity tracker.

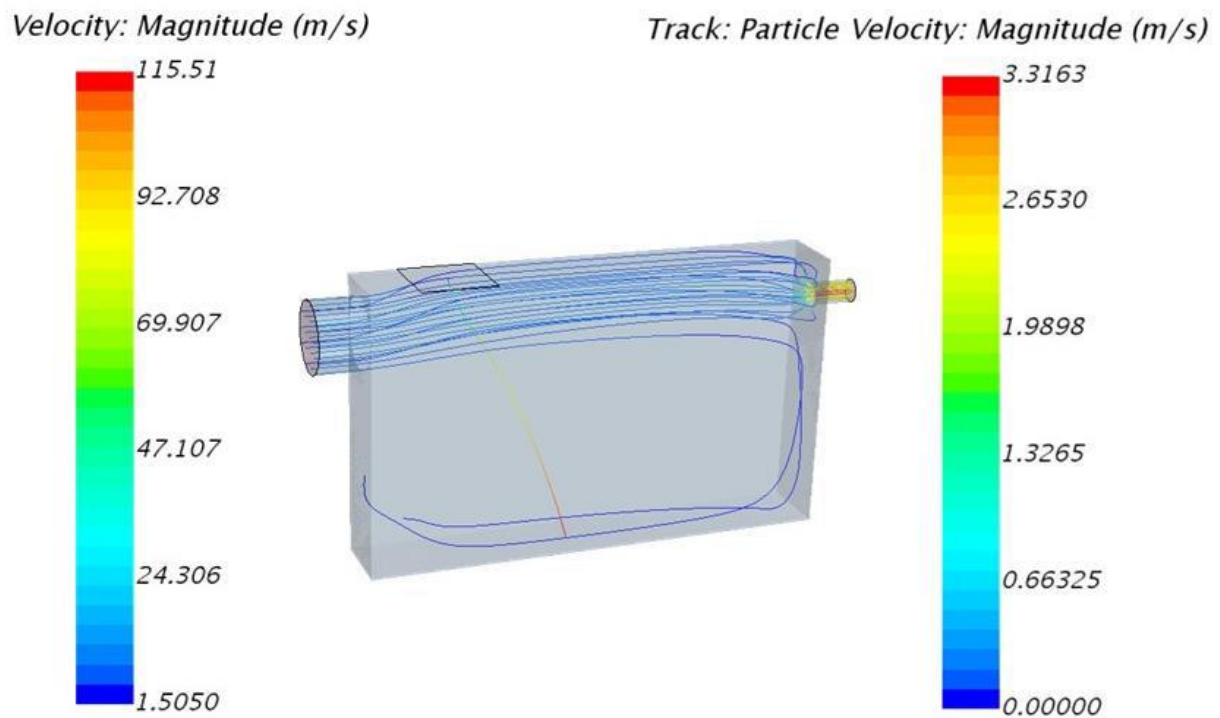


Figure A 4: Particle and airflow tracking scene

Figure A 4 shows the movement of the air as it enters and exits the unit, with the velocity of the air colour coded and shown by the colour bar on the left-hand side. Figure A 4 also predicts the movement of a particle once it enters the system. The prediction shows the displacement and the particle velocity throughout the separation unit and is colour coded in accordance with the colour bar on the right-hand side of the figure.

To determine the displacement of the particle a measuring tool in Star CCM + is used which determines the distance between the particle inlet and the final displacement point of the particle. This measurement is taken for each particle that enters the system and serves as the recorded displacement data for the simulation.

Following the above procedure, several versions of these scenes are generated each one with a change in either the airflow velocity, particle size or particle density. These results are seen in the displacement matrix in Chapter 2 and aided in the design of the winnowing chamber.