



Dry beneficiation of South African coals using an upwards cyclic air flow

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Promoter: Prof M le Roux

Co-promoter: Prof QP Cambell

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PREFACE

This manuscript is a culmination of the author's doctoral research at North-West University, submitted with the aim of examination and completion of a PhD. The preface of this thesis serves the purpose of providing an organized synopsis, elucidating pertinent rules, guidelines, preferences, consent protocols, deliverables, and acknowledgements relevant to the research undertaking. Additionally, an abstract is incorporated to furnish an overview of the study's scope, broader objectives and primary outcomes of the investigation.

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Rules, thesis outline and preferences

This thesis comprises four distinct original articles, prepared in a state ready for submission to and publication in a scholarly journal. Supplementary information, pertinent to the thesis but not integrated within the articles, is presented in intervening chapters. This arrangement adheres to the stipulations delineated by the General Academic Rules outlined by the North-West University, initially sanctioned on September 21, 2017, and revised in March 2020. The list of complete rules can be obtained at: http://www.nwu.ac.za/content/policy_rules. Rules pertaining to the submission of the thesis include numbers 5.3.1, 5.10.4, 5.10.5, 5.10.8, 5.10.9, 5.12.5, 5.12.6, 5.12.7 and 5.12.8 find relevance within the context of the present study. These are quoted below.

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It is essential to acknowledge that text formatting, numbering of figures and tables, and referencing style underwent standardization to ensure a consistent and uniform presentation of the thesis layout. A compilation of references consulted during each chapter is furnished at the conclusion of the respective chapter.

Declaration

I, **Nikki Hughes**, hereby declare that the thesis entitled:

Dry beneficiation of Southern African coals using upward cyclic airflow

is the original outcome of my own diligent effort and has not been previously presented to any other academic institution. In instances where publications have been co-authored and information has been derived from collaborative endeavors, due permissions have been procured in written form from the respective authors. The contributions of these co-authors are duly acknowledged within the pertinent chapters of this thesis.

A handwritten signature in black ink, appearing to read 'Nikki Hughes', is positioned above a horizontal line.

Nikki Hughes

Statements from co-authors

This study has benefited from the valuable contributions of several co-authors, whose involvement is duly recognized and disclosed in the respective chapters of this thesis. Enclosed herewith are signed letters of consent from each co-author, affirming their agreement and approval to be acknowledged in this research endeavor.

- Professor Marco le Roux.....(Page VII)
- Professor Quentin P. Campbell.....(Page VIII)
- Doctor Fardus Nakhaei.....(Page IX)
- Mister Frikkie van der Merwe.....(Page X)

Statement of consent: Professor Marco le Roux

To Whom It May Concern,

I, **Marco le Roux**, hereby grant my full consent to **Nikki Hughes**, a candidate pursuing the degree of Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of North-West University, to incorporate the following publications, in which I have co-authored, into her thesis titled **“Dry Beneficiation of South African Coal with Upward Cyclic Airflow”**:

Hughes, N., le Roux, M., Campbell, Q.P. 2019. Dry processing for coal preparation: a review. Southern African Coal Processing Society International Coal Conference, Secunda. 19–22 August 2019.

Hughes, N., le Roux, M., Campbell, Q.P. 2019. Dry processing for coal preparation: a review. Coaltech Colloquium, Witbank. 11 October 2019.

Hughes, N., le Roux, M., Campbell, Q.P. 2019. Dry processing for coal preparation: a review. XXX International Mineral Processing Congress, Cape Town South Africa. 18–22 April 2021.

Hughes, N., le Roux, M., Campbell, Q.P. 2021. Dry processing for coal preparation: a review. Australian Coal Processing Conference, NSW Australia. 8 –12 March 2021.

Hughes, N., le Roux, M., Campbell, Q.P., Nakhaie, F. 2021. Dry coal beneficiation practices: a review. Submitted to Minerals Engineering.

Hughes, N., le Roux, M., Campbell, Q.P., van der Merwe, F. 2023. CFD evaluation of the airflow characteristics in an air-gravity separation unit using suction fluidization. Submitted to Separation and Purification Technology.

Hughes, N., le Roux, M., Campbell, Q.P. 2023. Evaluation of pneumatic suction fluidization for the beneficiation of +3.2-6.7 mm Southern African coal. Submitted to Coal Preparation and Utilization.

Hughes, N., le Roux, M., Campbell, Q.P. 2023. Beneficiation of +6.7-13.2 mm Southern African coal using pneumatic suction fluidization. Submitted to Coal Preparation and Utilization.



Statement of consent: Professor Quentin Peter Campbell

To Whom It May Concern,

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Hughes, N., le Roux, M., Campbell, Q.P. 2023. Beneficiation of +6.7-13.2 mm Southern African coal using pneumatic suction fluidization. Submitted to Coal Preparation and Utilization.



Statement of consent: Doctor Fardis Nakhaei

To Whom It May Concern,

I, **Fardis Nakhaei**, hereby grant my full consent to **Nikki Hughes**, a candidate pursuing the degree of Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of North-West University, to incorporate the following publications, which I have co-authored, into her thesis titled "**Dry Beneficiation of South African Coal with Upward Cyclic Airflow**":

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F. nakhaei

Statement of consent: Mister Frikkie van der Merwe

To Whom It May Concern,

I, **Frikkie van der Merwe**, hereby grant my full consent to **Nikki Hughes**, a candidate pursuing the degree of Philosophiae Doctor in Chemical Engineering at the Potchefstroom Campus of North-West University, to incorporate the following publications, in which I have co-authored, into her thesis titled "**Dry Beneficiation of South African Coal with Upward Cyclic Airflow**":

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F. vd Merwe

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- Lastly, I extend my heartfelt gratitude to our Creator and Protector, God Almighty. With profound humility, I bow before You and express gratitude for fortitude and the myriad of blessings that You have bestowed upon me.

“The value of achieving goals, lies in the person that you become during the pursuit.”

Deliverables

i. Local colloquium proceedings

Hughes, N., le Roux, M., Campbell, Q.P. 2019. Dry processing for coal preparation: a review. Coaltech Colloquium, Witbank. 11 October 2019.

ii. International conference proceedings

Hughes, N., le Roux, M., Campbell, Q.P. 2019. Dry processing for coal preparation: a review. Southern African Coal Processing Society International Coal Conference, Secunda. 19–22 August 2019.

Hughes, N., le Roux, M., Campbell, Q.P. 2019. Dry processing for coal preparation: a review. XXX International Mineral Processing Congress, Cape Town South Africa. 18–22 April 2021.

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iii. Papers ready for publishing in conference proceedings or peer reviewed journals

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Hughes, N., le Roux, M., Campbell, Q.P., van der Merwe, F. 2023. CFD evaluation of the airflow characteristics in an air-gravity separation unit using suction fluidization. Submitted to Separation and Purification Technology.

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Hughes, N., le Roux, M., Campbell, Q.P. 2023. Evaluation of pneumatic suction fluidization for the beneficiation of +3.2-6.7 mm Southern African coal. Submitted to Coal Preparation and Utilization.

iv. Video and other interviews

Video interview with Laura Cornish from Mining Review Africa at the SACPS International Coal Conference. Link: https://lnkd.in/ea_k8iD

Personal interview with Johan De Korte from CSIR regarding the future of dry coal beneficiation in South Africa. Pretoria, May 2019.

Personal interview with Andrey Stepanenko from Gormash Export, Novosibirsk Russia, regarding the SEP-AIR process for dry coal beneficiation. Novosibirsk, September 2019.

Abstract

Globally, coal retains its pivotal role as a significant energy resource and in manufacturing steel. This is due to its recognized abundance, cost-effectiveness, and reliability. However, the water-intensive nature of the current coal processing practices raises concerns about their practicality and sustainability, particularly in arid, frigid, and underdeveloped regions.

Consequently, the existing coal processing practices may necessitate adaptation due to their unsustainable water usage, regardless of potential technical and economic feasibility improvements. Developing efficient dry beneficiation methods has emerged as an attractive area of research. This thesis presents a comprehensive review article that consolidates information regarding the principles and outcomes of commercially available and experimental dry coal beneficiation processes. These methods exhibit significant potential and, with careful consideration of potential limitations and further investigation, could find future application through the establishment of new large and small-scale plant installations, expansions, and processing of coal fines.

Among these methods, the SEP-AIR unit, developed by Gormash Export in Novosibirsk, Russia, exhibits promise in addressing specific challenges encountered by the South African coal processing industry. These challenges involve water scarcity and depleting reserves, which force the processing of finer particles (already being processed wet for many types of non-oxidized coal) and mining coal deposits in remote and underdeveloped regions. Traditional water-based mining methods may prove impractical for these conditions.

The SEP-AIR system employs density separation using air as a medium to induce particle fluidization and subsequent stratification based on size, shape, and density. Diverging from most commercial dry, dense medium processes, the SEP-AIR employs suction force generated by a centrifugal fan and a specially designed separation nozzle to elevate particles and create a semi-fluidized bed with pseudo-fluid characteristics. The inventive separation nozzle design creates a vortex that captures sufficiently fluidized particles. The modular design of the SEP-AIR unit, coupled with its ability to handle dust, proves crucial. Additionally, the absence of water or additional dense medium materials eliminates the need for post-processing separation and drying, leading to decreased capital and operational expenses. While the separation efficiency of the SEP-AIR unit aligns with that of other dry processes, it may not reach the level achieved by wet processes. Nevertheless, it offers substantial throughput at high yield for particles ranging from 1 to 100 mm, including the typically discarded in dry cleaning (1–6 mm) for which studies are not as extensively reported.

Hence, this study aims to examine the potential of employing the SEP-AIR process to efficiently beneficiate smaller size fractions within Southern African coal types, encompassing the range of +3.2-13.2 mm. To achieve this objective, a laboratory-scale separation unit resembling the SEP-AIR was constructed per manufacturer specifications. The unit was subsequently established and operationalized at the North-West University Potchefstroom Campus. A sequence of experiments was undertaken to investigate airflow characteristics, single-particle dynamics, multi-particle interactions, and assessments of coal separation efficiency. The findings from these experiments constitute the core content of this thesis.

Fluidization-based separation mechanisms are influenced by both the characteristics of airflow and particle interactions. Therefore, understanding the airflow dynamics and particle behaviour within the separation unit is crucial. To explore the former, this thesis includes an article detailing airflow simulation within the laboratory-scale SEP-AIR using Computational Fluid Dynamics (CFD) and subsequent validation experiments. The investigation includes three distinct airflow intensities: low, medium, and high. Comparison between modelled and experimental velocities demonstrates a notable degree of agreement. For the low flow system, the coefficient of determination (R^2), root-mean-square-error (RMSE) and mean absolute error (MAE) values were determined as 0.95, 1.13, and 0.81, respectively. Similarly, the R^2 , RMSE, and MAE values for the medium flow system were found to be 0.93, 4.09, and 3.09, respectively. Lastly, the R^2 , RMSE, and MAE values were obtained for the high flow system as 0.94, 6.78, and 5.14, respectively.

A series of experiments were executed utilizing single particle tracers of 8 mm, with varying densities of 1.4, 1.6, 1.8 and 2.0 SG. These experiments aimed to discern the particle dynamics within the separation unit across different airflow settings. Qualitative observations were documented, focusing on the movement, fluidization, and retention of both single-particle tracers and multiple-particle tracers. From these observations, optimal parameters relating to airflow settings, residence time, and mass loading were determined to efficiently separate particles with distinct densities and sizes. It was noted that individual particles' behaviour aligned with the prevailing airflow conditions. Furthermore, the interactions among multiple particles in conjunction with the air during the fluidization process yielded the formation of a semi-fluidized bed characterized by pseudo-fluidic traits. Consequently, lower airflow settings were found to be a prerequisite for achieving effective separation, compared to the conditions observed in single-particle experiments. These characteristics were evident in the simulated particle tracks, corroborating the findings.

The thesis includes articles detailing investigations conducted to assess the potential of the SEP-AIR for beneficiating smaller coal fractions in Southern Africa, specifically the +6.7-13.2 mm (referred to as 'pea-sized') and +3.2-6.7 mm (referred to as 'duff-sized') ranges. Within the former study, three coal samples—WB1, WB2 (from Waterberg coalfield in Limpopo, South Africa), and MOAT (from Moatize coalfield in Tete, Mozambique)—were examined, resulting in separation efficiencies (Ecart Probable Moyen — EPM) of 0.25, 0.05, and 0.04, respectively. Notably, high yields of 81%, 81%, and 82% were achieved for WB1, WB2, and MOAT, respectively. Improvements were observed in product ash values, with reductions from 36% to 26% for WB1, 20% to 10% for WB2, and 17% to 12% for MOAT. Calorific values increased from the feed's 22, 28, and 30 MJ/kg for WB1, WB2, and MOAT to 26 MJ/kg for WB1 and 32 MJ/kg for both WB2 and MOAT. Additionally, slight enhancements were observed in cut-point densities, transitioning from the feed's 1.63 SG to 1.53 SG in the product for WB1, 1.47 SG to 1.44 SG for WB2, and 1.44 SG to 1.40 SG for MOAT.

For the +3.2-6.7 mm particle size range, coal samples from the Waterberg and Moatize coalfields were investigated, yielding separation efficiencies (EPMs) of 0.15 and 0.05, respectively. The product ash value improved, reducing from 34.12% in the feed to 27.91% for Waterberg and from 16.52% in the feed to 13.12% for Moatize. Calorific values improved from 22.60 MJ/kg in the feed to 25.06 MJ/kg for the Waterberg and from 29.56 MJ/kg in the feed to 30.75 MJ/kg for the Moatize. The yield was reported at 75% and 95% for the Waterberg and Moatize, respectively. Furthermore, slight enhancements were observed in the cut-point densities, with values changing from 1.61 SG in the feed to 1.55 SG in the product for Waterberg and from 1.44 SG in the feed to 1.43 SG in the product for Moatize.

Furthermore, considering the varied coal qualities tested, different airflow settings were explored. An Analysis of Variance (ANOVA) test revealed that coal feed quality, more specifically particle properties relating to size and density distributions, played a dominant role in separation efficiency and product quality. Moreover, the particle size separation, combined with the trends observed in particle misplacement, indicates that the separation mechanism is governed by particle weight and not density. Conversely, air speed notably affected product yield, with higher air speeds corresponding to increased yields. Notably, adjustments to fan settings (airspeed) had limited influence on product quality.

The efficacy of the SEP-AIR in beneficiating +3.2-13.2 mm Southern African coal fractions is evident through enhancements in ash and calorific values, achieved at substantial throughput and yield. While separation efficiencies achieved fall below those of wet processes employed for analogous size ranges, they remain consistent with other dry methods. The interplay between

particle and airflow properties is important, affecting different aspects of the separation process. The characteristics of the fluidization and subsequent separation process are governed by particle properties such as size, shape, and density, as well as the interaction of these properties with one another, the air, and unit walls.

Key terms: small coal beneficiation, dry processing, fluidization, computational fluid dynamics (CFD).

TABLE OF CONTENTS

PREFACE.....	I
STUDENT AND STUDY DETAILS	II
RULES, THESIS OUTLINE AND PREFERENCES.....	III
DECLARATION	V
STATEMENTS FROM CO-AUTHORS	VI
ACKNOWLEDGEMENTS	XI
DELIVERABLES	XII
ABSTRACT	XIII
TABLE OF CONTENTS	XVII
LIST OF TABLES	XXI
LIST OF FIGURES.....	XXV
LIST OF EQUATIONS	XXVIII
LIST OF ABBREVIATIONS	XXIX
LIST OF UNITS AND SYMBOLS	XXXI
CHAPTER 1: INTRODUCTION.....	1
1.1 BACKGROUND AND MOTIVATION	1
1.2 AIM AND OBJECTIVES.....	4
1.3 HYPOTHESIS.....	5
1.4 SCOPE OF STUDY	6
1.5 LAYOUT OF THE THESIS.....	6
1.6 REFERENCES FOR CHAPTER 1	9
CHAPTER 2: OVERVIEW OF COAL PREPARATION.....	14
2.1 COAL RESOURCE.....	14
2.1.1 <i>Defining coal and its origins.....</i>	<i>14</i>
2.1.2 <i>Coal geology.....</i>	<i>15</i>
2.1.3 <i>South African coal resources</i>	<i>19</i>
2.1.4 <i>Coal products and utilization</i>	<i>20</i>
2.1.5 <i>Preparation.....</i>	<i>22</i>
2.1.6 <i>Beneficiation</i>	<i>23</i>
2.1.7 <i>Dry beneficiation methods</i>	<i>25</i>
2.2 REFERENCES FOR CHAPTER 2	27
CHAPTER 3: A REVIEW OF DRY COAL BENEFICIATION (PAPER 1).....	31

3.1	A REVIEW OF THE DRY METHODS AVAILABLE FOR COAL BENEFICIATION (PAPER 1).....	31
3.1.1	<i>Abstract</i>	32
3.1.2	<i>Introduction</i>	32
3.1.3	<i>Dry coal processing techniques</i>	34
3.1.4	<i>Applicability and limitations of the various dry processing techniques</i>	47
3.1.5	<i>Operating parameters</i>	53
3.1.6	<i>Performance</i>	55
3.1.7	<i>Conclusions</i>	69
3.2	REFERENCES FOR CHAPTER 3	71
CHAPTER 4: THE POTENTIAL FOR SEP-AIR IN SOUTH AFRICA		91
4.1	SEP-AIR FOR SOUTH AFRICAN COAL PROCESSING	91
4.2	OPERATING PRINCIPLE AND RELEVANT THEORY	93
4.2.1	<i>Fluidization principle</i>	93
4.2.2	<i>Minimum fluidizing velocity</i>	96
4.2.3	<i>Bubble formation</i>	98
4.2.4	<i>Particle classification</i>	98
4.3	DESIGN AND COMMISSIONING OF A LABORATORY SCALE SEPARATING UNIT.	99
4.3.1	<i>Feeding process</i>	99
4.3.2	<i>Separating process</i>	100
4.3.3	<i>The centrifugal fan</i>	101
4.3.4	<i>The laboratory-scale unit</i>	102
4.4	AIRFLOW BEHAVIOUR	104
4.5	PARTICLE BEHAVIOUR	109
4.5.1	<i>Theoretical minimum fluidizing velocity</i>	109
4.5.2	<i>Single particle behaviour</i>	111
4.5.3	<i>Multiple particle behaviour</i>	115
4.6	CONCLUSION AND RECOMMENDATIONS	117
4.7	REFERENCES FOR CHAPTER 4	118
CHAPTER 5: CFD SIMULATION OF AIRFLOW (PAPER 2).....		121
5.1	COMPUTATIONAL FLUID DYNAMICS (CFD).....	121
5.1.1	<i>Meshing</i>	122
5.1.2	<i>Continua</i>	124
5.1.3	<i>Boundary and initial conditions</i>	125
5.1.4	<i>Solution and Convergence</i>	126
5.1.5	<i>Governing equations</i>	127
5.1.6	<i>Summary</i>	131

5.2	CFD EVALUATION OF THE AIRFLOW CHARACTERISTICS IN AN AIR-GRAVITY SEPARATION UNIT USING SUCTION FLUIDIZATION (PAPER 2)	133
5.2.1	<i>Abstract</i>	134
5.2.2	<i>Introduction</i>	135
5.2.3	<i>Description of the laboratory-scale separation unit and function</i>	136
5.2.4	<i>Model development</i>	138
5.2.5	<i>Experimental method</i>	141
5.2.6	<i>Results</i>	142
5.2.7	<i>Discussion</i>	153
5.2.8	<i>Conclusion and Recommendations</i>	155
5.3	CFD SIMULATION OF PARTICLE FLOW	157
5.3.1	<i>Lagrangian multi-phase simulation of particles</i>	157
5.4	REFERENCES FOR CHAPTER 5	163
CHAPTER 6: DRY BENEFICIATION OF +6.7-13.2 MM COAL (PAPER 3)		168
6.1	AIR-GRAVITY BENEFICIATION OF +6.7-13.2 MM SOUTHERN AFRICAN COAL USING A COMBINATION OF SUCTION AND VORTEX FLUIDIZATION (PAPER 3)	168
6.1.1	<i>Abstract</i>	169
6.1.2	<i>Introduction</i>	169
6.1.3	<i>Background and motivation</i>	170
6.1.4	<i>Experimental</i>	171
6.1.5	<i>Results</i>	177
6.1.6	<i>Analysis of variance (ANOVA)</i>	179
6.1.7	<i>Suction velocity</i>	179
6.1.8	<i>Feed quality</i>	181
6.1.9	<i>Particle size</i>	182
6.1.10	<i>Efficiency tests at best operating conditions</i>	183
6.1.11	<i>Beneficiation results in context to the South African coal market</i>	185
6.1.12	<i>Conclusion</i>	187
6.2	REFERENCES FOR CHAPTER 6	189
CHAPTER 7: DRY BENEFICIATION OF +3.2-6.7 MM COAL (PAPER 4)		193
7.1	EVALUATION OF PNEUMATIC SUCTION FLUIDIZATION FOR THE BENEFICIATION OF +3.2-6.7 MM SOUTHERN AFRICAN COAL (PAPER 4)	193
7.1.1	<i>Abstract</i>	194
7.1.2	<i>Introduction</i>	194
7.1.3	<i>Background and motivation</i>	196
7.1.4	<i>Experimental</i>	196

7.1.5	<i>Results and discussion</i>	202
7.1.6	<i>Conclusion</i>	209
7.2	REFERENCES FOR CHAPTER 7	211
CHAPTER 8: CONCLUSION AND RECOMMENDATIONS		215
8.1	CONCLUSIONS	215
8.2	RECOMMENDATIONS	219

LIST OF FIGURES

Figure 2.1: The stages of coalification categorized into rank (modified from WCI's 2009 publication).....	16
Figure 2.2: South African coalfields holding economic significance (SACPS, 2015)	20
Figure 2.3: Schematic depicting the standard procedure for coal washing (adapted from SACRM, 2011)	24
Figure 3.1: Schematic of the functioning of a DE-XRT sorter.....	37
Figure 3.2: Schematic of (left) and picture (right) of an ADMFB separator (adapted from Fu <i>et al.</i> , 2019).....	41
Figure 3.3: The SEP-AIR pneumatic separator (from Gormash Export, 2016b).....	42
Figure 3.4: Schematic of an NPPS (left) and a semi-industrial NPPS (right) (Stanczyk <i>et al.</i> , 2021).....	43
Figure 3.5: Schematics of a Winnower (left) (Liu, 2009) and Reflux Classifier (right) (Kopparthi <i>et al.</i> , 2020).....	44
Figure 3.6: Schematic of the operating principle of the RERMS (From Arvidson and Norrgran, 2014).....	45
Figure 3.7: The draft of triboelectrification separation system (Yushuai <i>et al.</i> , 2021).	46
Figure 4.1: The states of fluidization (adapted from Kunii and Levenspiel, 2001).....	94
Figure 4.2: Characteristics resembling a fluidized bed (from Luo and Chen (2001); Mohanta <i>et al.</i> (2011)).....	95
Figure 4.3: Image of suction fan and control box (left) and schematic (right) providing fan dimensions.....	102
Figure 4.4: Images of the separating unit (left) and suction nozzle (right) including labelled sections.....	102
Figure 4.5: Image labelling of the air inlets and conveyor plate.....	103
Figure 4.6: Different perspectives of the separating unit commissioned at the NWU.	104
Figure 4.7: Velocity measuring points in the suction nozzle from the front and side views.....	105

Figure 5.1: Tetrahedral mesh (top left), polyhedral mesh (top right) and polyhedral mesh with prismatic layer (bottom centre) from Symscape (2013).	123
Figure 5.2: Example of residual graph for K-Epsilon Turbulence Model from STAR-CCM+... 132	
Figure 5.3: Schematic (left) and image (right) of the separating unit with components labelled.....	136
Figure 5.4: Suction nozzle assembly constructed in NX-12, trimetric view with compartments labelled (left) and front view with inlets and outlet labelled (right).	138
Figure 5.5: Resulting mesh with cells, inlets, outlet and walls visible.	139
Figure 5.6: Physics models selected for the STAR-CCM+ simulation (made from information from Symscape, 2012; Anderson, 2017; Fernandez, 2019; Ferziger, 2020; Siemens, 2023).	140
Figure 5.7: The points within the suction nozzle where velocity readings were measured (left and right) and the horizontal cross-sections across the height of the fluidizing box (right).	141
Figure 5.8: Parity plot comparing the simulated and experimental velocities in the low flow system.	146
Figure 5.9: Parity plot comparing the simulated and experimental velocities in the medium flow system.	147
Figure 5.10: The parity plot compares the simulated and experimental velocities in the high flow system.....	148
Figure 5.11: CFD simulation results portraying planar views of velocity vectors (A1, B1 and C1) and velocity scalars (A2, B2 and C2) of the airflow in the suction nozzle for the low flow system.....	150
Figure 5.12: CFD simulation results portraying planar views of velocity vectors (A1, B1 and C1) and velocity scalars (A2, B2 and C2) of the airflow in the suction nozzle for the medium flow system.....	151
Figure 5.13: CFD simulation results portraying planar views of velocity vectors (A1, B1 and C1) and velocity scalars (A2, B2 and C2) of the airflow in the suction nozzle for the high flow system.	152

Figure 5.14: OS (A), FS (B) and side views (C and D) of the suction nozzle illustrating particle velocity tracks.	158
Figure 5.15: Magnified views of the particle tracks in the fluidizing box (A and B), vortex chamber (C) and an image of the front OS view with solid particles visible (D)....	160
Figure 5.16: OS (A), FS (B) and side views (C and D) of the suction nozzle illustrating particle residence time tracks.	161
Figure 6.1: Schematic of the laboratory-scale suction nozzle from a trimetric view (left) and front view (right).....	172
Figure 6.2: Separating unit with suction nozzle, feeding belt, suction fan and collecting bin labelled.....	173
Figure 6.3: Comparison of the PSDs in the feed for the WB1, WB2 and MOAT coal samples.....	174
Figure 6.4: Comparison of the density distributions in the feed for the WB1, WB2 and MOAT coal samples.	175
Figure 6.5: Comparison of PSD for the feed, product and discard of repeated efficiency tests (ETs) with WB2.....	176
Figure 6.6: Comparison of density profile for the feed, product and discard of repeated efficiency tests (ETs) with WB2.	177
Figure 6.7: Partition curves of the product for the WB1, WB2 and MOAT +6.7-13.2 mm efficiency tests at best operating conditions.	185
Figure 6.8: PSD of the feed, product and discard for the WB1, WB2 and MOAT +6.7-13.2 mm efficiency tests at best operating conditions.....	185
Figure 7.1: The laboratory-scale separating unit from different angles shows the feeding system and suction fan (left), suction nozzle with fluidizing box, vortex chamber and connecting pipe (centre) and collection bin (right).	197
Figure 7.2: A comparison of the PSDs of the Waterberg and Moatize coal samples.....	199
Figure 7.3: Comparison of the density distributions for the Waterberg and Moatize coal samples.....	199
Figure 7.4: Comparison of PSD for the feed, product and discard of repeated efficiency tests (ETs) with MOAT.	201

Figure 7.5: Comparison of density profiles for the feed, product and discard of repeated efficiency tests (ETs) with MOAT.....	201
Figure 7.6: The density distributions of the feed and partition curves for the product and discard for the Waterberg +3.2-6.7 mm efficiency test at best operating conditions.....	204
Figure 7.7: The density distributions of the feed, product and discard for the Waterberg +3.2-6.7 mm efficiency test at best operating conditions.	205
Figure 7.8: The density distributions of the feed, product and discard for the Moatize +3.2-6.7 mm efficiency test.....	206

LIST OF TABLES

Table 2.1: Common traits of coal products from South Africa (IPC, 2016; SACRM, 2011; Steyn and Minnitt, 2010)	21
Table 2.2: Coal size classification and typical characteristics for South African coals (SACRM, 2011).....	23
Table 3.1: A comparison of the principle of operation of various air jigs and air tables (Hughes <i>et al.</i> , 2019).....	39
Table 3.2: Particle size distribution and capacity ranges for the dry processing techniques.....	49
Table 3.3: Typical performance data for a DE-XRT.	55
Table 3.4: Performance data for some commercially available dry coal gravity separation methods.	56
Table 3.5: The performance data available for experimental dry coal gravity separation methods.	64
Table 4.1: Description and units of the symbols used in the Ergun equation.	97
Table 4.2: Dimensions of the laboratory-scale separating unit.....	103
Table 4.3: Summary of the velocity vectors (in m/s) measured in the separating unit at different suction fan settings.....	106
Table 4.4: Theoretical minimum fluidizing velocities for different particle properties.	109
Table 4.5: Particle capture rate, time and observations noted for differing density tracers at various suction fan settings.	111
Table 4.6: Particle capture rate, time and observations noted for differing density tracers at specific suction fan settings.....	113
Table 4.7: Results of the combined coal and density tracer tests at various suction fan settings	115
Table 4.8: Results of the productivity tests conducted at different residence times.....	117
Table 5.1: Dimensions of the laboratory scale separating unit.	137
Table 5.2: The mean velocity magnitudes and standard deviation observed at different suction fan settings.	142

Table 5.3: Velocity in the fluidizing chamber at different horizontal planar views in the z-direction	144
Table 5.4: Comparison of the ranges of velocity magnitude and direction between the experiment and simulation for the different sections of the suction nozzle in the low flow system.	146
Table 5.5: Comparison of the velocity magnitude and direction ranges between the experiment and simulation for the different sections of the suction nozzle in the medium flow system.	147
Table 5.6: Comparison of the ranges of velocity magnitude and direction between the experiment and simulation for the different sections of the suction nozzle in the high flow system.	149
Table 6.1: Feed quality of the WB1, WB2 and MOAT coal samples under consideration.	174
Table 6.2: Product quality and process efficiency variables demonstrating repeatability.	176
Table 6.3: Suction fan setting and corresponding fan-side, other-side and connecting pipe velocities.	178
Table 6.4: Efficiency test results obtained at different suction fan settings for WB1, WB2 and MOAT coal.	178
Table 6.5: Two-factor ANOVA with replication for the interaction of coal feed quality and suction fan setting with process efficiency and quality of product and discard streams.	179
Table 6.6: Single factor ANOVA for the interaction of suction fan setting with process efficiency and quality of product and discard streams.	180
Table 6.7: Single factor ANOVA for the interaction of coal feed quality with process efficiency and quality of product and discard streams.	181
Table 6.8: Results of the WB1, WB2 and MOAT coal efficiency tests at best operating conditions.	183
Table 6.9: Product specifications of coal for several South African coal markets (Steyn and Minnit, 2010).	187
Table 7.1: Feed quality of the Waterberg and Moatize coal samples under consideration.	198
Table 7.2: Product quality and process efficiency variables demonstrating repeatability.	200

Table 7.3: Suction fan setting and corresponding fan-side, other-side and connecting pipe velocities.	202
Table 7.4: Efficiency test results obtained at different suction fan settings for Waterberg and Moatize coal.	202
Table 7.5: Two factor ANOVA with replication for the interaction of coal feed quality and suction fan setting with process efficiency and quality of product and discard streams.	203
Table 7.6: Results of the Waterberg coal efficiency test for +3.2-6.7 mm particle size range.....	204
Table 7.7: Results of the Moatize coal efficiency test for +3.2-6.7 mm particle size range.	205
Table 7.8: Single factor ANOVA for the interaction of suction fan setting with process efficiency and quality of product and discard streams.....	207
Table 7.9: Single factor ANOVA for the interaction of coal feed quality with process efficiency and quality of product and discard streams.....	208
Table 7.10: Product specifications of coal for various South African coal markets (Steyn and Minnitt, 2010).	209

LIST OF EQUATIONS

Equation 4.1.....	95
Equation 4.2.....	95
Equation 4.3.....	95
Equation 4.4.....	95
Equation 4.5.....	95
Equation 4.6.....	95
Equation 4.7.....	95
Equation 4.8.....	95
Equation 5.1.....	125
Equation 5.2.....	125
Equation 5.3.....	127
Equation 5.4.....	126
Equation 5.5.....	126
Equation 5.6.....	126
Equation 5.7.....	127
Equation 5.8.....	127
Equation 5.9.....	127
Equation 5.10.....	127
Equation 5.11.....	128
Equation 5.12.....	128
Equation 5.13.....	128
Equation 5.14.....	128

LIST OF ABBREVIATIONS

ADMFB	Air dense medium fluidized bed
ANOVA	Analysis of variance
ARD	Apparent relative density
AV	Ash value
BD	Bulk density
CFD	Computational fluid dynamics
CFB	Continuous fluidized bed
CV	Calorific value
D ₅₀	Cut point at 50%
DC	Direct current
DES	Detached eddy simulation
DE-XRT	Dual energy x-ray transmission
DMR	Department of Mineral Resources
DMRE	Department of Mineral Resources and Energy
DMVFB	Dense medium vibrated fluidized bed
DRC	Dense medium reflux classifier
GCM	Groote Geluk Mine
<i>et al</i>	and colleagues
EMP	Euler multi-phase
EPM	Ecart Probable Mooyen
EOS	Equation of state
FB	Fluidizing box
FS	Fan side inlet
LES	Large eddy simulation
LMP	Lagrangian multi-phase
MAE	Mean absolute error
MOAT	Moatize coal sample
NPPS	Negative pressure pneumatic separator
NWU	North-West University
OS	Other side inlet
PSD	Particle size distribution
R ²	Coefficient of determination
RC	Reflux classification
RANS	Reynolds averaged Navier-Stokes
RERMS	rare-earth-roll-magnetic separators

RMSE	Root mean square error
ROM	Run of mine
RPM	Revolutions per minute
RST	Reynolds stress turbulence
RTS	Rotary triboelectrification separator
SA	South Africa
SACPS	Southern African Coal Processing Society
SACRM	South African Coal Roadmap
SBS	Sensor based sorting
SG	Specific gravity
TBS	Tribo-electrostatic
TRD	True relative density
VFB	Vibrated fluidized bed
WB1	Waterberg coal sample 1
WB2	Waterberg coal sample 2
WCI	World Coal Institute
3D	Three dimensional
2D	Two dimensional

LIST OF UNITS AND SYMBOLS

α	Model constant
A_t	Cross-sectional bed area (m^2)
β	Model constant
d_p	Particle diameter (mm)
D_{ij}	Diffusion
ε	Bed voidage (dimensionless)
ε	dissipation of turbulence kinetic energy
e	Internal energy (J)
F	Force (N)
f	Friction (N)
g	gravitational constant (m/s^2)
g/cm^3	gram per cubic centimetre (unit for density)
GHz	Giga Hertz (unit for frequency)
H_b	Bed Height (m)
Hz	Hertz (unit for frequency)
κ	turbulence kinetic energy
kg/m^3	kilogram per cubic meter (unit for density)
KW	Kilowatt (unit for power)
m	mass (kg)
m^3/hr	cubic meter per hour (unit for volumetric flow)
mm	Millimetre (unit for distance)
m/s	meters per second (unit for speed)
MJ/kg	Mega-joules per kilogram (unit for heating value)
μ	Dynamic viscosity ($kg/m/s$)
Ω_{ij}	Rotation
ω	specific dissipation of turbulence kinetic energy
%	Percent
P	Pressure
Pa	Pascal (unit for pressure)
P_{ij}	Production
ΔP	Pressure difference (Pa)
Π_{ij}	Pressure strain
Q	Heat (J)

Re	Reynolds number (dimensionless)
Rij	Rate of dissipation
ρ	density (kg/m ³)
S	Surface area (m ²)
σ	Model constant
ϕ	Particle sphericity (dimensionless)
T	Tesla (unit for strength of magnetic field)
tph	tonnes per hour (unit for throughput)
τ	Model constant
U _{mf}	Minimum fluidizing velocity (m/s)
u	Superficial velocity (m/s)
V	Velocity (m/s)
ν_t	Turbulent viscosity (kg/m/s)
W	Watt (unit for power)
W	Work (J)
W _b	Bed weight (N)
x	x-direction
y	y-direction
z	z-direction

CHAPTER 1: INTRODUCTION

This chapter provides the background and motivation that underpins this research study. The focal point of this introduction lies in addressing the pressing issues evident in the South African coal mining industry, particularly pertaining to the challenges posed by substantial water requirements in coal processing which results in substantial wastage and environmental pollution. The financial repercussions and ecological implications stemming from wet coal processing serve as the catalyst for the development of enhanced dry beneficiation technologies. Additionally, the challenges posed by the decreasing coal reserves are addressed with a focus on mining in remote areas and on a small scale while including usually discarded fine coal fractions. This study seeks to assess the efficacy of a novel dry processing operation, with the goal of identifying its potential for implementation in South African coal beneficiation practices.

1.1 Background and motivation

Given its widespread availability and cost-effectiveness, coal serves as an indispensable energy source on a global scale (World Energy Council, 2017). However, the non-renewable nature of coal underscores the imperative of employing optimal preparation, beneficiation and utilization techniques to ensure its prolonged viability. Presently, coal fulfils approximately 27% of the worldwide energy demand (Ritchie, 2021), and this contribution is projected to persist for the foreseeable future with worldwide consumption rising to 7,947 million tonnes in 2021 reaching an all-time high (International Energy Agency, 2022). South Africa (SA), Mozambique and Zimbabwe are the largest coal-producing countries in Africa, with production of 247.4, 7.44 and 2.70 million metric tonnes of coal in 2020, respectively (Statista, 2023).

South Africa is the seventh-largest coal producer (Smith, 2018) and the seventh-largest coal consumer (Worldometer, 2023) in the world. Therefore, coal takes centre stage in South Africa's national energy portfolio, as evidenced by a contribution of 72% to the country's primary energy needs (Eskom, 2021). This energy landscape is projected to remain relatively unchanged over the next few decades due to the dearth of feasible alternative energy sources. South Africa's coal sector played a significant role in the global export market, accounting for 28%, with a mere 1% directed towards imports, and making South Africa the fifth largest exporter of coal globally (Department of Mineral Resources and Energy, 2023; Workman, 2022; Eskom, 2021). Furthermore, within the South African context, coal assumes a critical role in industries such as steel, iron, and cement production using 12% of the total coal production. A further 33% is used

in petrochemical industries such as Sasol to produce synthetic fuels, and 2% is used for domestic heating and cooking (Eskom, 2021).

The coal mining sector in South Africa emerges as a cornerstone of the nation's workforce, offering substantial employment opportunities. In 2019, the broader mining industry supported more than 485,000 individuals, with approximately 92,000 contributing to coal mining as reported by the Minerals Council of South Africa (2020). Thus, constituting nearly 19% of the overall mining workforce, the South African coal mining sector ranks as the third-largest employer within the national mining landscape (Minerals Council of South Africa, 2020). Given its significance as a global energy source and its profound economic implications, the sustainable trajectory of coal holds immense importance for South Africa's stability and growth.

The heterogeneous composition of coal necessitates a pre-consumption impurity separation process, known as coal beneficiation, which yields higher-quality coal, thereby mitigating environmental consequences and energy losses (Southern African Coal Processing Society (SACPS), 2015; Chen and Yang, 2003). This beneficiation procedure employs a range of mechanization and water treatment methods. Wet beneficiation techniques, presently industrialized for their high separation efficiencies and throughput, involve significant water consumption (Jambal *et al.*, 2016). Consequently, challenges encompassing licensing, handling, transport, and storage, alongside elevated capital and operational expenses, have arisen (Choung *et al.*, 2006; Kramer, 2022).

Water-scarce coal-producing nations, such as Kazakhstan, India, South Korea, Australia, Indonesia, Japan, South Africa, and China, encounter obstacles in adopting wet beneficiation due to inadequate water resources and seasonal variability (Luo *et al.*, 2014). South Africa contends with a pronounced strain on its water resources, characterized by an annual average rainfall of approximately ± 460 mm, which notably falls well below the global mean of ± 980 mm (Britannica, 2023; SA Facts, 2023). This scarcity of water is exacerbated by irregular precipitation patterns and frequent drought events, as indicated by a drought risk index of 4.44 (Statista, 2023; Department of Forestry, 2023; SA Facts, 2023). Furthermore, general coal mining activities can have enduringly deleterious effects on water resources, including pollution from acid mine drainage, heightened erosion, siltation of surface water, and contamination of local groundwater and borehole yields (South African Coal Roadmap (SACRM), 2011; Shiao and Maddocks, 2014; Ray and Dey, 2020). Notably, South Africa witnesses coal mining operations situated in riparian areas of the Vaal River Basin rendering it susceptible to water pollution (Shiao and Maddocks, 2014).

In addition, contemporary mining operations yield valuable small coal fractions, often dismissed (Modiga *et al.*, 2020). Yet, the growing demand for premium coal necessitates the utilization of these smaller particles at larger capacities (Honaker *et al.*, 2008). However, the distinctive characteristics of smaller coal particles (Sivamohan, 1990; Majumder *et al.*, 2003; Amariei *et al.*, 2014; Das and Sarkar, 2018) engender complexity in wet beneficiation processes, making them intricate and resource-intensive (Bada *et al.*, 2010). However, Wet treatment of these finer particles typically yields lower ash products, helpful in marketing the product and contributing to increased energy recovery. Furthermore, numerous coal reserves are situated in remote and underdeveloped areas of South Africa, characterized by limited infrastructure, rendering the mining and beneficiation of coal infeasible (Jeffrey, 2005).

The preceding paragraphs highlight two significant issues concerning existing demand and beneficiation techniques: i) the presence of water shortages and associated pollution, and ii) the impending necessity to beneficiate untapped reserves, particularly the small coal fractions, and to engage in mining within remote and underdeveloped coalfields. Consequently, a search for innovative beneficiation methodologies has emerged with the goal of enhancing coal processing efficiency for both large and small coal fractions, while concurrently minimizing reliance on water and its accompanying disadvantages. This impetus has sparked widespread global research initiatives directed at investigating dry beneficiation technologies for coal. Notably, dry processes, characterized by their compactness, modularity, and exemption from post-processing requirements such as dense medium separation or water removal, offer an appealing solution to address issues of water scarcity, water pollution, the processing of small coal fractions, and the challenges associated with mining and processing in remote and underdeveloped regions.

Globally, a diverse array of dry beneficiation techniques has been extensively explored, encompassing methods like pneumatic oscillating tables (Wotruba *et al.*, 2010; Jambal *et al.*, 2022), air jigging (Weinstein and Snoby, 2007), air-dense medium fluidized bed (ADMFB) (Chen and Wei, 2003, 2005; Chen and Yang, 2003; Langner *et al.*, 2018; Hughes *et al.*, 2017; Diedericks *et al.*, 2022), winnowing (Morgan *et al.*, 2019, 2020, 2021; Sakhre *et al.*, 2018), and suction fluidization approaches including the negative pressure pneumatic separator (NPPS) (Stańczyk, 2020; Stańczyk *et al.*, 2021), AMSEP (Moszko *et al.*, 2016), and SEP-AIR (Stepanenko, 2016a; Stepanenko, 2016b). These processes exhibit potential for coal beneficiation within South Africa, where distinct challenges related to water scarcity, coal quality, and the potential necessity to exploit remote reserves and smaller materials in the future are prominent. Nevertheless, consideration must be given to constraints in particle size range, machine capacity, and separation efficiency. Moreover, the effects of coal nature (such as the density profile and near-dense material) need to be considered.

1.2 Aim and objectives

The aim of this research is to discern the most suitable dry processing method for application within the South African small coal processing industry while effectively addressing its distinct challenges in terms of applicability and optimal design and operating parameters. Concurrently, the inquiry aims to evaluate the method's efficacy utilizing Computational Fluid Dynamics (CFD) simulations and physical experiments of beneficiating small coal particles sized below 13.2 mm.

To accomplish this, the study has established the following specific objectives:

- Construct an exhaustive literature review aimed at recognizing and comprehensively examining diverse concerns pertinent to the beneficiation of small coal within the South African coal industry.
- Conduct an extensive review of the existing literature on dry coal processing methods, with a primary emphasis on elucidating their fundamental operational principles, suitability, and efficacy.
- Based on the review, discern a processing approach that demonstrates suitability for integration into the coal processing sector in South Africa, with a specific emphasis on its capacity to effectively tackle the distinct challenges encountered therein.
- Design, construction and commissioning of a laboratory-scale separation unit to scrutinize the intricacies of the separation mechanism and the dynamics governing both airflow and particle interactions. The investigation of airflow attributes will be undertaken through a sequence of tests encompassing varying suction forces. To assess the distinct behaviours of individual and multiple particles, a diverse array of airflow conditions will be applied, and these assessments will be performed through the utilization of coal and tracers characterized by predetermined dimensions and densities. The culmination of these endeavours will enable the determination of key operational parameters, including feed mass, residence time, and optimal air speed and velocity profile.
- Use the results from the airflow and particle behaviour tests to facilitate the simulation of airflow and particle phenomena. NX-12 is an AutoCAD program that renders three-dimensional geometries, and STAR CCM+ is a CFD modelling tool.
- Perform a series of experiments utilizing the laboratory-scale separation unit with the aim of scrutinizing the viability of beneficiating run-of-mine (ROM) coal within the range of +3.2-13.2 mm. These experimental investigations will yield valuable insights into the operational effectiveness of the unit and its associated conditions. Challenges encountered during the experimentation will be identified, thereby facilitating subsequent refinements and

advancements in this technological approach. Parameters subject to testing encompass coal particle size distribution, coal quality attributes, and air velocity.

- Evaluate the separation unit's efficacy by quantifying essential metrics, including mass yield, cut-point density, separation efficiency, and the tally of erroneously misplaced particles. Furthermore, conduct a comprehensive comparison of the characteristics of the resultant product with those of the initial feed, focusing on parameters such as ash number, calorific value, particle size distribution, and density distribution. Through this meticulous assessment, discern the optimal operational conditions that emerge from the experimental test work, representing the most pragmatic and efficient settings for the process.

1.3 Hypothesis

The hypothesis posits that while dry beneficiation processes present notable advantages, it is crucial to acknowledge their associated constraints. While successful separation can be achieved in both large and small coal fractions through dry beneficiation, it is recognized that the efficiency and throughput attained might not consistently match those attainable in wet processing plants. Consequently, the realization of coal beneficiation plants exclusively reliant on dry techniques remains an objective yet to be fully accomplished. These techniques are predominantly employed in regions marked by extreme environmental conditions, and they find utility in pre-concentration applications, scavenging operations, scenarios involving small or remote reserves, instances where extensive coal upgrading is unnecessary, and with coals that are inherently 'easy to separate'. However, given the reliance on coal and the dwindling of coal and water reserves along with the environmental and financial implications of coal beneficiation practices, coal producers may soon be forced to shift to dry processing techniques, even if only partially and in combination with wet processing methods. This is particularly true for the increasing amounts of finer coals (as a result of increased mechanisation in mining), which are more difficult and costly to process with current water-based methods.

The novel SEP-AIR process shows increased potential in dry processing areas where other techniques may lack, offering a comprehensive solution for dry processing that delivers sufficient separation efficiency and product yield at high capacity for both small and large coal fractions. Nevertheless, limited studies have been published regarding the separation efficiency achieved for smaller South African coal fractions. This aspect, where the SEP-AIR exhibits an advantage over other available dry processes, serves as the primary objective of the research compiled in this thesis: confirming the capabilities of the SEP-AIR to beneficiate small-sized southern hemisphere coals.

1.4 Scope of study

This thesis encompasses a tripartite scope of investigation. It involves conducting an exhaustive review study to assess the applicability and efficacy of existing dry coal processing methodologies. This evaluation aims to discern those techniques that align with the specific requirements of the South African coal industry from which one is selected for further investigation. Secondly, a series of meticulously designed and executed experiments are conducted on three different qualities of small coal (+3.2-13.2 mm), two from the Waterberg coalfield in Limpopo, South Africa and one from the Moatize coalfield in Tete, Mozambique, using a laboratory-scale unit. This unit, conceived, constructed, and operationalized as a study component, is the platform for these investigations. From these experiments, the efficiency of the separating unit can be determined. Lastly, the study involves the CFD simulation of airflow dynamics and particle trajectories using the STAR CCM+ software.

It is essential to highlight the inclusion of the Moatize coal sample in these studies. Mozambique, the second-largest coal producer in Africa, has recently faced severe drought conditions. Therefore, any method proven applicable to South Africa should also be relevant to Mozambique and other coal-producing nations across the African continent. Utilizing a Waterberg coal sample from South Africa is crucial to ensure the effectiveness of the dry processing technique for this specific coal quality. This choice is motivated by the fact that the Waterberg coalfield contains a significant portion of South Africa's untapped coal reserves, primarily because it is in a remote and largely underdeveloped region. As reserves in other coalfields decline, there will be a growing emphasis on mining within the Waterberg region.

The investigation, discussion, and explanation of the techniques for pre-and post-processing of the +3.2-13.2 mm do not form part of the scope of this study. This includes techniques for crushing, screening, handling, storage, and transport. Similarly, not included in the scope, are techniques for processing the -3.2 mm particles.

1.5 Layout of the thesis

Each subsequent chapter in this thesis delves into distinct facets of the study outlined in preceding sections. The arrangement and structure of these chapters are expounded upon in the following sections.

- **Chapter 1: Introduction**

In Chapter 1, the thesis establishes its foundation by presenting the contextual background and rationale for the undertaken research. This section delves into the prevailing challenges and concerns within the coal industry, highlighting the imperative for enhanced and economically

viable dry beneficiation technologies within the South African mining sector. Furthermore, the discourse extends to the proposition of a suitable dry beneficiation approach and delineates the precise objectives that guide the course of the study.

- **Chapter 2: Overview of coal preparation**

Chapter 2 serves as a comprehensive literature review, addressing various aspects pertinent to the study. It traces the historical evolution of coal formation and delves into mining and its associated industries within South Africa. The chapter further elucidates the intricacies of coal preparation and beneficiation practices.

- **Chapter 3: A review of dry coal beneficiation (Paper 1)**

This paper offers an exhaustive review of dry coal processing methodologies concerning their operational principles, suitability, and efficacy across a spectrum of commercial and experimental techniques. It aims to discern the most pertinent dry processing methods for adoption within the South African coal industry, particularly in small coal processing and mining activities in remote and underdeveloped areas.

- **Chapter 4: The potential for SEP-AIR in Southern Africa**

This chapter discusses the merits inherent to the SEP-AIR dry beneficiation technique concerning its applicability within the South African coal processing sector. A compendium of the research conducted utilizing South African coal is presented, substantiating the rationale behind the ongoing laboratory investigations. The intricate facets of the laboratory-scale unit's conception and deployment are expounded upon, encompassing insights into airflow dynamics and particle behaviours.

- **Chapter 5: CFD Simulation of airflow (Paper 2)**

This paper presents a CFD-simulated model using STAR CCM+ delineating the airflow dynamics within the suction nozzle of the SEP-AIR across three distinct flow systems: low, medium, and high. Additionally, the paper encompasses rigorous model validation through comprehensive air speed and direction testing. Finally, the relevant theory related to the simulation in STAR CCM+ and particle trajectories is provided in this Chapter.

- **Chapter 6: Dry beneficiation of +6.7–13.2 mm coal (Paper 3)**

This paper explores the laboratory-scale separation unit's effectiveness in beneficiating small coal particles spanning 6.7 mm to 13.2 mm, commonly known as 'pea-size'. Investigating three distinct coal samples in conjunction with five varying airflow speeds, the study unveils the fundamental process attributes governing the mechanics of this separation mechanism.

- **Chapter 7: Dry Beneficiation of +3.2–6.7 mm coal (Paper 4)**

This paper thoroughly investigates the efficacy of a laboratory-scale separation unit for the beneficiation of smaller coal particles within the range of 3.2 mm to 6.7 mm, often referred to as 'duff-size'. These particles are commonly used as mined or disregarded due to certain challenges

associated with beneficiation. Through the examination of two distinct coal samples across three diverse airflow speeds, the study reveals the intrinsic process characteristics that govern the operational dynamics of this separation mechanism.

- **Chapter 8: Conclusions and Recommendations**

Chapter 8 encompasses the presentation of conclusions and recommendations pertaining to the study of using SEP-AIR for beneficiation of minus 13 mm coal.

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CHAPTER 2: OVERVIEW OF COAL PREPARATION

This chapter provides an exposition of the theoretical foundations pertaining to coal, its preparation, and governing principles. It initiates by providing an insightful overview of coal and its evolution. Subsequently, an in-depth exploration of coal products and their utilization within the specific framework of South Africa is undertaken. Furthermore, the chapter expounds upon the preparation and beneficiation methodologies used in coal processing.

2.1 Coal resource

Coal, a compound of intricate composition, consisting of valuable carbon juxtaposed with undesirable mineral elements and moisture. These undesired constituents culminate in diminished coal quality, accompanied by concomitant environmental and economic issues. Thus, coal undergoes preparatory and beneficiation processes aimed at reducing these undesirable components, facilitating the production of enhanced coal quality and mitigating the environmental and economic effects associated with coal processing.

2.1.1 Defining coal and its origins

Coal is a sedimentary rock containing combustible carbon — its genesis is rooted in the compaction and induration of variably metamorphosed plant remnants (Southern African Coal Processing Society (SACPS), 2015). Consequently, coal amalgamates organic and inorganic components, bereft of a crystalline structure or chemically homogeneous constitution. Its typical manifestation involves stratified sequences of alternating coal, shale, and sandstone sediments interspersed sporadically with conglomerates (SACPS, 2011).

Distinguishing characteristics of coal, encompassing plant remnants (type), impurity range (grade), and metamorphic extent (rank), are shaped by the distinctive climatic conditions prevailing during the coal's formation in various epochs of the Earth's history (SACPS, 2015). The evolution of coal unfolded as ancient vegetation underwent decomposition and biochemical transformations to give rise to peat. The progression to coalification ensues, wherein peat metamorphoses into coal through several stages involving biological, physical, and chemical processes (SACPS, 2015).

2.1.2 Coal geology

The intrinsic complexity of coal arises from the diverse conditions that govern its formation, resulting in a blend of organic and inorganic constituents. Consequently, the precise and comprehensive classification of coal hinges upon a range of chemical, physical, and thermal attributes. These attributes encompass the composition of organic matter (macerals), levels of moisture and mineral content, and the corresponding density and heating values. These collectively wield significant influence over coal quality and dictate its behaviour during processing. Higher coal quality is usually characterized by increased heating values, moderate densities, lower moisture content, and decreased mineral matter.

2.1.2.1 Rank

Coal rank, delineating the spectrum from peat to anthracite, is characterized by progressive compaction and thermal alteration. Advancing through the coalification stages, the coal's rank or maturity ascends, with peat representing the lowest rank (SACPS, 2015). In the initial maturation phase, peat undergoes partial decomposition and compaction of its original plant constituents to give rise to lignite. Subsequently, in the second stage of coalification (also referred to as the metamorphic stage), the sediment-buried lignite undergoes prolonged compaction and heating. Continuously influenced by elevated temperature and pressure, lignite progressively matures, undergoing a mesomorphic transformation into bituminous coal. Under favourable conditions of sustained heat and compression, the transition advances further, culminating in the formation of anthracite or high-rank coal (SACPS, 2015).

With the advancement of coalification, discernible shifts occur in moisture content, calorific value, density, and overall appearance of the coal (SACPS, 2015). Lower-rank coals, including peat, lignite, and sub-bituminous varieties, exhibit elevated moisture content and diminished calorific values. These are typified by an unremarkable and earthy aspect coupled with a friable texture. In contrast, higher rank coals, namely bituminous and anthracite, exhibit a harder texture and deep black lustre, featuring augmented carbon content and reduced moisture levels (World Coal Institute (WCI), 2009). Density, a property that evolves with increasing rank, adheres to the following guidelines proposed by Xie (2015). The coal density ranges are approximately 0.72, 0.80–1.35, 1.25–1.50, and 1.36–1.8 g/cm³ for peat, lignite, bituminous, and anthracite, respectively.

An intricate comprehension of coal's external appearance, compositional elements (organic and inorganic), and pertinent physical and thermal characteristics are pivotal in precisely determining rank and, thereby, quality. Figure 2.1 illustrates the coalification trajectory, along with its ensuing progressive attributes.

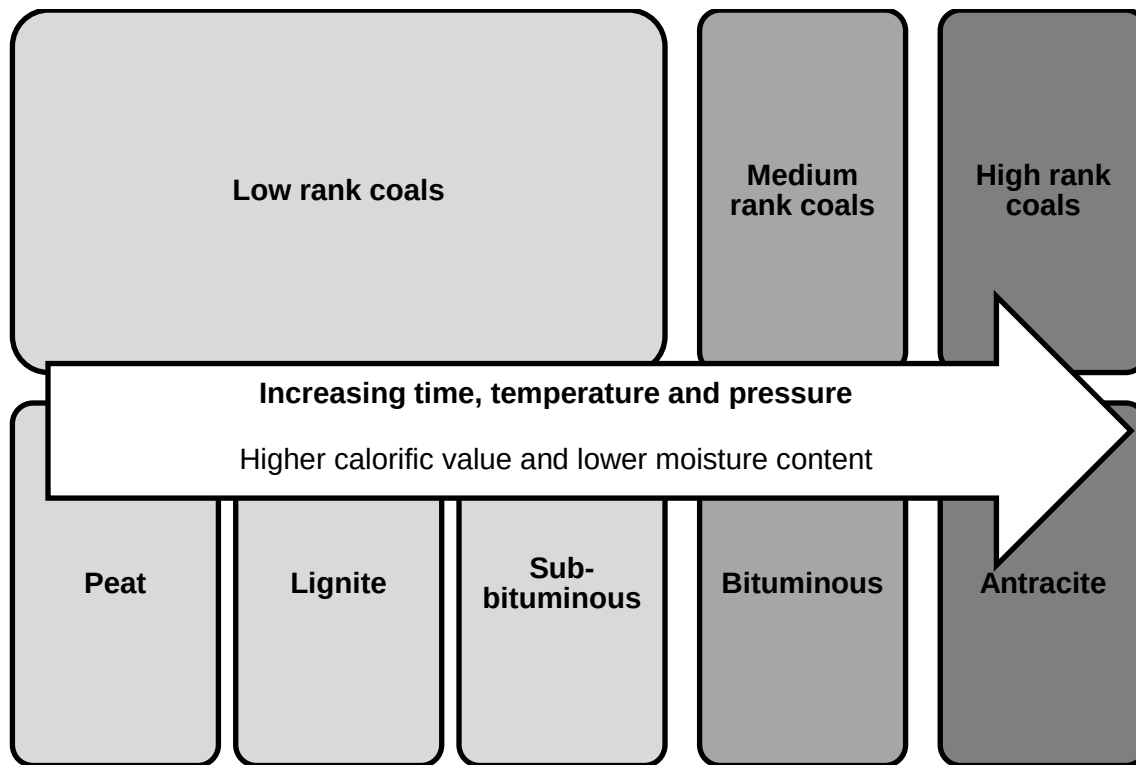


Figure 2.1: The stages of coalification categorized into rank (modified from WCI's 2009 publication)

2.1.2.2 Lithotypes

At the coal face, distinct bands characterized by differing brightness and texture become macroscopically evident. Termed lithotypes, these alternating bright and dull bands are broadly categorized into vitrain, durain, clarain, and fusain, providing a preliminary visual depiction of the coal sample (SACPS, 2015).

- i. Vitrain lithotypes are thin layers with a glossy jet-black appearance and display a soft, brittle texture commonly found in hard bituminous and anthracitic coals.
- ii. Durain lithotypes can be black or grey. Black durain mainly consists of remnants of leaves and seeds, while grey durain, similar in appearance to black durain, comprises a complex mixture of vitrain and fusain lithotypes.
- iii. Clarain lithotypes consist of alternating bands of vitrain and black durain, presenting as thin bands with a satin-like sheen.
- iv. Fusain lithotypes appear as separate flattened pieces within specific depths of a coal seam rather than continuous hard bands. They originate from plant material undergoing oxidation during the initial coalification stages.

2.1.2.3 Macerals

In bituminous and anthracitic coals, three significant macerals are distinguished. Macerals, representing fossilized remnants of ancient flora and fauna in coal and rock formations, include vitrinite, inertinite, and liptinite (Falcon and Ham, 1988).

- i. Vitrinite, forming the primary organic constituent in vitrain, clarain, and grey durain lithotypes, displays a glass-like sheen. Composed mainly of cellular plant matter such as roots, stems, trunks, and barks, vitrinite imparts coal with its coking properties.
- ii. Liptinite originates from spore coats, leaf cuticles, waxes, and resins. Due to its high resistance to biochemical changes, it exhibits minimal alteration from the original plant material. This maceral is predominant in black durain and clarain lithotypes.
- iii. Intertinite predominantly characterizes fusian lithotypes, representing extensively modified plant remnants within coal. It is widespread across most coal types.

Macerals can be further categorized based on reactivity, with vitrinite and liptinite designated as reactive, while inertinite is considered non-reactive (Falcon and Ham, 1988). Additionally, maceral classification influences the density of a particular coal rank, with density increasing in the sequence of liptinite, vitrinite, and inertinite. Notably, coals with exceptionally high carbon content show convergence in the density of the three macerals, experiencing a significant density increase simultaneously (Xie, 2015).

2.1.2.4 Mineral matter in coal

Coal's inorganic constituents include mineral matter, such as carbonates, sulphides, pyrites, quartz, and clays. These minerals, considered inert solid substances, reduce coal quality by persisting as ash residue after complete combustion (SACPS, 2015). Inorganic mineral matter can be divided into inherent and extraneous types. Inherent mineral matter comprises solid minerals intricately mixed within the coal, originating from the initial vegetation that formed the coal. Extraneous mineral matter includes sedimentary layers and lenses within the coal seam and shales, sandstones, and intermediate rocks introduced during mining (SACPS, 2011).

Coal grade, influenced by mineral type and quantity, varies based on the formation region and rank. The ash yield, indicative of grade, relates to various environmental and technological concerns during coal preparation and utilization (Schweinfurth, 2009). The presence of mineral matter in coal is linked to decreased efficiency in processing plants and potential adverse effects on processing and combustion equipment.

Of particular significance, especially in beneficiation contexts, is the impact of mineral matter, or ash yield, on coal density. Mineral densities surpass that of organic matter, substantially influencing coal density based on mineral content and composition. According to Xie (2015), a 1% increase in coal ash yield usually leads to an expected 0.01% rise in coal density. This notably impacts the behaviour of coal particles in processes dependent on density.

2.1.2.5 Other matter in coal

In addition to coal ash yield, two other constituents hold significant importance: moisture content and volatile matter. In many coal mining and operational contexts, water is utilized, resulting in coal with elevated free and surface moisture contents. Moisture content adversely affects coal quality, comparable to ash content. The energy required for moisture evaporation diminishes combustion efficiency, underlining its crucial role in coal processing performance.

The second component consists of a mixture of short — and long-chain hydrocarbons and sulphur, referred to as volatile matter. These volatiles are released at high temperatures without oxygen and contribute to environmentally harmful carbon, sulphur, and nitrogen oxide emissions during coal combustion (Schweinfurth, 2009). Typically, the volatile matter emitted provides heat, which is vital to the efficient operation of coal power plants. Effectively managing volatile matter becomes crucial in addressing these environmental concerns.

The chemical components, as enumerated and elucidated above, are quantified through ultimate and proximate analyses. These methodologies involve sequential high-temperature elimination of each component, enabling the calculation of moisture, volatile, ash, and fixed carbon content through mass differences.

2.1.2.6 Density

Among the manifold physical properties characterizing coal, density assumes significance in the present study. Density not only offers insights into the inherent nature and structure of coal but also facilitates coal grade determination. As previously highlighted, the density of a coal specimen closely correlates with its inorganic mineral matter constituents. Given the heterogeneous composition of coal, density profiles exhibit significant variation across coal fields and seams, underscoring the need for a comprehensive idea of density and its correlation with coal classification.

Density can be classified into three categories: true relative density (TRD), apparent relative density (ARD), and bulk density (BD). TRD represents a density value excluding coal pores and is primarily used in quality research, determined through pycnometer analysis. ARD, the second density measure, calculates the mass of ore per unit volume, considering pore structures. Lastly,

BD corresponds to the ratio of coal mass filling a container to vessel volume. Relatively, TRD typically yields the highest density value, followed by ARD and then BD (Xie, 2015). Most density-based separation processes are governed by ARD since usual mediums like air, water, and dense materials cannot penetrate coal pores.

There is a direct linear relationship for all coals worldwide between coal ash content and its incremental density. The ash produced in a washing plant depends on the density of separation and the distribution of coal/mineral particles of different densities and ashes. Well-liberated coals will produce a low ash product at a set density, while poorly liberated coals will produce a high product ash at the same washing density.

In conclusion, coal exhibits pronounced heterogeneity and can be categorized through diverse methodologies. Each parameter and its respective determination method furnish valuable insights into coal's characteristics and behaviour during processing. Consequently, a comprehensive grasp of coal's multifaceted attributes, as elaborated upon above, remains imperative. Furthermore, an understanding of the anticipated implications of these properties on the ongoing investigation is essential.

2.1.3 South African coal resources

South Africa's coal deposits originated around 300 million years ago in the Permian period, within the sedimentary layers of the primary Karoo Basin (SACPS, 2011). This basin formed as a retro-foreland basin due to tectonic movements, leading to prolonged subsidence of a part of the Gondwanaland supercontinent. This geological evolution fostered the development of peat swamps within the basin. Subsequently, igneous intrusions related to the uplift of the Drakensberg region impacted the forming coal deposits. This geological interplay created optimal conditions, ultimately elevating the coal rank and engendering a regional trend of increased rank from southwest to northeast zones (SACRM, 2011).

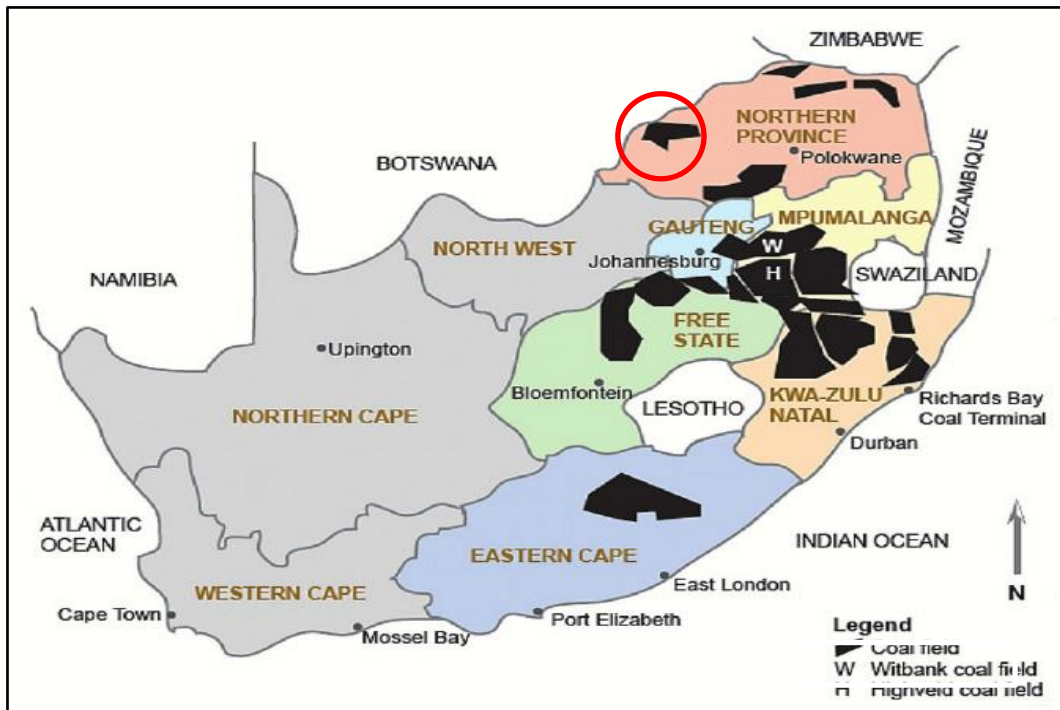


Figure 2.2: South African coalfields holding economic significance (SACPS, 2015)

The economically significant coal seams in South Africa are mainly located within the Ecca and Beaufort groups of the Karoo basin. Several notable coalfields are spread across the northeastern region of the country, primarily concentrated in the Mpumalanga, Free State, and Limpopo regions. These are typically associated with mud and sandstone sediments (SACRM, 2011; Jeffrey, 2005).

Notably, approximately 70% of South Africa's remaining coal reserves are concentrated in the Highveld, Witbank, and Waterberg coalfields situated in Mpumalanga and Limpopo (Jeffrey, 2005). These coalfields are delineated in black on the South Africa map, illustrated in Figure 2.2. with 'W' and 'H' for Witbank and Highveld, respectively, and a red circle indicating the Waterberg coalfield. The latter of which is of central relevance to the present study. The Waterberg coalfield holds approximately 40% of the nation's existing coal reserves (Department of Mineral Resources (DMR), 2009). This reservoir presents an underexplored potential for bolstering the country's coal reserves and amplifying production capacity. Nonetheless, this coalfield's remote geographical placement, coupled with water limitations and insufficient infrastructure, engender formidable challenges (Jeffrey, 2005; DMR, 2009).

2.1.4 Coal products and utilization

The coal deposits in South Africa are characterized by their relative shallowness and thick seams when compared to international standards, making them readily accessible, less complicated, and more cost-effective for mining operations. In 2020, South Africa achieved a coal production

of 247.4 million tonnes, underscoring its significant role in the coal mining industry (Statista, 2023). At the present production rate, South Africa is poised to sustain a coal supply for over 50 years. However, as the demand for energy continues its steady ascent, the ongoing challenge of aligning coal production to meet these increasing demands is expected to persist in the years to come.

In South Africa, coal finds extensive utilization across various domains, including metallurgical processes involving coking, the synthesis of fuels, local electricity generation, and international export. Each of these applications necessitates coal possessing distinct quality attributes, including specific properties like calorific value, ash yield, volatile matter, sulphur content, and moisture levels. The range of South African coal commonly includes four main products referred to as grades A, B, C, and D. Table 2.1 provides a comparative overview of essential characteristics encompassing South African run-of-mine (ROM) coal and these four principal coal products (IPC Coal, 2016; SACRM, 2011).

Table 2.1: Common traits of coal products from South Africa (IPC, 2016; SACRM, 2011; Steyn and Minnitt, 2010)

Grade	ROM	A	B	C	D
Ash (%)	20 – 40	12 – 14	14 – 16	16 – 18	20 – 25
Calorific value (MJ/kg)	16 – 21	27 – 29	26 – 28	24 – 26	21 – 23
Sulphur (%)	< 2.0	< 0.6	< 0.6	< 1.0	< 1.5
Moisture (%)	< 20	< 12	< 12	< 12	< 10

Table 2.1 displays a clear pattern showcasing improved coal quality from Grade D to Grade A, while the ROM coal category indicates moderately low quality. This is a function of the liberation of the coal, the plant cut-point density, and any coal size fractions that are bypassed. In the South African coal market, low-rank coals are generally of limited significance, with most mined coals falling within the bituminous to anthracite spectrum. These harder coal varieties primarily consist of vitrain and grey durain lithotypes and are closely linked with vitrinite and inertinite macerals (SACPS, 2015). Notably, there has been an increasing extraction of high-ash or low-grade coal in South Africa. Reported ash yield values as high as 40% (Jeffrey, 2005) indicate a growing trend in mining such coals.

Metallurgical coal, a crucial component for coking applications in the steel manufacturing industry, necessitates relatively low ash and sulphur content and the ability to form a stable coke. Notably, coal earmarked for export adheres to similar quality standards, containing a moisture content below 12% and a particle size ranging from 0 to 50 mm (Eberhard, 2011; Steyn and Minnitt, 2010). Furthermore, approximately 28% of South Africa's coal production is allocated for export establishing South Africa as the fifth-largest coal exporter globally (Workman, 2022).

Conversely, thermal coal used for domestic electricity generation and synthetic fuel production tends to exhibit considerably lower quality attributes. These coal types, falling under the Grade D classification, demonstrate calorific values below 23MJ/kg, ash values spanning from 20% to 34%, and moisture values below 10% (Eberhard, 2011; Steyn and Minnitt, 2010).

As previously indicated, the coal used in this study was sourced from the Waterberg coalfield in South Africa's Limpopo region. The Waterberg coalfield in South Africa is a significant source of coal used in steel production and power generation. A portion of this coal is exported via the Matola terminal in Mozambique for steam generation, enhancing its economic viability (Jeffrey, 2005). The Moatize coalfield, from where the second coal quality was obtained, produces coal for metallurgical and thermal applications (Zancan *et al.*, 2023).

Analysis of the characteristics inherent in ROM coal underscores the necessity of coal preparation and enhancement to achieve the required quality standards for these applications. It is important to acknowledge that the ROM coal grade and the specifications of end products are not exclusive arbiters dictating the imperative and scope of beneficiation. Rather, considerations of economic feasibility in operations and transportation exert considerable influence. Consequently, several coal mining operations adopt a bifurcated approach, resulting in both processed coal suitable for metallurgical and export purposes and an intermediary product designed for local consumption (SACRM, 2011).

The necessity of achieving specific coal quality for intended uses highlights its importance in the South African coal market. Therefore, the crucial role of beneficiation processes becomes paramount, addressing various challenges arising from extraneous and non-combustible constituents in coal. These challenges encompass reduced calorific value, increased material volume requiring handling and transportation, heightened wear on processing equipment, and the release of hazardous gases and particulate emissions. Preparing ROM coal involves removing unwanted impurities, resulting in a more uniform and suitable product (SACRM, 2011). Moreover, to evaluate a coal's ability to source a given market, detailed washability data needs to be developed. This will allow yield vs ash and yield vs CV relationships to be identified. Once this is done, an economic exercise will be performed to find the optimum market for a particular coal

2.1.5 Preparation

Two main coal preparation stages in South Africa are utilized: screening and washing. The initial step involves primary screening to remove major foreign objects from the coal, followed by crushing to reduce the top size. Subsequently, a secondary screening phase segregates the coal into different ranges, customized for direct sale or subsequent beneficiation processes (SACRM,

2011). The processing equipment in a plant, typically two or three circuits, is each only capable of processing a narrow size range efficiently. Accurate screening in the plant has to be done to ensure that each process is fed the appropriate sized material. Table 2.2 presents standard values, mass distributions, and moisture levels, categorizing various size fractions within South Africa.

Table 2.2: Coal size classification and typical characteristics for South African coals (SACRM, 2011).

Size Classification	Particle size range (mm)	Distribution of mass (% of total product)	As received moisture content (%)
Ultra-fine	0.10–0.15	4	27
Fine	0.1–1.0	7	13
Small	1.0– 12.0	28	9
Coarse	12–250	61	5

Coal particles spanning sizes from 3.2 mm to 13.2 mm fall within the ambit of this study. This range aligns with the category of small coal particles, as catalogued in Table 2.2, constituting 28% of the complete coal product and characterized by comparably low moisture levels of 9%. Within the domain of small coal, finer subdivisions can be established: duff coal (+3.2-6.7 mm) and pea coal (+6.7-13.2 mm) (Steyn, 2009).

2.1.6 Beneficiation

Beneficiation processes reduce the mineral content of coal, resulting in a product that conforms to necessary specifications. Most beneficiation processes capitalize on disparities in the physical properties of coal particles, including factors like size, shape, density, magnetic susceptibility, and electrical resistivity. Chapter 3 presents a more comprehensive exploration of these factors.

Currently, the predominant techniques rely on water-based processing methods, primarily density separation. Coal beneficiation involves the utilization of dense medium drums, cyclones, spirals, and froth flotation, requiring significant water volumes. This results in a moist product with reduced calorific value. Consequently, wet beneficiation processes require additional infrastructure for managing tailings disposal and water recovery (Yang *et al.*, 2013). Figure 2.3 illustrates a typical flowsheet for a comprehensive coal beneficiation plant in South Africa.

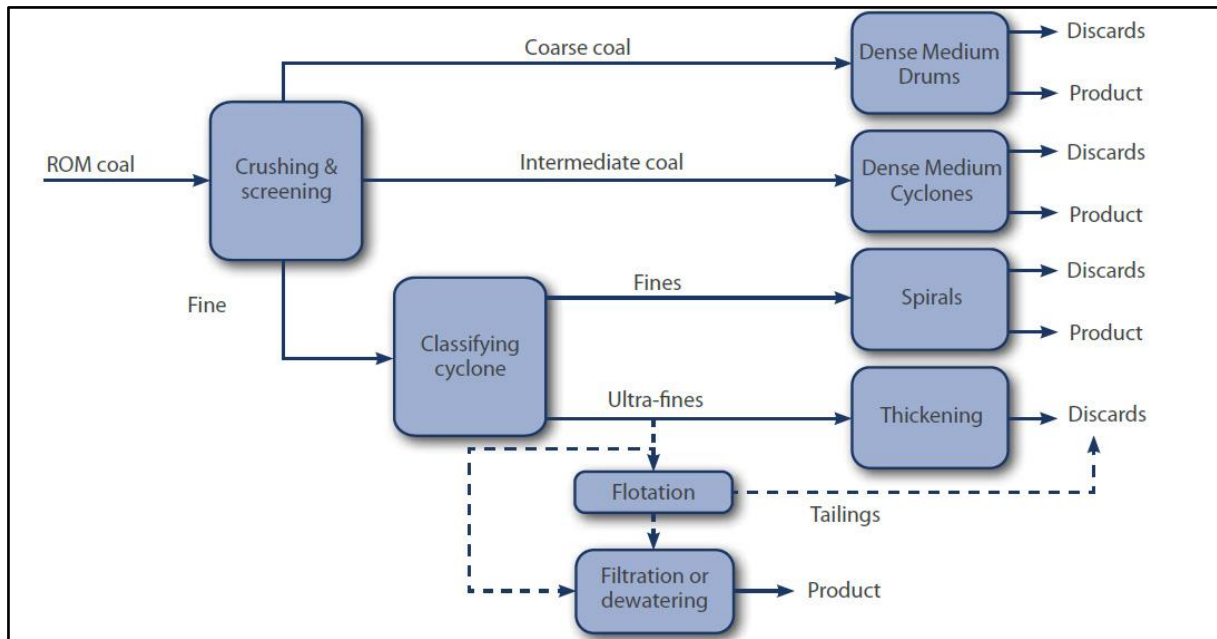


Figure 2.3: Schematic depicting the standard procedure for coal washing (adapted from SACRM, 2011)

In the flow diagram illustrated in Figure 2.3, the oversized coal undergoes classification into coarse and intermediate classes after the initial crushing and screening. These classes then undergo beneficiation via dense medium drums and dense medium cyclones, respectively. The undersized or fine coal fraction moves to a classifying cyclone, producing fine and ultra-fine coal products. The fine portion is then processed in a spiral concentrator, while the ultra-fine fraction progresses to thickeners or froth flotation tanks.

As previously emphasized, the beneficiation of the intermediate coal fraction is of notable importance to this dissertation. This is primarily achieved using dense medium cyclones. This process involves fine particulates, like magnetite, suspended in water as a dense medium. It uses enhanced centrifugal forces and a slurry density between the product and discard to separate the heavy, mineral-rich coal reject material from the desired lighter coal product (Wills and Napier-Munn, 2008).

The coal preparation techniques in South Africa must adapt to current resource, market, and environmental conditions. It's essential to maximize throughput while minimizing operational costs, especially with declining ore grades and environmental issues. These challenges have spurred various research initiatives to uphold and improve current standards. The advancement of dry coal beneficiation technology holds significant importance, particularly for countries with ample coal resources and experiencing prolonged periods of drought and irregular rainfall patterns.

As discussed in Chapter 1, creating a water-independent coal processing method offers significant advantages. It can potentially lower both capital and operating expenses, streamline coal handling and storage, and eradicate water pollution linked to coal processing (Sahu *et al.*, 2009).

2.1.7 Dry beneficiation methods

Various dry ore cleaning techniques have been developed since the 1850s, including early methods like hand sorting, raking, and picking machines, preceding the introduction of pneumatic concentrating machines around 1916 (Weinstein and Snoby, 2007). While air gravity separation gained traction with pneumatic tables and jigs, dry coal processing declined by the late 1980s, leaving very few operational processes (Weinstein and Snoby, 2007). Slow computer processing and limited detection technologies hindered sensor-based sorting development during that period (King, 2015).

The decrease in operational dry coal beneficiation plants was due to increased moisture levels in ROM coal from stricter dust suppression requirements (Weinstein and Snoby, 2007). Also, the demand for higher coal quality at maximum efficiencies and lower cut-point densities shifted processing to wet methods, dominating the coal preparation industry (Honaker *et al.*, 2008). The quality of coal reserves worldwide has decreased with increasing levels of ash in the feed necessitating deeper cleaning than was practiced historically.

Recent years have seen renewed interest in dry coal processing aiming to compete with wet methods in efficiency, yield, and product quality. Techniques include enhancing previous pneumatic tables and jigs, sensor-based sorters, and introducing new methods like the FGX, fluidized bed separator, suction fluidization treatments, and winnowing (Weinstein and Snoby, 2007; Wotruba *et al.*, 2010; Patil and Parekh, 2011; Jambal *et al.*, 2017; von Ketelhodt and Bergmann, 2010; De Korte, 2013; Chen and Wei, 2003; Yu *et al.*, 2016; Hughes *et al.*, 2017; Langner *et al.*, 2018; Zhao *et al.*, 2017; Akbari *et al.*, 2020; Zhang *et al.*, 2020; Diedericks *et al.*, 2022; Stańczyk, 2020; Stańczyk *et al.*, 2021; Moszko *et al.*, 2016; Stepanenko, 2016a; Stepanenko, 2016b; Morgan *et al.*, 2019, 2020, 2021; Sakhre *et al.*, 2018). Even water-based separation methods, like flotation for fine fractions, pose challenges in terms of dewatering, handling, and storage. Dry beneficiation methods may offer solutions for processing these fines.

Each method has the potential for waterless coal upgrading based on specific applications and process constraints. However, much of the information is in the early research stages, emphasizing the need for a comprehensive understanding and knowledge base of dry coal beneficiation practices. Chapter 3 offers an extensive review of literature and information on

global trends and dry processing technologies, aiming to evaluate the applicability, performance, success, or challenges of considered dry cleaning methods and to foresee the future of dry coal beneficiation.

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CHAPTER 3: A REVIEW OF DRY COAL BENEFICIATION (PAPER 1)

This chapter thoroughly examines dry beneficiation techniques employed in coal processing and contains the paper “A review of the dry methods available for coal beneficiation.” The review paper elucidates the operational principles, application scopes, and capacity and efficiency metrics associated with different dry beneficiation methodologies. The insights garnered from the content of paper 1 facilitated the discernment of a process deemed apt for addressing the distinct coal processing prerequisites prevalent in South Africa.

3.1 A review of the dry methods available for coal beneficiation (Paper 1)

Contributions by authors

Miss N. Hughes, during her time as a postgraduate student, conducted the investigation documented in this work. The scholarly oversight was provided by Prof. M. le Roux and Prof. Q.P. Campbell, under whose guidance the study's scope and rationale were devised. The culmination of this effort is manifested in the results and ensuing discussions encapsulated within this paper. These outcomes were cultivated through comprehensive dialogues involving Miss Hughes, Prof. le Roux, and Prof. Campbell. To disseminate the findings, Miss Hughes presented the paper's content at notable conferences including the Southern African Coal Processing Society International Coal Conference (Secunda, August 19, 2019), Coaltech Colloquium (Witbank, October 11, 2019), XXX International Mineral Processing Congress (Cape Town, April 18, 2021), and Prof. Campbell's presentation at the Australian Coal Processing Conference (New South Wales, March 8, 2021). Following these presentations, the manuscript underwent refinement, paving the way for its readiness for submission to a peer-reviewed journal. Miss Hughes is credited as the primary author, with the manuscript benefiting from the editorial contributions of Prof. le Roux and Dr. F. Nakhaei.

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A review of the dry methods available for coal beneficiation

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3.1.1 Abstract

Water is a precious global resource and important in most currently employed coal beneficiation practices. These processes are widely accepted and deliver consistent and precise separation efficiencies at desired product yields and throughputs. Although favoured, the water usage related to wet processing may be impractical and unsustainable in certain regions. Consequently, present-day practices used in coal processing may soon have to adapt irrespective of any improved technical and economic feasibility offered. The development of efficacious dry beneficiation methods has, therefore, become an appealing research topic.

This review assembles information pertaining to the principle and success of commercially available and experimental phase dry processes applicable to coal beneficiation. These methods show much potential and with some consideration of possible limitations and further investigation, may be established in future in the especially arctic, arid, and under-developed regions through new plant installations, expansions, and small mines and fines processing.

Keywords: Coal, dry processing, beneficiation, separation efficiency

3.1.2 Introduction

Coal is a key component in energy production and is, therefore, instrumental in economic development globally. Typically, coal requires processing to remove any gangue minerals. This increases the coal quality, reduces greenhouse gas emissions, and lessens transportation and waste disposal costs (Van Houwelingen and De Jong, 2004; Fu *et al.*, 2019).

The currently employed coal preparation techniques depend on wet separation processes such as cyclones, spirals, and floatation cells. These require large amounts of water and incur high operating expenses (Jambal *et al.*, 2016). Moreover, many countries (such as China, India, South

Africa, Russia and Turkey) experience water scarcity, and obtaining authorization for its industrial use is becoming increasingly challenging (Lv *et al.*, 2018; Zhu *et al.*, 2019; Zhou *et al.*, 2019). Therefore, wet processing methods may not be feasible in remote, under-developed or arid regions and areas with long periods of freezing temperatures. As a result, the replacement of wet separation techniques with alternative dry processes has been encouraged.

Dry beneficiation methods have some remarkable benefits when compared to wet methods and are intriguing to the coal industry due to the following: water scarcity, higher heating value, low capital and operational costs, low transportation costs, reduced environmental impacts related to water consumption and pollution, and developing coal mines in arid regions (Von Ketelhodt and Bergmann, 2010; Jambal *et al.*, 2020). These processes do not utilize water and post-processing for dewatering and wet waste disposal is not required. Moreover, they are compact, modular, and easy to erect, making them suitable for remote and under-developed areas (Weinstein and Snoby, 2007; Tomra, 2017).

Dry beneficiation processes prove beneficial and hold numerous advantages, but any associated limitations must be considered. Successful separation is obtainable, but the efficiency and throughput may not always compare to what is achievable in a wet processing plant. “Consequently, coal beneficiation plants operating on exclusively dry techniques is a goal that is yet to be completely achieved” as stated by Hughes *et al.* (2019). Therefore, most are currently limited to regions with extreme environmental conditions and find use in pre-concentration applications, scavenging, operations in small or remote reserves, beneficiation where the coal does not require much upgrading and finally, for “easy to separate” coals. One of the challenges for dry coal processing operations is the moisture content in run-of-mine (ROM) coals because of the water used in dust subduing (Weinstein and Snoby, 2007). Moreover, processing lower ore grades at finer particle sizes and large capacities has become necessary to meet the demand for good-quality coal. (Honaker *et al.*, 2008).

Given the recent economic and environmental drives for dry coal beneficiation globally, many research efforts have attempted to ameliorate any shortfalls (in terms of efficiency, capacity, and yield) formerly observed. Much investigation has since been conducted into these processes, and improvements have been made to some of the previously abandoned methods, such as the pneumatic concentrators and sensor-based sorters (Manoucherchi, 2003; Weinstein and Snoby, 2007). Some state-of-the-art techniques have emerged, including fluidized bed separators (De Korte, 2013; Chen and Wei, 2005; Zhang *et al.*, 2014; Zhang *et al.*, 2017; Diedericks *et al.*, 2022), suction fluidization treatments (Stepanenko, 2016a; Stepanenko, 2016b; Stanczyk, 2020, Stanczyk *et al.*, 2021) and winnowing (Sahkre *et al.*, 2018; Morgan *et al.*, 2019, 2020, 2021).

Additionally, the possibility of dry processing fine coal has arisen with investigation into numerous of the above-mentioned techniques and electrostatic and magnetic separation (Dwari and Rao, 2007). Studies relating to pyrolysis and microwave treatment for enhancing the magnetic and electro-physical properties of coal have progressed but have not yet reached commercial status (Binner *et al.*, 2014).

Given the lack of a recent comprehensive review paper on dry separation techniques, understanding the status, development and challenges is perplexing. Therefore, this paper systematically summarizes the historical development and knowledge of dry coal processing. Processing for coarse, intermediate, fine, and ultrafine particle sizes is distinguished. The impact of operating parameters on separation performance is also studied and variations of ash content, Ecart Probable Mooyen (EPM) and yield values are provided. The inefficiency of existing dry separation methods is pointed out, and future research needed for dry coal processing is proposed.

3.1.3 Dry coal processing techniques

Coal is heterogeneous in nature, consisting of carbonaceous matter (that is burned for energy) and volatile and mineral matter (that forms the impurities) (SACPS, 2015). Beneficiation (or cleaning) is required to remove these contaminants for the coal to meet the requirement. Parameters used to measure the product quality are the calorific value and ash, sulphur, moisture, and fine contents (SACRM, 2011). Two additional parameters determine the effectiveness of a particular beneficiation process: the EPM and the required cut-point density.

The EPM is an index which represents the sharpness with which the coal and impurities are sorted. It provides an indication of the deviation of the distribution curve from a perfect gravity-based separation (Wills and Finch, 2016; Galvin *et al.*, 2018). A lower EPM describes a sharp separation and less particle misplacement while a higher EPM generally represents a low separation accuracy (Kopparthi *et al.*, 2020). The usual EPM for dry coal separators ranges from 0.15–0.3 (Pradhan and Mohanta, 2020; Patil and Parekh, 2011) while the water-based processes usually range from 0.02–0.025 EPM (De Korte, 2013). The cut-point density (SG_{50}) is the density at which 50% of the material reports to the heavier (or lighter) fraction in a density concentration. Separations at lower-density cut-points tend to be sharper than separations at higher-density cut-points (Pradhan and Mohanta, 2020). The coal feed quality, market, and adeptness of the selected beneficiation process are the determining factors for successful and profitable coal upgrading (WCI, 2009; SACRM, 2011).

Mineral beneficiation (wet or dry) is comprised of two fundamental operations: liberation and concentration. During the former operation, the valuable coal is released from gangue minerals and then separated in the latter operation (Wills and Napier-Munn, 2008). Separation of the valuable coal from the discard components is made possible by exploiting some difference in their physical properties in terms of size, shape, density, magnetic predisposition, and electric resistivity (Chen and Wei, 2003; Chen and Yang, 2003; Dwari and Rao 2007; Patil and Parekh, 2011). Five processing categories can, therefore, be observed: comminution and screening (generally for liberation), sensor-based sorting, gravity-based concentration, magnetic separation, and electrostatic separation. These five categories have advantages and constraints for beneficiating different coal qualities and various particle sizes to efficiently yield a desirable coal product at the required capacity.

3.1.3.1 Comminution and screening

Comminution is used to liberate valuable coal constituents from the associated inorganic components, increase surface area for high reactivity, and facilitate the transport of coal particles between unit operations. Comminution is accomplished by crushing in hammer mills and rotary breakers, grinding in ball and pebble mills and screening for particle size classification. These processes rely on differences in hardness and crushability between the coal and gangue counterparts. During comminution, the particles are reduced by three forces: compression, impact, and attrition and separated into sizes appropriate for further processing (Asghari *et al.*, 2020).

Perfect particle liberation may not be possible in practice and so the ore is merely reduced to a workable size (Wills and Napier-Munn, 2008). Comminution removes harmful objects, large uncrushable ore, and fine material thus acting as a pre-process separation stage (SACPS, 2015).. Equipment used to treat coal in this aspect are rotary breakers, slate pickers, and scalping screens, all described in the works by SACPS (2015), Mamoodhabadi (2015) and Wills and Napier-Munn (2008). These units are, however, implemented for feed ore preparation as they are incapable of beneficiating coal to the desired specification because they rely on a high degree of liberation at a larger particle size and specific particle shapes.

3.1.3.2 Sensor-based sorting

Sensor-based sorting (SBS) encompasses the detection of discrete particles and removal of those particles that are deemed undesired. SBS is applied in various industries due to the availability of a wide range of detection techniques and the powerful computing capabilities currently available (Harbeck and Kroog, 2008). In SBS, particles are mechanically sorted based

on certain physical features that are identified by a sensor. Robben and Wotruba (2019) put forward a rundown of SBS development and introduced different applications. Most sensor-based sorters operate similarly, apart from the means of detection as detailed by Manoucherchi (2003). While focusing on coal beneficiation, the dual-energy x-ray transmission (DE-XRT) sorter is considered the most applicable. Some investigation into other types, such as the electromagnetic sorter for coal, has commenced, but further evaluation may be required (De Jong et al., 2004); as such, these will not be discussed here.

The DE-XRT sorter has been well-described (Robben *et al.*, 2014; Robben and Wotruba, 2019; Strydom, 2010; Lessard *et al.*, 2014; Zhang *et al.*, 2021; He *et al.*, 2022) and works similarly to the baggage scanning devices at airports. These observe the transmission and attenuation of hard X-rays as they move through a solid medium (Robben *et al.*, 2014). The denser fragments transmit fewer x-rays through the matter (Strydom, 2010; Lessard *et al.*, 2014). These dense components can be told apart from lighter ones based on the relative difference in transmission of the x-rays through the material (Lessard *et al.*, 2014).

Figure 3.1 displays the schematic setup of a belt-type DE-XRT sorter. The DE-XRT sorters radiate x-rays over feed ore in a set of arrays at differing relative energies, normalizing any effects of material thickness (Harbeck, 2004; Lessard *et al.*, 2014). The detectors operate as line-scan cameras that register the penetration of the X-rays and convert the information into electrical signals used to create grey-scale X-ray images. The image processing performed by the software allows the use of a colour scale, which shows high-density volumes in navy blue, intermediate-density volumes in royal blue, and low-density volumes in red. A sorting algorithm is applied, and the ejector circuit is employed to separate the desired and undesired particles by either a burst of air or mechanical flaps and plungers (Manoucherchi, 2003). The operation sensitivity can be varied to either reject or retain more or less unwanted gangue based on some threshold value.

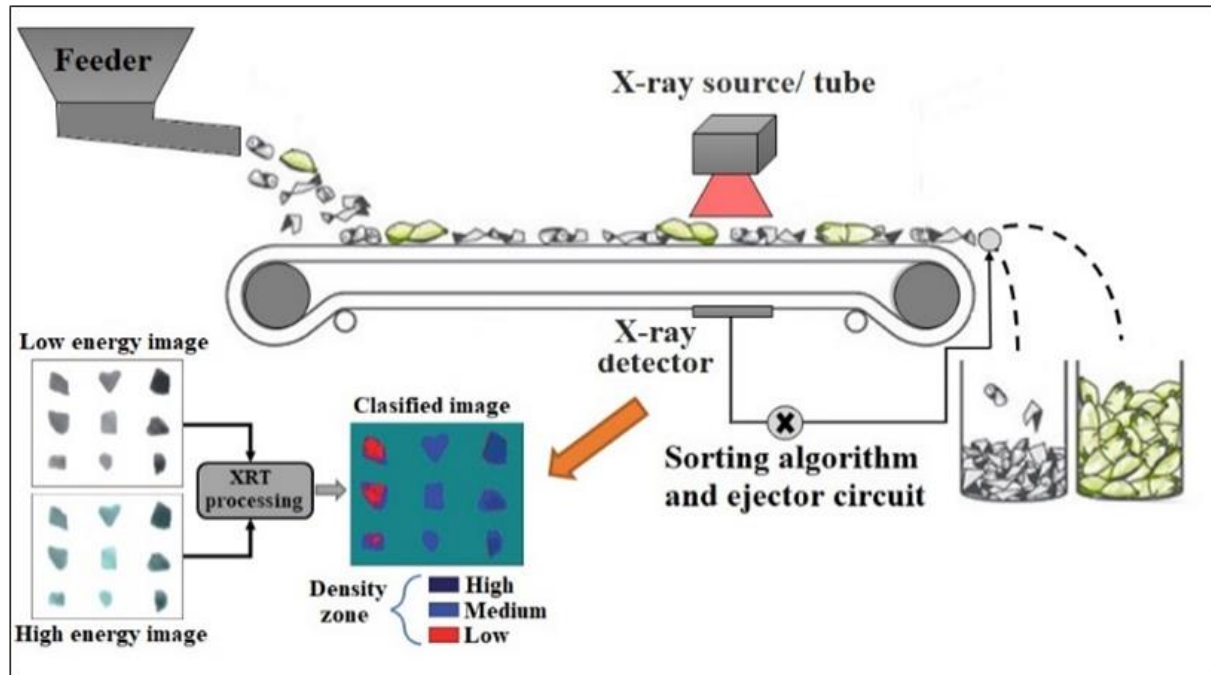


Figure 3.1: Schematic of the functioning of a DE-XRT sorter.

The DE-XRT sorter, being useful as a tool for the concentration of particles, can also be implemented in certain analytical aspects of the washability of individual coal particles (Zhang *et al.*, 2021). Another method available is 3D imaging, such as the novel RhoVol machine developed by De Beer Mining Company (South Africa), which can analyse individual particles by measuring their size, volume and density. The RhoVol makes use of a rapid mass measurement system and seven cameras placed at various angles. These cameras capture seven silhouettes of a particle at a given time, and the system develops a 3D model of the said particle by back-projecting the silhouettes from different camera views (Fofana and Steyn, 2019). This particle volume model and mass measurement can be used to calculate certain properties of the particle. The RhoVol is equipped with a sorting functionality to sort a sample based on certain parameters, such as density (Mangera *et al.*, 2016; Botlhoko *et al.*, 2022).

As a competitive alternative to the sink-float method, Botlhoko *et al.* (2022) used the RhoVol. The coal particles (+3-8 mm) were subjected to standard sink-float (1.2–2.1 g/cm³) and RhoVol tests. It was found that the RhoVol could successfully sort coal particles into a broad range of densities, and it can potentially replace the standard sink-float analysis. This study formed the first effort to determine if 3D imaging could be used to separate coal particles based on density and the potential for its application as an industrial process. Further research, involving a wide range of coal samples is necessary to determine if 3D imaging is suitable for industrial sorting applications along with an economic analysis.

3.1.3.3 Gravity-based separation

Observing a significant density disparity between two materials allows for their separation using gravity-based techniques, extensively discussed in the literature (Kelly and Spottiswood, 1982; Wills and Napier-Munn, 2008; SACPS, 2015). Variations in the behaviour of particles with different densities within a fluid medium occur due to gravity, centrifugal, and frictional forces. These forces influence the differential movement of particles with varying densities concerning the resistance posed by the viscous medium. Therefore, achieving separation of particles with differing densities is feasible in an appropriate medium (Wills and Napier-Munn, 2008). Additionally, particle attributes (such as size and shape) and medium characteristics (including type, density, and viscosity) further impact the potential and degree of separation in a density-based sorter (Wills and Napier-Munn, 2008; Sahu *et al.*, 2013; Zhao *et al.*, 2015).

Numerous dry coal gravity beneficiation methods have been investigated, such as pneumatic oscillating tables (Patil and Parekh, 2011; Kademli *et al.*, 2013; Chavaldi *et al.*, 2016; Jambal *et al.*, 2020), ADMFB separation (Chen and Wei, 2003; Luo *et al.*, 2007; 2008; He *et al.*, 2016a, b, c; Zhao *et al.*, 2017; Hughes *et al.*, 2017; Langner *et al.*, 2018 Jiang *et al.*, 2019; Fu *et al.*, 2019;; Diedericks *et al.*, 2022), air jigging (Weinstein and Snoby, 2007; Sampaio *et al.*, 2020), suction fluidization (Stepanenko, 2016a, Stepanenko, 2016b; Stanczyk, 2020; Stanczyk *et al.*, 2021), winnowing, and reflux classification (Macpherson and Galvin, 2010; Morgan *et al.*, 2019, 2020, 2021; Kopparthi *et al.*, 2020).

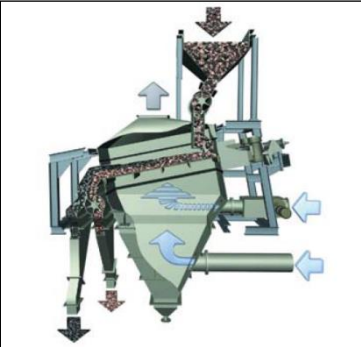
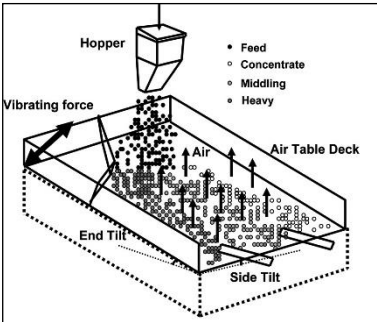
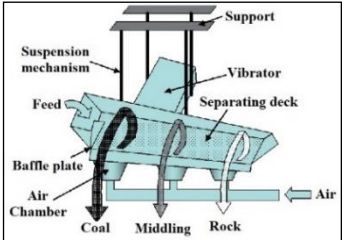
3.1.3.3.1 Elutriation methods

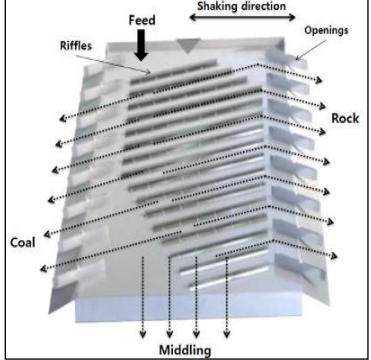
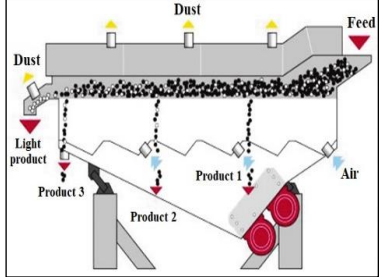
Air jigging (All-Air jig) and air table variants (Standard Air Table, FGX, KAT and AKA-FLOW) make use of particle fluidization, hindered settling and consolidation trickling. During these methods, particles are subjected to a combination of continuous and pulsating airflow, vibration, and inclination to dilate and fluidize particulates (SACPS, 2015; Wills and Napier-Munn, 2008). A particle stratification then occurs according to density, where heavy, dense particles migrate to the bottom whilst the light fractions float to the top of the suspension. A given cut-point density determines the point of separation where the heavy and light fractions will be transferred to their respective recovery devices (SACPS, 2015).

Differences between jigging and the various air table designs are attributed to the bed depth, direction of movement of the product and discard fractions and the discharge thereof. Jigs are deep bed separators (Weinstein and Snoby, 2007) whereas air tables are shallow (Chavaldi *et al.*, 2016). Furthermore, several middling fractions can be obtained from the air tables whereas the jigs can only produce one clean coal fraction and one discard. A co-current flow of product

and discard fractions is observed in the All-Air Jig and AKA-FLOW (Dwari and Rao, 2007, Wotruba *et al.*, 2010) whereas the Standard Air Table, FGX and KAT rely on the counter-current flow of the product and discard fractions (Gupta, 2016; Dwari and Rao, 2007; Jambal *et al.*, 2016). Table 3.1 provides the principle of operation of the air jigs and pneumatic oscillating tables discussed above.

Table 3.1: A comparison of the principle of operation of various air jigs and air tables (Hughes *et al.*, 2019).

Method	Schematic	Description
All-Air Jig	Ore is fed onto a perforated deck through which air is both continuously distributed and pulsated. A stratification occurs according to size and density. Two layers are formed as the particles move along the deck. The discard layer forms close to the deck with the product layer at a certain height above the deck. Separation is controlled by the discard discharge valve (Weinstein and Snoby, 2007).	
Standard Air Table	A particle density stratification is produced by an upward airflow through a porous deck, which is angled and oscillating. Separation is achieved by particles moving in a helical form caused by the deck oscillation. Moments of inertia and traction force the heavier particles towards the higher end of the table. Gravity aids the light and slightly fluidised particles, over the denser bed and towards the lower section of the deck (Dwari and Rao, 2007; Chavaldi <i>et al.</i> , 2016; Gupta, 2016).	
FGX air table	The FGX integrates an air table with an autogenous medium, where the airflow is specifically designed to fluidize and convey fine, dense material. This creates an autogenous particle bed suspension, allowing lighter particles to float (Ghosh, 2013).	

KAT air table	The KAT operates by employing airflow and vibration on a flat perforated deck, featuring slanted riffles and block plates positioned on opposing sides. Heavier material settles and travels in the direction of vibration, while lighter material floats and shifts towards the opposite direction. Accumulation of material occurs against the block plates until it reaches an overflow point. The intermediate material progresses through the table and is discharged at the lower end (Jambal <i>et al.</i>, 2016).	 The diagram illustrates the KAT air table process. Material is fed onto a deck with slanted riffles and block plates. As the material moves along the deck, heavier particles (like rock) settle and move in the direction of vibration, while lighter particles (like coal) float and move in the opposite direction. The material is then discharged at the lower end, with different fractions (coal, rock, middling) being separated.
AKA-FLOW air table	Coal is introduced onto a flat screen within three successive air chambers. The particles are fluidized by a blend of vibration and airflow. Vibrations aid particle movement along the channels, resulting in material segregation. Heavier waste material is released at the conclusion of each chamber, while the clean coal fraction and intermediate material are extracted at the channel's terminus (Wotruba <i>et al.</i>, 2010).	 The diagram shows the AKA-FLOW air table process. Coal is fed onto a flat screen within three successive air chambers. The particles are fluidized by a blend of vibration and airflow. The material is then separated into three distinct streams: Product 1 (heavy waste material), Product 2 (intermediate material), and Product 3 (clean coal fraction). Dust and light product are also shown being separated from the main stream.

3.1.3.3.2 Methods utilizing dry dense medium separation

The phenomenon of particle fluidization and density stratification is also used in dry dense medium separation. Herein, however, a fine and very heavy material is used as a dense medium. This medium is fluidized with air forming a particle suspension with unique pseudo-fluid properties (i.e., density and viscosity) (Kunii and Levenspiel, 1991). A density stratification of differing density coal particles occurs once the coal is added to the pseudo-fluid medium (Luo and Chen, 2001). Heavy particles sink into the medium and the lighter particles float (Firdaus *et al.*, 2012). A dense medium is known to improve fluidization stability and aid in separation efficiency. However, additional processing is required post beneficiation to remove the dense medium from the product and clean it for re-use in the process.

A process called the air dense medium fluidized bed (ADMFB), extensively studied in China, was established for coal beneficiation (Luo *et al.*, 2003). The research included the incorporation of vibration into the ADMFB, evaluations of deep and shallow bed separators, enhancements through magnetically stabilized and dual-density beds, and computer-assisted modelling (Chen and Wei, 2005). A commercial ADMFB was introduced in China by the Chinese University of

Mining and Technology and Shenzhou Ltd. (Chen and Wei, 2005). The commercial ADMFB is portrayed in Figure 3.2 along with a schematic of operation.

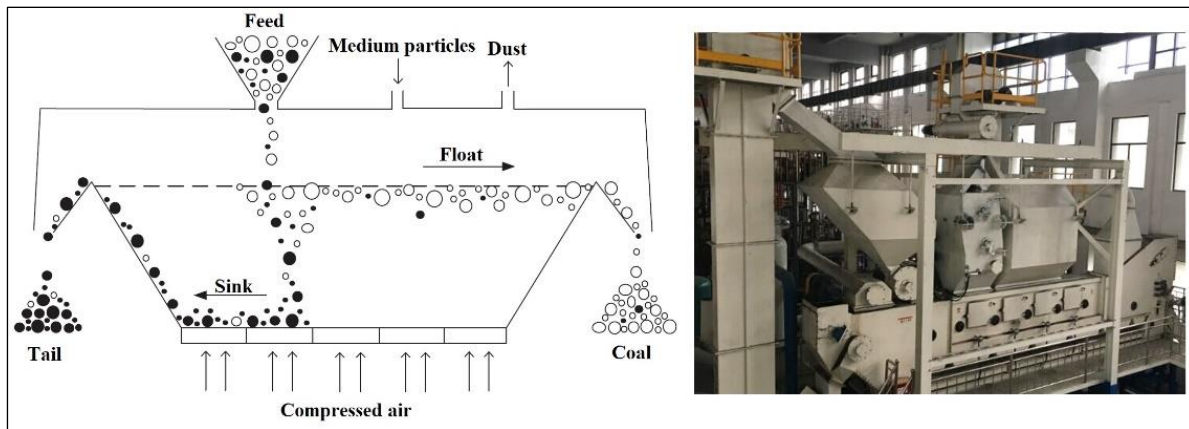


Figure 3.2: Schematic of (left) and picture (right) of an ADMFB separator (adapted from Fu *et al.*, 2019).

Coal and dense medium are fed into a chamber where air enters in an upward direction, fluidizing the dense medium. The heavy discard particles sink onto the tail conveyor and the lighter coal particles float to the product discharge. Dust collection and correct cleaning and disposal are also compensated for (Luo and Chen, 2001). The ADMFB makes use of lower air flow rates and, consequently, less and smaller dust-collecting equipment. It also has minimum moving parts and the possibility of using waste heat for simultaneous coal drying. These are some of the advantages of the over the other dry processing techniques (Azimi *et al.*, 2013). The applicability of the ADMFB for the South African coal market has been investigated by Hughes *et al.*, 2017; Langner *et al.*, 2018; and Diedericks *et al.*, 2022.

3.1.3.3.3 Negative pressure pneumatic separator

A particle can be fluidized using a suction force stronger than the effects of gravity and friction acting on the particle. This separation technique makes use of a vacuum that is created by a nozzle of a specific design, which is located above a layer of particles. The particles are thus set into motion and fluidized by the force of suction. The SEP-AIR unit that was introduced by Gormash Export in Novosibirsk Russia (portrayed in Figure 3.3) is based on this principle (Stepanenko, 2016a; Stepanenko, 2016b).

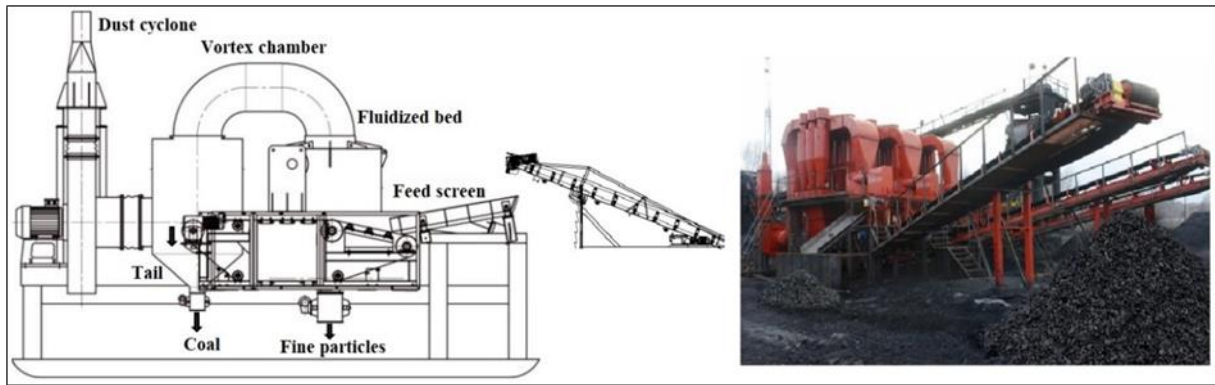


Figure 3.3: The SEP-AIR pneumatic separator (from Gormash Export, 2016b).

In this unit, the fine fraction is eliminated by a perforated screen. Coal particles remaining on the screen are transported beneath the suction nozzle. The nozzle is made up of a fluidization and vortex chamber wherein the particles are exposed to an upward airflow. The force of suction causes the lighter particles to lift into the fluidization chamber through the vortex chamber and are collected as a product. The heavier particles are not affected by the suction force and remain on the conveyor until discharged at the end (Stepanenکو, 2016a; Stepanenko, 2016b).

The density at which separation takes place is specified by the hydraulic size of the particles forming a layer on the conveyor, which in turn is set by the speed of the gas phase passing through the fluidized layer. Cyclones and filters are used for the treatment of any dust that is generated (Stepanenکو, 2016a; Stepanenko, 2016b). In the SEP-AIR process, each particle experiences a double separation, first a fluidization and second a capturing in the vortex. This contrasts with the traditional means of fluidization and the reason such a high yield is attributed to this process (Stepanenکو, 2016a; Stepanenko, 2016b). Moreover, former pneumatic separators tried to merely copy the operating principles of water-based separators. Many unit inefficiencies will be observed without considering any changes in the properties of the air medium, (Stepanenکو, 2016a; Stepanenko, 2016b). A commercial SEP-AIR plant was commissioned in Kuzbass at the Bungursk coal mine in Russia and can produce up to 12 different density products. The SEP-AIR process can also be classified according to particle size and shape.

Another design pertaining to the negative pressure pneumatic separators was provided by Stanczyk, (2020). In this unit, the particles are transferred onto a perforated rotary cylinder consisting of upward-facing air nozzles and an auxiliary blower. This design generates an overpressure underneath the layer of particles. It works together with the curve of the cylinder to initiate particle vibrations and displacement and thereby increase the productivity of the sorting process. This also allows for particle drying and reduction in any particle sticking because of moisture. A suction nozzle, connected to a fan, is located above the rotary cylinder where particles

are lifted by suction into a separator, which removes them from the air stream and leads them into a reservoir. The particles that did not succumb to the suction force slid from the cylinder. The general idea of how the NPPS system works and a semi-industrial separator are presented in Figure 3.4 (Stanczyk *et al.*, 2021).

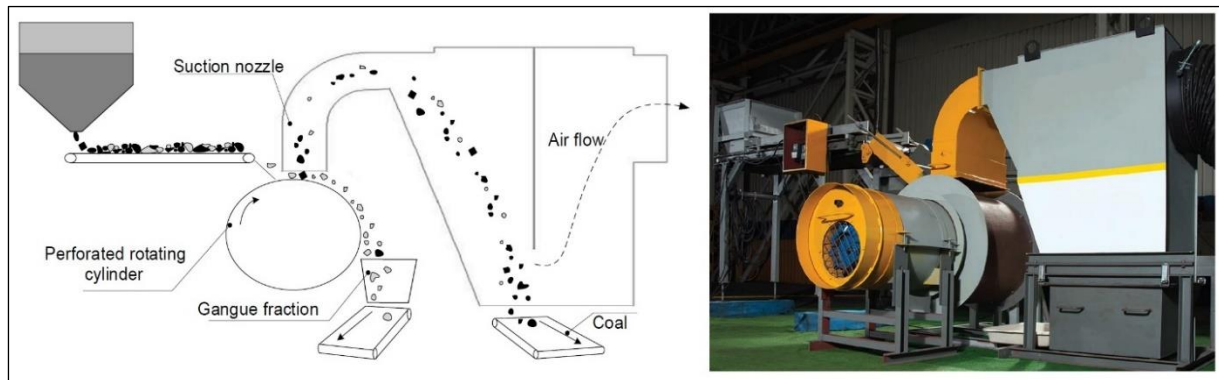


Figure 3.4: Schematic of an NPPS (left) and a semi-industrial NPPS (right) (Stanczyk *et al.*, 2021).

3.1.3.3.4 Methods under investigation

Winnowing (Liu, 2009; Sinha *et al.*, 2016; Sakhre *et al.*, 2018; Morgan *et al.*, 2019, 2020, 2021) and dry reflux classification (Galvin, 2004; Laskovski *et al.*, 2006; Macpherson and Galvin, 2010; Kopparthi *et al.*, 2020) currently show promise in developmental stages with coarse and finer coal fractions, respectively. However, a deeper investigation and possible upscaling to provide a more realistic idea of the capabilities are still required.

The fundamental principle of winnowing involves using wind to displace lighter material, leaving heavier material behind. This system employs horizontal airflow where lighter particles are propelled into the collection chute, while denser particles, being more influenced by gravity, descend into the heavy fraction bin. Winnowing can yield multiple products varying in size and density (Sinha *et al.*, 2016; Sakhre *et al.*, 2018).

Reflux classification (RC) has been proven effective in water-based fine particle separation. Therefore, some studies have tried to determine if it is applicable for processing in dry fine coal fractions. Some research into the performance of RC has progressed on this subject on laboratory and commercial scale (Galvin *et al.*, 2002; Galvin, 2004 Doroodchi *et al.*, 2006, Laskovski *et al.*, 2006; Macpherson and Galvin, 2010a). The RC makes use of a section made up of parallel inclined channels that are placed above a conventional fluidized bed (Galvin, 2004). Air is injected (at a given velocity) into the fluidized bed and coal is added at the top to fluidize. The fine and light particles move into the inclined channels and exit at the top. If the particles are too dense or

too large, they will sediment onto the channel walls and return to the fluidizing channel. The heavy material ultimately discharges at the bottom. Due to the increased vessel area arising from the incline channels, the RC allows for higher throughputs than the traditional fluidized bed (Callen *et al.*, 2007).

The separation within the vertical fluidization section relies on mechanisms of hindered settling which is affected by particle terminal velocity (closely related to size). The use of the inclined section overcomes the inefficiency of the fluidizing section where the similar movement of heavier particles that are fine and lighter particles that are large (having the same terminal velocity) is compensated for. This section induces a re-suspension of particles to ensure that light particles move to the overflow. Heavier particles settle on the inclined plates and subsequently re-enter the fluidized bed section. This process fluidizes them once more and returns them to the inclined plates for potential secondary separation before ultimately moving to the underflow (Laskovski *et al.*, 2006; Macpherson and Galvin, 2010a). An accumulation of fine and dense particles in the mixing zone generates an autogenous dense medium that helps the coarse light particles move directly to the overflow (Das and Sarkar 2018). One disadvantage of an air-fluidized RC is that the separation happens based on size rather than density (Callen *et al.*, 2007). Figure 3.5 portrays the schematics of a winnower and reflux classifier.

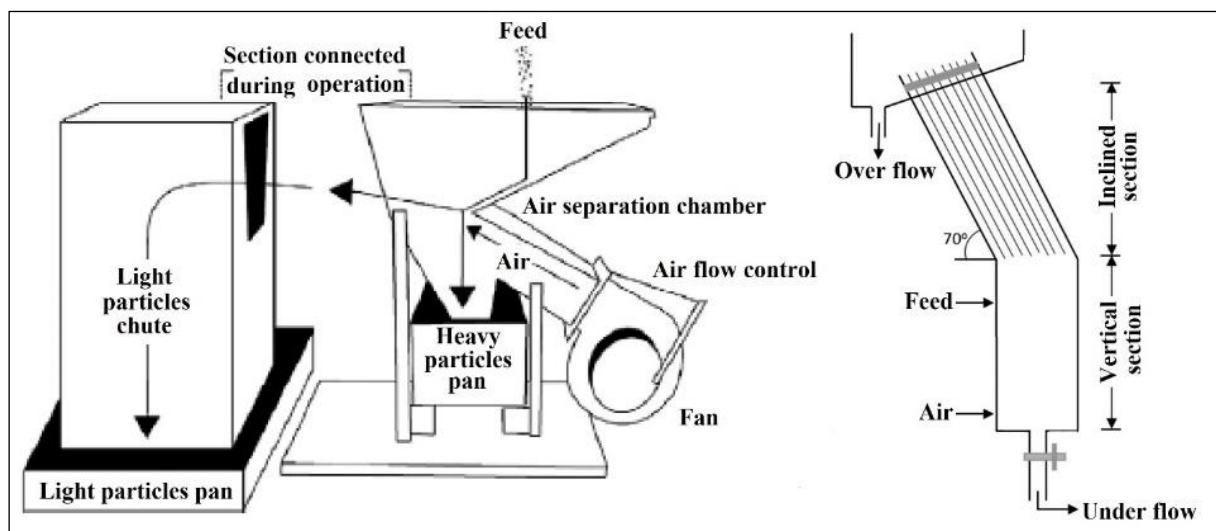


Figure 3.5: Schematics of a Winnower (left) (Liu, 2009) and Reflux Classifier (right) (Kopparthi *et al.*, 2020).

3.1.3.4 Magnetic separation

The valuable content of coal is diamagnetic and mineral matter could be diamagnetic or paramagnetic. Therefore, it is possible to process using high-intensity magnetic separation where the mineral matter associated with coal is paramagnetic such as pyrite (Van Driel *et al.*, 1984). An important phase in the dry separation of coal is the desulfurization process, where pyrite-

bearing minerals are removed to prevent the formation of sulphur oxides during the combustion of the coal. Techniques most applicable to coal are the rare-earth-roll-magnetic-separators (RERMS) which provide stronger magnetic forces, have higher capacities, lower power consumption and are available and affordable when compared to other magnetic techniques (Elder, 2003, Order *et al.*, 2003; Tripathy *et al.*, 2017; Chen *et al.*, 2019).

The RERMS comprises a magnetic roll and an idler roll covered by a thin conveyor belt made of non-stick Kevlar or glass Teflon. The magnetic roll consists of disk-shaped permanent magnets within mild steel rings (Tripathy *et al.*, 2017). Coal particles are fed onto the belt and transported across the magnetic roll, encountering the magnetic field. Paramagnetic materials attracted to the magnetic roll, adhere to the belt's surface and are released upon the roller's rotation away from the magnetic field. Diamagnetic particles, unaffected by the magnetic field, separate from the conveyor. The system includes splitters and collection hoppers at the belt end to redirect and gather different particles, facilitating their separation (Elder, 2003; Tripathy *et al.*, 2017). Figure 3.6 illustrates the operational principle of the RERMS.

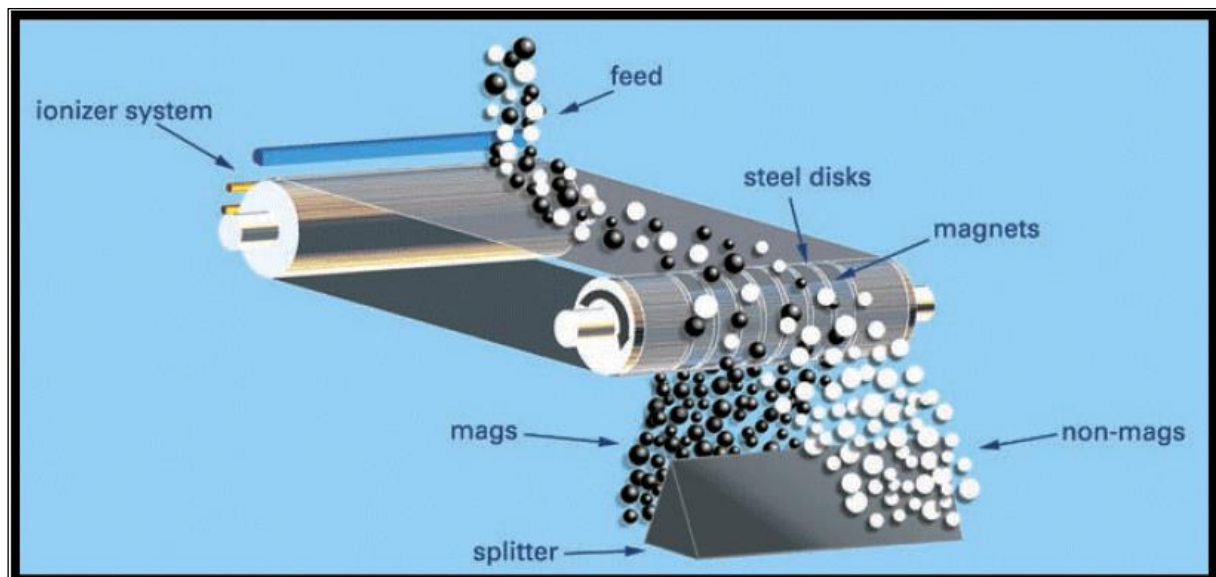


Figure 3.6: Schematic of the operating principle of the RERMS (From Arvidson and Norrgran, 2014).

3.1.3.5 Electrostatic separation

Electrostatic separation can be used to separate coal from gangue minerals (Wills and Napier-Munn, 2008; Dance and Morrison, 1992). Tribo-electrification seems to be the most viable method since it is suitable for ultra-fine materials (smaller than 75 μm) and minerals with similar electro-physical properties (Kelly and Spottiswood, 1989; Manouchehri *et al.*, 2000; Dwari and Rao, 2008).

The tribo-electrostatic (TBS) system involves a tribo-charging zone and a subsequent separation zone. Particles undergo differential charging in the former and subsequent physical separation in the latter. This system includes a feeder, free fall separator, two adjustable electrode plates, collection bins, and a high voltage direct current (DC) source (Mohanta *et al.*, 2016). Numerous studies have delved into aspects of the TBS process, including tribo-charging characteristics, methods, and configurations of the separation unit (Mukherjee *et al.*, 1987; Ban *et al.*, 1993; Higashiyama *et al.*, 1998; Trigwell *et al.*, 2003; Dwari and Rao, 2008; Dwari and Rao, 2009; Bada, 2010; Zhang *et al.*, 2016; Wang *et al.*, 2017).

During tribo-charging, the particles are charged by contact friction against other particles or a container wall, such as in a rotary tube (Dwari and Rao, 2007). The work functions of the surfaces in consideration determine the magnitude of the charge and its polarity (Mohanta *et al.*, 2016). During the subsequent separation, the charged particles are allowed to fall through an electric field generated by the electrode plates and are deflected according to the magnitude and polarity of their charges. Literature shows that clean coal will take on a positive charge while ash-forming minerals charge negatively (Lockhart 1984; Tao *et al.*, 2008).

The rotary triboelectrification separator (RTS) is characteristic of a copper-covered rotary wheel which charges materials through friction movement. Copper is used for the friction wheel because it provides an optimal work function (falling in between the minerals and macerals) (Dwari and Rao 2006). Figure 3.7 shows a schematic of an RTS. This system has been proven successful for several materials, including coal (Bada *et al.*, 2010; Tao *et al.*, 2011).

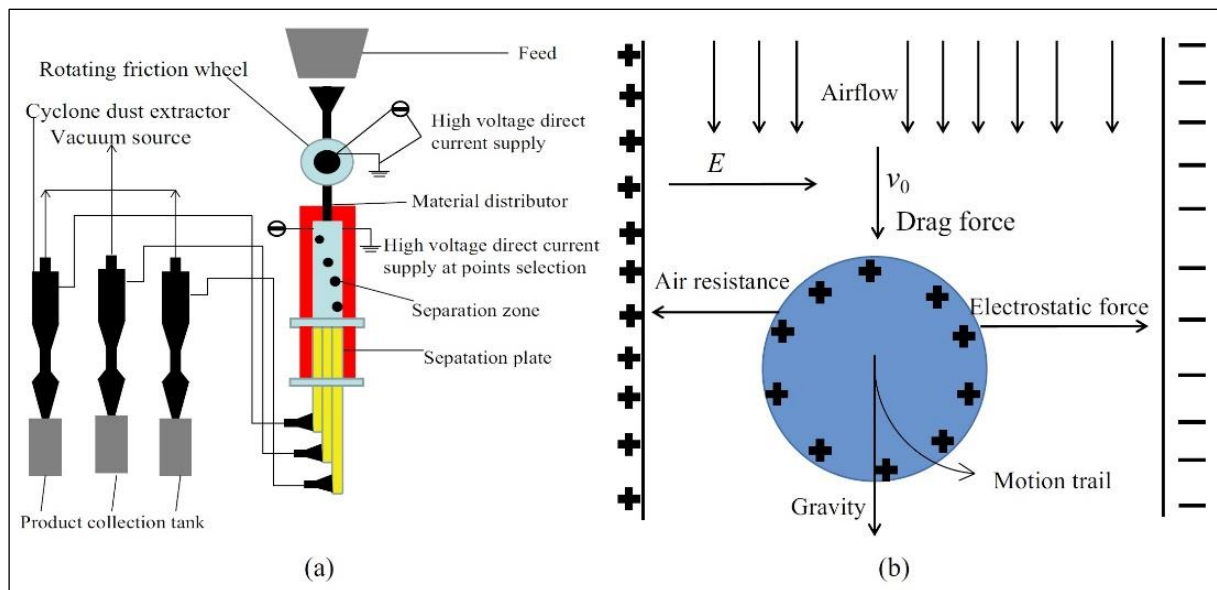


Figure 3.7: The draft of triboelectrification separation system (Yushuai *et al.*, 2021).

3.1.4 Applicability and limitations of the various dry processing techniques

All the separation methods described above have merit for dry coal processing, but their applicability and any associated limitations must be considered. This includes the following factors: coal type and densimetric properties, particle size range, capacity, moisture content, feed preparation and feed presentation.

3.1.4.1 Coal type and densimetric properties

Some dry processing techniques may be more suited to specific applications because of feed coal quality and the operating principle and capabilities of the separator. A distinction should be made between de-stoning and concentration. Most dry beneficiation methods can be successfully used in de-stoning, pre-concentration, and salvage because of the ease of separation of the extremely poor-quality shale from coal, as well as the generally larger particle sizes involved (Wotruba, 2006; Weinstein and Snoby, 2007; Tripathy *et al.*, 2017). Preparing coal particles prior to processing offers opportunities to enhance mine productivity and profitability. Initially, it reduces the volume of material requiring downstream crushing, screening, and processing, consequently diminishing the waste handled by the coal washing plant and discarded in tailings ponds post-processing. Moreover, by reducing both waste material and water usage during processing, it contributes to a decrease in tailings dam size and water demands, thereby lowering the overall operational costs (Lessard *et al.*, 2014; Lessard *et al.*, 2016; Wills and Finch, 2016; Revuelta, 2018).

When beneficiating to a clean coal product, dry processing is appropriate for materials where near-dense material is minimal or in cases where a significant upgrade in coal quality is not required to meet specifications (De Korte, 2013). The portion of material that is present in an ± 2 EPM density range is defined as near-dense material (De Korte, 2013). Near-dense material can complicate a process by causing increased particle misplacement, lower yields, and less control of the product quality (De Korte, 2013). This is particularly true for the gravity-based separation techniques. In a study conducted by (Jambal *et al.*, 2017) where the middling characteristics were found to be nearly identical to the feed, it proves necessary to keep the middling amount as low as possible. In plant operations, the middlings produced ($\pm 20\%$) may need to be recycled into the feed for further recovery. When considering a DE-XRT sorter, it is possible to overcome issues pertaining to near-dense material by implementing stricter selectivity which may, however, significantly affect throughput and production (Von Ketelhodt and Bergmann, 2010). Due to the capabilities of DE-XRT to detect other particle and material properties, sorting can also be utilized for desulphurization, separation of the density similar torbanite from coal and size, shape, and washability classification (Von Ketelhodt and Bergmann, 2010; Zhang *et al.*, 2021). This is also

true for the novel Rhovol 3D imaging process. In gravity-based separation, pyrite inadvertently coincides with the heavy material due to its higher density and is, in so, removed (Sampaio *et al.*, 2008; Weinstein and Snoby, 2007). Density separations are quite reliant on mass and surface area, and therefore, some of these techniques can also be utilized for size and shape classifications (A.I. Stepanenko, CEO Gormash Export, personal communication, September 2019).

The magnetic and electrostatic processes are not severely affected by the presence of near-dense material. This is because these processes do not rely on density and the fine grain size required is associated with a high degree of liberation. These techniques are, however, mostly applicable to pyrite-bearing coals and used in desulphurization applications. This is because pyrite possesses significantly differing magnetic and electro-physical properties when compared to the carbon and other mineral matter present in coal (Van Driel *et al.*, 1984; Ciccu *et al.*, 1991). It is, however, still possible to separate other medium and weakly magnetic materials in the RERMS depending on magnet strength (Tripathy *et al.*, 2017). Similarly, separation of small amounts of conductive from large amounts of non-conductive material and concentration of materials of largely differing electro-physical properties is also possible in TBS (Kelly and Spottiswood, 1989). Some studies show that treating a coal sample with heat can improve the magnetic and electric properties making it easier to separate them with RERMS and TBS. Examples of these are pyrolysis and microwave pre-treatments. These treatments also show potential in dewatering applications and improving grindability (Binner *et al.*, 2014).

The possibility of using TBS to separate different coal macerals has also been investigated and several techniques have been reported by different researchers (Nag *et al.*, 2021). Vitrinite and inertinite have different oil production rates. Vitrinite proves better because of stronger fluidity and decomposition reaction (Jin *et al.*, 2014). The electrification ability of vitrinite differs from that of inertinite, the former charges positively while the latter takes on a negative charge. (He *et al.*, 2018). Yushuai *et al.* (2021) separated the macerals of low-rank coal by TBS. In comparison to the other maceral separation techniques, TBS has significant advantages. Zhang *et al.* (2022) implemented permittivity and charge–mass ratio measuring systems to analyse the charging properties of vitrinite and inertinite under several modified conditions.

3.1.4.2 Particle size, cost and capacity

Proper particle-size distribution (PSD) before separation is important not only for handleability but also for the feed particle size, especially the top and bottom size, which is often a limiting factor in the applicability of a specific method. In general, in most dry separators, the separation efficiency significantly deteriorates for particles smaller than 6 mm (Patil and Parekh, 2011).

Moreover, efficient dry processing can be achieved at PSD ratios between 2:1 and 4:1 (Jambal *et al.*, 2020). This is proven by the theory of equal settling particles developed by Pittenger in 1867, as explained in work by Patil and Parekh (2011).

The All-Air Jig and ADMFB can process feed with a large PSD ratio (10:1) (Weinstein and Snoby, 2007). Dense medium, vibration and oscillating motion can assist in stratification and efficient separation of possibly wider size ranges (Patil and Parekh, 2011). Particles falling outside of the operating ratio range may be misplaced. A narrow particle size range is imperative for most dry processes. Table 3.2 lists the PSD data for the techniques considered in this paper.

Table 3.2: Particle size distribution and capacity ranges for the dry processing techniques.

Dry processing technique	Particle size distribution (mm)	Capacity (tph)	Reference
DE-XRT	10–120	70–240	King, 2015
All Air Jig	0.5–50	50–120	Weinstein and Snoby 2007
Air table (fine)	0–6 [*]**	0–5 [***]	*Chalavadi <i>et al.</i> , 2016 ** Patil and Parekh 2011; *** Gupta, 2016
Air table (coarse)	6–75 [*]**	300–1200 [****]	* Patil and Parekh, 2011; ** Honaker, 2008; *** Stotts <i>et al.</i> , 1987
FGX	6–80 [*]**	10–350 [***]	*De Korte, 2013; **Dwari and Rao, 2007; ***Zhang <i>et al.</i> , 2011
KAT	1–10	100	Jambal <i>et al.</i> , 2016
AKA-FLOW	0.045–3	5–25	Wotruba <i>et al.</i> , 2010
ADMFB	6–300 [*]	150 [***]	Dwari and Rao, 2007; ** Sahu <i>et al.</i> , 2009; *** Chen and Wei, 2003
Modified ADMFB	0–6 [*]	0.15 8 [*]	*Dwari and Rao, 2007; **Hughes <i>et al.</i> , 2017
SEP-AIR	1–100	45–200	Gormash Export, 2016
Dry reflux classifier	0.2–8	300 gr/min	Macpherson <i>et al.</i> , 2011
Winnower	6–100	0.006–0.01	Sahkre <i>et al.</i> , 2018
RERMS	0.075–25	2–10	Tripathy <i>et al.</i> , 2017
TBS	0–1 [*]**	0.012 [***]	*Mohanta <i>et al.</i> , 2016; ** Dwari <i>et al.</i> , 2015

When considering a size benchmark of 6 mm to distinguish between fine and coarse coal, the gravity-based processes such as the DE-XRT sorter, All-Air Jig, air table, FGX, ADMFB, SEP-AIR and winnowing methods are suitable for processing larger PSD ranges. All these methods can process coal at relatively large capacities, but the cost differs depending on the method type. The DE-XRT sorter proves costly at higher operating capacity owing to the requirement of proper x-ray detection and residence times. The FGX, All-Air Jig and air tables are low-cost options at higher capacities but may suffer from separation inefficiency. The SEP-AIR and NPPS units perform well and at high throughputs. The ADMFB is considered a high-cost process due to the dense medium removal post-processing. These methods are also capable of processing finer coal, but most of this work is at an early developmental stage (Chen and Wei, 2005; Macpherson

et al., 2011). Moreover, some of the processes aren't practical at smaller particle sizes due to the reduction in processing capacity. This is especially true for the DE-XRT sorter (King, 2015; Strauss, 2016; Wotruba, 2006; von Ketelhodt and Bergmann, 2010).

Inefficient fine particle recovery using conventional gravity separators is a recognized challenge (Majumder *et al.*, 2003). Due to the small mass and high surface area of a fine particle, low particle momentum, hypercoagulation, difficulty in overcoming the interparticle energy barrier, low settling rates and high viscosity are observed (Sivamohan, 1990; Amariei *et al.*, 2014). As the particle size reduces, the difference between the settling velocities of heavy and light particles decreases and then the performance of gravity separation becomes weak (Das and Sarkar, 2018). When particles are ultra-fine, the settling kinetics are very slow. Thus, for these particles, even though the density criterion is favourable, the time needed for efficient separation is impossibly long.

Traditional gravity separators are not able to provide such long residence times and are, making them impractical for fine particles. As a result, sorting fine particles at high throughput poses challenges. However, finer particle sizes often result in increased mineral liberation, necessitating the economical and rapid separation of these liberated valuable particles. Advanced gravity separators must address this technological gap to enable the cost-effective and swift separation of fine minerals, paving the way for their commercial viability in fine coal cleaning applications.

Extracting the fine undersized material is crucial not only to mitigate particle misplacement, as previously discussed but also to decrease the fraction of dust particles requiring treatment in the dust-handling system (De Korte, 2013). Systems like the FGX and ADMFB utilize an autogenous or dual-density medium. The presence of fine material in the feed aids in an improved medium particle suspension (Ghosh, 2013). The number of fine particles present needs to be controlled to below 10%_{wt} so that the stability and properties of the suspension are not altered (He *et al.*, 2016). Moreover, fines removal prevents particle sticking and equipment plugging where moisture is present (De Korte, 2014).

The standard air table, AKA-FLOW and KAT separators are available for the fine coal particle size ranges. The RERMS and TBS methods find most use in fine and ultrafine coal processing (<1mm). Most dry magnetic separators are suitable for treating coal larger than 75µm whereas the TBS is comfortable with processing coal particles as fine as 45µm (Trigwell *et al.*, 2003b; Tripathy *et al.*, 2017; Mohanta *et al.*, 2016; Dwari *et al.*, 2015).

The fact that particles that fall outside the allowable operating PSD range could lead to displacement has already been mentioned. This may be because of issues related to dilution, liberation, mineral exposure, detection, ejection force and trajectory. A similar particle

misplacement phenomenon is observed in processing with RERMS and TBS but concerning magnetism and electric charge, respectively. The effects of PSD on separation efficiency in RERMS separators have been extensively studied. The overlapping trajectories of large, weakly attracted particles with small non-magnetic particles in a magnetic field were found to be an issue (Gehauf, 2004; Tripathy *et al.*, 2017; Ibrahim *et al.*, 2017). Particle size also influences charging and, therefore, separation in TBS (Kelly and Spottiswood, 1989). Larger particles obtain a lower charge than that of a smaller particle. Therefore, displacement of large and conducting particles into the non-conducting material may be observed because of a weaker attraction in the electric field. Similarly, the fine conducting material may be contaminated with small non-conducting particles since small particles are more readily influenced by surface charge (Wills and Napier-Munn, 2008; Kelly and Spottiswood, 1989).

3.1.4.3 Moisture

The moisture content of the feed proves important in dry processing. Processes such as the DE-XRT, air jig, air table, SEP-AIR, NPPS and coal winnower can operate in the presence of moisture provided that the amount of fine material is limited and the particles are able to free-flow without plugging the material handling systems (De Jong *et al.*, 2004; Weinstein and Snoby, 2007; Von Ketelhodt and Bergmann, 2010; De Korte, 2014; Gupta, 2016). Therefore, extensive drying is not always necessary before processing.

Typical coal surface moisture for the air table, air jig and SEP-AIR ranges between 3–7% (Stotts, 1987; Gupta, 2016; Weinstein and Snoby, 2007; Stepanenko, 2019). Meanwhile, the NPPS can process coal in the moisture range of 12–20% (Stanczyk *et al.*, 2021). Particle surface adhesion and agglomeration cause particle misplacement due to entrainment and misdetection (Weinstein and Snoby, 2007). This is observed in the FGX, where a portion of the fine coal is used as an autogenous fluidized bed (De Korte, 2014). Kademli *et al.* (2021) examined the influence of moisture (7–25%) on the FGX separator performance. The findings indicated a notable impact of moisture content on separation efficiency. As moisture content increased, both separation efficiency and EPM values showed an inverse relationship, with optimal outcomes observed at minimal moisture levels. Xia *et al.* (2015) investigated the utilization of hot gas in drying and cleaning processes, concluding that the amalgamation of dewatering and separation holds promise for cleaning low-rank coals like lignite and others within this range.

In separators where a dense medium such as magnetite is used (ADMFB, DRC), similar adhesion of the medium particles to each other, the coal and vessel walls are observed in the presence of moisture. As a result, a portion of the magnetite powder agglomerates, the contact efficiency between air and particle reduces, nonuniformity in bed density increases, and the particle

dispersion decreases. Moisture contents ranging from 3–4% are necessary in these cases (Sahu *et al.*, 2009; He *et al.*, 2015). Luo *et al.* (2010) suggest a method for increasing the surface hydrophobicity of the magnetite particles (using stearic acid as the modifying agent) to control the moisture content to less than 2%. It proves an effective technique for increasing gas-solid fluidized bed applicability to dry beneficiation of feedstocks with different external moisture contents.

The RERMS and TBS processes are primarily used for dry mineral processing. Some investigations of the RERMS conducted on a wet basis have been done by Rylatt and Popplewell (1999). Even so, suitable moisture content during RERMS processing only requires particles not adhering to each other and the machine (Mineral Technologies, 2018). TBS is only concerned with particles that are bone dry. Some studies have attempted to use a medium other than air (such as a dielectric liquid) (Wills and Napier-Munn, 2008; Kelly and Spottsiwood, 1989). Moisture, temperature, and relative humidity are important parameters during the charging of particles (Cruise *et al.*, 2022).

3.1.4.4 Additional feed preparation

Feed preparation includes comminution, screening for the removal of undersized material, drying to ensure a suitable moisture content, and particle surface cleaning or de-sliming. The importance of crushing and the control of the amount of fine material and moisture contents in the feed has already been discussed. Additionally, removal of any minute particulate contaminants on the particle surface may be necessary. This is particularly true for cases where the separation mechanism depends on surface characteristics such as the RERMS and TBS processes. For these, the particle surfaces must be free of organic materials and dust as this may affect the magnetic susceptibility and the charge formation and dissipation, respectively (Fraas, 1962).

3.1.4.5 Feed presentation

The way the feed ore is presented to the separator plays a role in some processes. A monolayer of particles presented at the correct particle speed is required for belt-driven operations such as the DE-XRT and RERMS (Strauss, 2016; Tripathy *et al.*, 2017). However, the orientation of the particle is inconsequential in DE-XRT sorting as the entire mass of the stone is detectable, and the dual-energy sensor array negates the effects of geometry (Strydom, 2010; Lessard *et al.*, 2014). The RERMS is, on the other hand, affected by particle orientation and may require the magnetic portion of a coal particle to be exposed to the magnetic roll. The feed to the SEP-AIR unit is also belt driven but only requires a particle monolayer when processing feed with a large particle size ratio and works optimally when processing a multi-layer feed with a small particle size ratio (A.I. Stepanenko, CEO Gormash Export, personal communication, September 2019).

The coal winnower, utilizing a single-line particle flow, may also be affected by particle speed and orientation. If the proper flow of the feed is maintained, particle orientation should not affect most other dry-density separations (Weinstein and Snoby, 2007).

Feed rates in the air table variants prove important to ensure readily fluidized particles. Feed flow rates that are too high can cause a thick particle bed that cannot fluidize effectively. On the other hand, feed rates that are too low lead to inadequate bed formation (Chalavadi *et al.*, 2016; Patil and Parekh, 2011). Similar results were obtained in a study by Jambal *et al.* (2017) investigating the feed flow rates in a KAT separator. At low rates, a stable, dense medium suspension is not achieved, and middling yield increases due to the heavy light fractions being misplaced. Ample dense material during operation forms a stable, dense layer suspension on the deck; this is obtained at increased coal feed rates. Additionally, the kinetic energy of the feed flow forces the separation to the lower deck portions which allows for efficient reduction of the middling fractions. However, high feed rates reduce the residence time causing poor stratification and possible back-mixing.

The feeding position in an ADMFB affects the movement of coal particles. The impact of the feed height on the fluidization characteristics was studied by Jiang *et al.* (2019). Efficient separation was achieved when the material was introduced into the ADMFB from the upper or middle sections. Conversely, poor separation efficiency was observed when particles were fed from the bottom due to the inability of low-density particles to float to the upper layer of the fluidized bed. Initial fluidization of dense medium is required before introducing coal particles in processes such as the ADMFB and DRC. Ineffective separation could be attributed to improper presentation of the particles to the process (Wotruba, 2006; Kelly and Spottiswood, 1989).

3.1.5 Operating parameters

Some studies have focused on investigating the effects of certain operating parameters on separation efficiency. Regarding the air table separator, operating variables such as vibration frequency, table inclination, feeding speed rate and baffle properties were proven to directly impact separation efficiency (Chavaldi *et al.*, 2016; Patil and Parekh, 2011). A proper residence time is essential for acceptable separation. Similar results were obtained for a study on the effects of airflow rate, cross-table inclination, and vibration frequencies in a KAT separator (Jambal *et al.*, 2017). The effects of the vibration amplitude, frequency, vibration direction angle, longitudinal deck angle, feeder frequency and baffle plate height on the FGX were proven imperative in studies by Zhang *et al.* (2011) and Yu *et al.* (2016).

Factors that influence the fluidization quality in the ADMFB include the air distributor, the fluidised bed's geometry, the dense medium's characteristics, and the air velocity. Among these factors, air velocity seems more important for attaining optimal separation as it significantly affects fluidization characteristics and the behaviour of bubbles and particles. Adequate loosening of the material is the premise of the stratification based on density to obtain an effective separation (Jiang *et al.*, 2019). It is essential to avoid excessive bubbling or turbulence, which results in back mixing in ADMFB. Investigation of the fluidized bed stability was done by Zhang *et al.* (2020), wherein the effects of gas velocity on density distribution were analysed. At lower velocities, the bubble sizes were small, proving unsuitable for fine particle processing. As the gas velocity increases, so does the bubble size, which negatively affects the bed stability, causing increased density fluctuations. Yang *et al.* 2013 described that the mixing and stratification in an ADMFB mainly depend on the bubbles. Thus, bubble characteristics such as size and rise velocity significantly affect the separation performance. Small bubbles create a drag force sufficient to lift light coal particles to the top of the bed. The force of gravity supersedes the drag force, meaning that the movement of the heavier particles remains unaffected. Clearly, appropriate gas velocity improves density stratification leading to a higher separation efficiency (Diedericks *et al.*, 2022).

Additionally, as the bed height increases, the bubbles become larger. However, bed heights that are too low do not provide adequate space for proper particle segregation. At increased bed heights, the rising distance of the bubbles increased, weakening their activity and enhancing back mixing and aggregation. Thus, the static bed height should be maintained in the appropriate range (He *et al.*, 2016b). Fu *et al.* (2019) revealed that ADMFB performance is not sensitive to the excess gas velocity allowing for comparatively wide airflows during operation. Choung *et al.* (2006) investigated the separation efficiency of ADMFB with variations in operating parameters, including air speed and particle size (coal and medium). Enhancing the separation efficiency of the ADMFB process for fine coal involves employing a smaller medium size, thereby creating a more stable fluidized bed with moderate airflow. However, when utilizing magnetite particles smaller than 45 μm , the fluidized bed became excessively viscous, resulting in poor separation. Azimi *et al.* (2017) used response surface methodology to investigate the effects of superficial air velocity, residence time and bed height on the performance of the ADMFB separator. Other investigations emphasized the impact of superficial gas velocity and the coal-to-magnetite weight ratio on the separation efficiency of the ADMFB (Mohanta *et al.*, 2011, 2015; Hughes *et al.*, 2017; Diedericks *et al.*, 2022). Findings indicated that product ash was more reliant on the superficial gas velocity than the coal-to-magnetite weight ratio. Additionally, Sahu *et al.* (2011, 2013) conducted a study focusing on the stability characteristics of various fluidized bed shapes. The geometry of the fluidized bed column cross-section notably impacts the bed's stability.

Specifically, the rectangular cross-sectional shape exhibits superior stability properties when compared to square or circular shapes.

Operating parameters proving important for the negative pressure particle separation type units include the flow patterns and speed of the air produced by the main fan, particle behaviour in the fluidization section, feed layer thickness and residence time (Stepanencko, 2016a; Stepanenko, 2016b; Stanczyk *et al.*, 2021).

The variables affecting the RERMS include feed rate, roller speed, and splitter position (Fujita *et al.*, 1981; Hucko and Maronde, 1982; Van Driel and de Kerk, 1983; Male, 1984). Dwari and Rao (2009) established that the time for tribo-charging, voltage, airflow, and fluidization residence time may affect the separation efficiency.

3.1.6 Performance

The performance and success of a particular dry coal beneficiation process are vacillating and strongly rely on the process application and limitations (as described). EPM, cut-point density, reduction in ash value and product yield can be used to determine the efficiency of a certain process. These are discussed for each of the processes in the sections that follow.

3.1.6.1 Sensor-based sorting

Typical performance data available for a DE-XRT sorter is provided in Table 3.3. These results are supported by De Korte (2013), Robben *et al.* (2014) and Von Ketelhodt and Bergmann (2010). As mentioned, stricter thresholds can produce higher efficiencies at the expense of throughput. Table 3.3 shows a significant decrease in ash content and an improvement in the calorific values of the product by using DE-XRT. This sorter has the potential to become an integral component of future dry coal cleaning plants but may not be capable of delivering a product quality at a capacity that competes with a wet beneficiation plant unless it is operating numerous machines with re-processing.

Table 3.3: Typical performance data for a DE-XRT.

Technique	Particle size (mm)	EP	Cut-point density (SG)	Ash (%)	Yield (%)	Reference
DE-XRT	+50	0.29	2.06	Feed = 71 Product = 59.5	47.6	De Korte, 2013
Belt-type sorter (50 tph)	20–30	0.09 0.19 0.14	2.1 1.9 1.9	Feed = 28.3, 29.5, 29.3 Product = 21.4, 20.4, 20.9	84.5 77.9 78.8	Robben <i>et al.</i> 2014

Belt-type sorter (100 tph)	30–100	0.17	1.9	Discard = 66.0, 61.6, 60.4			
		0.04	1.8	Feed = 43.8, 43.0	59.1 54.4	Robben <i>et al.</i> 2014	
Chute-type sorter (100 tph)	30–100	0.11	1.7	Product = 23.3, 21.8			
		0.13	1.6	Discard = 73.5, 68.4			
		0.12	1.7	Feed = 31.2, 43, 33.8,	55 36.7	Robben <i>et al.</i> 2014	
		0.11	1.6	27.7	51.6		
DE-XRT	20–53 53–75 75–100	-	-	Product = 19.5, 25.7, 20.3, 21.1			
				Feed =	75.2	von Ketelhodt and Bergmann, 2010	
				24.12, 25.76, 29.71	82.5 80.6		
				Product = 16.11, 16.82, 16.67			
				Discard = 48.09, 67.88, 83.85			

3.1.6.2 Gravity-based separation

Table 3.4 summarises published performance data for the established gravity-based separation units regarding the EPM, yields, ash value, and cut-point density. The data for each method are further discussed in the sections that follow.

Table 3.4: Performance data for some commercially available dry coal gravity separation methods.

Technique	Particle size (mm)	EPM	Cut-point density (SG)	Ash (%)	Yield (%)	Reference
Air Jig	12.7–50.8	0.16	2	Feed = 14.81 Product = 13.06 Discard = 51.03	-	Weinstein and Snoby (2007)
Air Jig	-19	0.21	2.2	Feed = 21.29 Product = 6.69 Discard = 60.4	-	Weinstein and Snoby (2007)
Air Jig	1–15	-	-	Feed = 37.70 Product = 19.80 Discard = 68.60	59.8	Boylu <i>et al.</i> (2015)
Air Jig	-4	-	-	Feed = 31.75 Product = 25.57 Discard = 54.67	60.5	Boylu <i>et al.</i> (2013)

Air table	-1	0.18–0.20	1.70–2.01	Feed = 30.56–49.7 Product = 21 – 37	40–60	Chavalidi <i>et al.</i> (2016)
Air table	0.15–1	-	-	Feed = 34.2 Product = 30.15	66	Kumar <i>et al.</i> (2010)
Air table	1.4–6.3	-	-	Feed = 23 Ash rejection = 77–80	80	Patil and Parekh (2011)
FGX	0–80	0.13	-	Feed = 27.90 Product = 18.43 Discard = 80.53	86.87	Zhao <i>et al.</i> (2014)
FGX	3.36–6.35 2.–6.35 1–6.35	0.25 0.29 0.36	2.01 1.97 1.70	Feed = 31–36 Product = 13.8–14.5 Discard = 52.9–59.7	-	Akbari <i>et al.</i> (2020)
FGX	0–80	0.145	1.66	Feed = 8.92 Product = 0.93 Discard = 28.59	71.24	Yu <i>et al.</i> (2016)
FGX	4.75–63.5	0.17	1.98	Feed = 22.71 Sulphur 4.17 Product = 11.74 Sulphur = 3.05	-	Zhang <i>et al.</i> (2011)
FGX	+6.4	0.25	1.8–2.2	Feed = 18.21 Sulphur = 1.58 Product = 10.76 Sulphur = 1.41	76.8	Honaker <i>et al.</i> (2008)
FGX	6–50	0.22	2	Feed = 40.4 Product = 31.9 Discard = 60.2	70.08	De Korte, (2013)
KAT	5–10 1–5	0.08–0.1 0.1–0.12	1.8–2.0	Feed = 44 Product = 8.4 Feed = 33.7 Product = 9.4	-	Jambal, <i>et al.</i> (2017)
AKA-FLOW	-3	-	-	Feed = 29.5 Product = 18.3	73.5	Wotruba <i>et al.</i> (2010)
AKA-FLOW	0.05–3	-	-	Feed = 47.5 Product = 25.8	54.4	Wotruba <i>et al.</i> (2010)
ADMFB	13–25	0.115	-	Feed = 39.14 Product = 32.0	Combustible recovery = 71–75	Mohanta <i>et al.</i> (2015)
ADMFB	10–100	0.055	1.49	Feed = 23.98 Product = 3.46	67.88	Zhao <i>et al.</i> (2017)
ADMFB	3.35–5.6	0.03–0.1	1.6	Feed = 14 Product = 6	90	Choung <i>et al.</i> (2006)

ADMFB	3–6 2–3 1–2	-	-	Feed = 22.13, 20.68,19.40 Product = 9.65,10.33, 11.74	77.45 81.52 83.65	Zhang <i>et al.</i> (2020)
ADMFB	3–6	0.13	1.87	Feed = 45.92 Sulphur = 3.02 Product = 31.29 Sulphur = 2.57 Discard =70.27 Sulphur = 3.42	Combustible recovery = 89.26	Fu <i>et al.</i> (2016)
ADMFB	6–80	0.055	1.42	Feed = 15.69 Product =3.71	67	Zhang <i>et al.</i> (2014)
ADMFB	6–25	0.12	1.68	Feed = 40 Product = 32– 35.5	60–72	Sahu <i>et al.</i> (2011)
ADMFB	3–6 6–10 10–13	0.07 0.055 0.05	1.62 1.71 1.80	Feed = 36.48 Product = 12.47, 11.57, 10.90 Discard = 66.69, 69.31, 71.41	50.79 56.83 61.24	He <i>et al.</i> (2015)
ADMFB	6–300	0.05– 0.07	1.3–2.2	Feed = 39–46 Product = 16.4–18.2 Discard = 63.8–67.5	41–56	Luo and Chen, (2001)
SEP-AIR	1–100	0.1– 0.17	1.78–1.90	Feed =13.1– 19.0 Product = 7.0– 14.8 Discard = 51.0–69.6	85–93	De Korte (2018)

3.1.6.2.1 Air jig

Most of the jigging applications for dry coal processing are in the coarse coal circuit. Herein, an air jig can provide separation efficiencies ranging from 0.16–0.21 but at quite a high cut-point density (2.0–2.2 SG) (Weinsten and Snoby, 2007). The ash value data shows a larger difference in the discard from the feed than from the product, indicating that the separation is predominantly de-stoning. Charan *et al.* (2011) used the All-Air jig manufactured by Allmineral in Germany to beneficiate Indian high-ash non-coking coals. At a capacity of 50 t/h, coal (+5-40mm) with an ash content of 40% produced a concentrate with an ash content of 33%.

Some studies have been conducted on fine coal fractions. Boylu *et al.* (2013) investigated air jigging of three coal samples in the minus 4 mm size range. The ash value reduction from feed to

concentrate for the first, second, and third samples was 31.75% to 25.57%, 33.64% to 19.59%, and 37.28% to 24.24%, respectively. This coincides with 60.5%, 51.2%, and 62.3% yields.

Sampaio *et al.* (2008) used dry jigging to desulphurize low-rank coals in Brazil. A reduction of sulphur content from 2.33% in the feed coal to 1.08% in the concentrate was obtained.

3.1.6.2.2 Air table

The Standard Air Table discussed is mostly suitable for fine coal and offers EPM values in the range of 0.18–0.20 (Chavaldi *et al.*, 2016). It is evident that for a wide range of ash contents (30–50%) in the fine coal (+0.1–1.0 mm), the air table successfully reduced the ash value by 9–10% points. Cicek (2008) established an improved air table to clean Turkish coal. The results indicated that the coal samples with three size fractions of 5–8, 3–5 and 1–3 mm can be efficiently beneficiated by this modified air table with EPM values of 0.21, 0.14 and 0.09, respectively, representing an acceptable separation performance.

Studies have been done using air tables in coarse coal fractions. Stotts *et al.* (1987) examined the dry separation of coal using an air table for 6.3–19.0 mm and observed EPM values in the range of 0.24–0.26. An air table was used for coarse coal separation with a top size of 50 mm by Killmeyer *et al.* (1979) and a top size of 19 mm in a plant with a 1200 t/h capacity by Wright (1985). Zhou *et al.* (2021) claimed that coal of 6–38 mm is the best range size for an industrial separation scale air table separator so EPM values of about 0.13–0.23 can be achieved. Honaker (2005) revealed that 70–90% of +6.3–50 mm coal with a relative density higher than 2.0 kg/m³ could be removed using an air table. A reduction of sulphur content from 2.33% in the feed coal to 1.08% in the concentrate was obtained.

3.1.6.2.3 KAT

The KAT is a modified air table mostly applicable to fine coal. This process can effectively remove and produce clean coal with ash values ranging from 7–10%. A stable separation efficiency is observed with EPM values varied from 0.08 to 0.12 and 84–90% yield (Jambal *et al.*, 2017). Two KAT air table separators were used for 1–5 mm (3.7–5 t/h) and 5–10 mm (5–31 t/h) raw coal cleaning of the Naryn Sukhait mine (Mongolia) by Jambal *et al.* (2016). In the results, the ash content of 1–5 mm coal was reduced from 35.6% to 12%. Meanwhile, the ash value of 5–10 mm particles was reduced from 48.4% to 9.4%. Therefore, the KAT air table separator can effectively remove gangue from fine coal.

3.1.6.2.4 AKAFLOW

AKAFLOW is the result of a modification to a conventional air table for a coal size range of minus 3 mm (Akbari *et al.*, 2020). EPM values are scarce in literature but yields of 73.5% are possible with a reduction in ash value from 29.5% in the feed to 18.3% in the product (Wotruba *et al.*, 2010). Another study shows an ash reduction to 25.8% in the concentrate from 47.5% in the feed with a 54.4% yield (Wotruba *et al.*, 2010).

3.1.6.2.5 FGX

The FGX, an enhanced air table developed in China, is proficient in beneficiating coarse coal, exhibiting separation with EPM values ranging from 0.2 to 0.3. Zhang *et al.* (2011) extensively evaluated the FGX separator's performance in handling Illinois Basin coal. Their findings highlighted the FGX's efficiency in beneficiating raw coal within the 6–75 mm size range, achieving a density cut of 1.98 and an EPM of 0.17. Subsequent research by Akbari *et al.* (2018) explored the development of a comprehensive dry processing plant flowsheet for raw coal beneficiation. This design incorporated a rotary breaker for reducing ROM coal size below 75 mm before its optimal use in the FGX separator. The FGX middling stream underwent re-crushing to enhance coal particle liberation (1.0–6.3 mm) for further cleaning in the second stage by the FGX. The resultant concentrate exhibited an ash content of 16%, derived from a feed initially possessing 33.4% ash content. De Korte (2013) investigated the FGX's applicability for South African coal types, yielding an EPM of 0.22 with a 70.8% yield and an improvement in ash content from 40.4% to 31.9%.

3.1.6.2.6 ADMFB

The EPM value of the ADMFB is reported to be in the range of 0.04–0.12, which is the best compared to the other dry methods available. It also provides the most flexible SG₅₀ values. High magnetite losses and complicated dense medium recovery, cleaning, recycling (and drying) can lead to operational difficulties and larger capital and operation expenses (Yang *et al.*, 2013). An example of an ADMFB is the Bohou unit, implemented in China, and has proven effective for beneficiating 13–200 mm coal (Zheng, 2016). Designed for 500 t/h, it can successfully separate coal at a cut point of 1.58 g/cm³ with feed coal containing less than 5% moisture, producing clean coal of 9.85% ash content; the separation has an EPM of 0.05–0.08.

ADMFB has been widely used for cleaning various kinds of coal with particle sizes of 1–100 mm. Luo *et al.* (2001) used the ADMFB process to separate 6–50 mm coal particles with an EPM value of 0.05. Duan *et al.* (2018) used ADMFB for pyrite recovery from 13–50 mm and 6–13 mm coal fractions and achieved recovery rates equal to 81.69 and 79.51, respectively. Sahu *et al.* (2011;

2013) studied the stability characteristics of different shapes of fluidized beds and established an ADMFB system to separate 6–25 mm coal particles. Luo *et al.* (2007) and Zhao *et al.* (2017) sorted coal sizes 6–50 mm and 10–100 mm at a separating density of 1.5 g/cm³.

Fu *et al.* (2019) performed experiments on a pilot scale ADMFB with four coal types in 25–50, 13–25, 6–13, and 2–6-mm size ranges. A close-to-perfect partition curve was observed for the 25–50 mm coal with an EPM value of 0.03, showing exceptional separation performance. For 13–25 mm and 6–13 mm coals, the EPM reported 0.07 and 0.10, respectively. The EPM for 2–6 mm coal was not calculated due to its 75% partition coefficient being unavailable. From this, it is noted that EPM increased with decreasing particle size, independent of coal type. This can be attributed to rising gas bubbles, where fine coal particles fall into the bubbles. Moreover, the cut-point density also increases when particle size decreases. Separation densities of 1.85, 1.90, 1.95 and 2.05 were reported for the 25–50, 13–25, 6–13 and 2–6-mm PSD ranges, respectively. An increased cut-point density allows more impurities to remain in the concentrates, lowering the quality of the clean coal product. In conclusion, the separation efficiency of ADMFB reduces with reducing coal PSD, not only because of EPM and cut-point density increases but due to the variation of partition coefficients above 2.0 and 1.3. This may be attributed to bubbling behaviour and back mixing of the medium suspension preventing efficient separation of finer coal particles (Luo, *et al.*, 2001; Mohanta *et al.*, 2011). Similar outcomes were reported by Azimi *et al.* (2017), that feeding finer coal particles (2.8–5.6 mm) deteriorates the separation efficiency and leads to higher product ash contents compared to larger particles (5.6–13.2 mm).

Chikerema and Moys (2012) affirmed the influence of particle size and shape on ADMFB separator efficiency when using a mix of magnetite and silica. They noted that larger particles (37–53 mm and 22–31.5 mm) exhibited faster and more efficient separation, averaging an EPM of 0.05, compared to smaller particles (16–22 mm and 9.5–16 mm). However, a reduction in particle size led to higher EPM values and a consistent shift in the cut density. The study emphasized that particle shape, though challenging to control, significantly impacted the ADMFB's performance, particularly in separating 16–22 mm particles of various shapes. Three different particle shapes, including the flat, blockish, and sharp-pointed prism, were investigated by Chikerema and Moys (2012). A small surface area-to-volume ratio is observed for the blockish particles, making them less susceptible to the effects of viscosity. Therefore, the blockish shapes separate more effectively than the other shapes considered.

Fu *et al.* (2016) examined the feasibility of using an ADMFB to separate 3–6 mm fine coal and expand its lower separation limit with the modified magnetite powders. In this study, four types of magnetite powders (0.3–0.4 mm, 0.225–0.3 mm, 0.15–0.225 mm, and 0.074–0.15 mm) were

used. The results showed a significant reduction of the ash content from 45.92% to 31.29% and total sulfur from 3.02% to 2.57% with a clean coal yield of 27.33% using the 0.074–0.15 mm magnetite particle-size fraction. Although the ADMFB with improved magnetite powders shows satisfactory performance for 3–6 mm, it is difficult to obtain a purified clean-coal product with a low-ash content. It becomes clear that a practical technique for purifying coal in the smaller fractions must still be found, and further investigation is required to improve upon the performance obtained using these methods on an experimental scale.

Jiang *et al.* (2019) examined particles' movement and separation process in different densities within the bed. The bed was divided into five layers according to its height. There are particles with a density lower than the separation density in the heavy product. There are also particles with a density higher than the separation density existing in the light product during the sorting process, resulting in pollution of concentrate and loss of coal. During the actual production process, the feeding position, media features, separation time and gas velocity have important effects on the fluidization characteristics and separation process of coal particles in ADMFB, thus, affecting the beneficiation of coal. The particle characteristics and composition of medium materials are significant factors that affect bed density. The pivotal standards for selecting a suitable medium include the composition, particle size, viscosity, cost, recoverability, and ease of cleaning. Previous studies on ADMFB have employed magnetite (45–500 μm) and fine coal (<1 mm) to create a suitable dense medium (Sahu *et al.*, 2009). Magnetite is used to attain the required cut densities. Still, its recovery and recycling are problematic because it attaches to the surface of the coal and gangue particles, and their surfaces become contaminated. When using coal with a surface moisture content of more than 2%, some challenges may emerge. Magnetite is hydrophilic and readily attaches to a wet coal surface thus affecting the quality of fluidization due to an increased viscosity (Luo *et al.*, 2010; Mohanta and Meikap, 2015). Agglomeration of the magnetite occurs because of its magnetic features (especially during recycling), reducing contact efficiency between the particles and the air and affecting particle dispersal and growing non-uniformity in the bed density. The polluted medium may also be difficult to recover or only be liberated with difficulty. Subsequently, the bed fluidization and sorting performance are inclined to decrease, and the operating cost is enhanced (Luo *et al.*, 2010).

To achieve an optimized fluidized, different monodispersed mixtures of particles have been treated as the medium materials (Wei *et al.*, 2003; Firdaus *et al.*, 2012; Oshitani *et al.*, 2013; Luo *et al.*, 2001; Zhao *et al.*, 2012). It is certified that the separation density can be controlled by changing the composition of medium particles (Luo and Chen, 2001; Tang *et al.*, 2009). Fu *et al.* (2019) mixed fine coal particles with magnetite in two mass fractions to generate two kinds of medium material with a fine coal content of 12.08% (A) and 20.88 % (B). The results of this study

revealed that the cut-point density could be reduced by 0.05 with the latter medium mixture (B), along with an increase in EPM (by 0.03).

The interest in the use of ilmenite (FeTiO_3) as a dense medium in ADMFB lies in its high specific gravity (SG) of 4.5–5 g/cm³, along with its typically smooth pebble-like structure (Wills, 2016). Ilmenite is hydrophobic and paramagnetic; therefore, it does not readily attach to a hydrophilic mineral and can be recovered using magnetic separation (Drzymala, 2007; Wills and Finch, 2016). Kalenda *et al.* (2019) focused on using ilmenite as an alternative dense medium in the ADMFB. They found that ilmenite as a medium (63–355 μm) generated cleaner surfaces and higher recoveries at higher moisture contents than magnetite.

During the ADMFB process, a suitable size range of medium particles is needed in conjunction with the optimum gas flow rate to achieve the best performance. Mohanta and Meikap (2015) compared the different magnetite powder sizes with performance parameters for two coal-size fractions. The results showed that distinct size fractions of the same feed coal respond differently with the same size fraction of medium particles and vice versa. Misplacement of clean coal to the high-density discards increases as the medium particle size reduces, leading to separation performance reduction. Considering the EPM values and different performance criteria, the size magnetite powder of 106–150 μm is the most appropriate for coal cleaning in size range of 13–50 mm.

Investigations into the applicability of the ADMFB for the South African small coal market yielded similar results. Hughes *et al.* (2017) studied the effects of magnetite-to-coal ratio and vibration on +5.7–13.2 mm coal from the Witbank coalfield. These studies show that minimum fluidization is affected by changes in the amount of dense medium and vibration. However, the overall performance is not enhanced. Similar studies were conducted by Diedericks *et al.* (2022) but also included minus 6.7 mm particle size ranges from the Witbank coalfield, concluding that larger PSDs perform better, but adding vibration and amending the amount of magnetite yield minimal improved separation. Different dense medium types (magnetite, sand and fine coal) were investigated for minus 5.6 mm Witbank coal beneficiation in a study by Langner *et al.* (2018). An improvement in coal quality was observed, but differing media and adding vibration did not significantly increase separation efficiency.

3.1.6.2.7 SEP-AIR and NPPS

The SEP-AIR can produce a product at EPM values ranging from 0.10–0.17 and provides options for broad PSD applications (1–100 mm) and increased productivity. This method can obtain yields

of 85–93% with an ash content reduction ranging from 13.1–19.0% to 7.0–14.8% and a cut-point density of 1.78–1.90 (De Korte, 2018).

The NPPS is a recently introduced technique. Therefore, a need emerges for further investigation into the optimization of its performance with the use of modelling techniques. Stanczyk (2020) suggested a numerical model to explain the operation of the NPPS to accurately predict the separation results. The model computes the trajectory of movement, velocity, and acceleration of individual particles considering the feed material's properties and the device's operating variables. Stanczyk *et al.* (2021) examined the effect of certain operating parameters on the performance of an NPPS coal separator. The results show the possibility of a 10–25% reduction in ash content. The calorific value of the sorted particles was increased by 5–40%, while a minimal output yield of products (60–70%) was maintained.

3.1.6.2.8 Air-gravity separators in the experimental phase

The performance data of dry density processes still in the experimental and developmental stages, is provided in Table 3.5.

Table 3.5: The performance data available for experimental dry coal gravity separation methods.

Technique	Particle Size (mm)	EPM	Cut-point density (SG _{d50})	Ash (%)	Yield (%)	Reference
Vibrated ADMFB	6–3 3–1	0.19– 0.225 0.175– 0.195	1.52–1.89	Feed = 40.76, 39.76 Product = 15.56, 14.42 Discard = 70.07, 71.02	36.62– 37.50	Yang <i>et al.</i> (2013)
Vibrated ADMFB	0.5–6	0.07	1.81	Feed = 17.53 Product = 8.50	82.76	Luo <i>et al.</i> (2008)
Magnetically stabilised ADMFB	0.5–6	0.065	1.516	Feed = 31 Product = 12.62 Discard = 61.5	61.3	Luo <i>et al.</i> (2002)
Winnower	2–100	0.065– 0.25	1.76–1.97	Feed = 28–46 Product = 22–39 Discard = 38–60	30–80	Sahkre <i>et al.</i> (2018)
DRC	4–6.35 2–4 1–2	0.07 0.13 0.23	1.49 1.530 1.650	-	-	Macpherson <i>et al.</i> (2010; 2011)

It is challenging to beneficiate the fine coal for a size smaller than 6 mm using the traditional ADMFB. A magnetically stabilized fluidized bed introduced by Fan *et al.* (2001) and a vibrated ADMFB investigated by Luo *et al.* (2008) presented to tackle this obstacle. However, these fine coal dry cleaning processes all meet limitations in industrial applications due to unmanageable external factors and low processing capacity. The vibrated fluidized bed (VFB) enhances gas-solid fluidization by applying external vibration, improving gas-solid contact compared to conventional fluidized beds (Dong and Beeckmans, 1990; Savage, 1989; Wank *et al.*, 2001). Optimal operation of the DMVFB exhibits effective separation for fine coal below 6 mm, achieving an EPM value of 0.07, surpassing the efficiency of a wet jig at 0.11 (Luo *et al.*, 2008). Consistent findings are reported in the research conducted by Hughes *et al.* (2017) and Diedericks *et al.* (2022).

Winnowing, however still in the experimental phase, has shown satisfactory results for beneficiating coal in both the coarse and fine coal fractions. With EPM values ranging from 0.065–0.25, cut-point densities of 1.76–1.97 and a product ash value ranging from 22–39% from a feed of 28–46% (Sahkre *et al.*, 2018). Studies on the method of winnowing for the fine coal fraction are underway in South Africa at the NWU by Morgan and colleagues (from 2019, 2020, 2021).

Studies showed that DRC can clean 4–6.35 mm fine coal with an EPM value of 0.04 (Galvin 2004; Macpherson 2011; Macpherson *et al.*, 2010). In the inclined settling zone, vibration aids in particle re-suspension in the DRC. It contributes to diminishing the bed voidage and the minimum fluidization velocity (Marring *et al.*, 1994). Luo *et al.* (2008) and Macpherson *et al.* (2011) effectively separated dry coals sized between 0.5–6.0 mm and 1.0–6.35 mm, respectively, achieving an EPM of 0.07, utilizing a vibrated fluidized bed with fine magnetite and sand dense medium. The Reflux Classifier with an air-sand medium and vibration also has effective separation performance for 1–8 mm fine coal (Macpherson *et al.*, 2010; 2011).

Density-based separation can be obtained by increasing the density of the fluidizing gas and this is performed through the addition of a dense medium such as sand (2,600 kg/m³ with a size range of 355–125 µm) and magnetite (5,100 kg/m³ and a size range of 212–150 µm). Adjusting the ratio of air to the dense medium can be used to set the density of the fluidizing medium and, thus, the cut-point of the separation (Macpherson and Galvin, 2010). Macpherson and Galvin (2010) examined the efficiency of different dense media (magnetite and sand) and adding of vibration in a DRC. The utilization of a sand medium accompanied by vibration resulted in superior separations compared to the absence of vibration and the use of a magnetite medium. The

amalgamation of a sand-dense medium and vibration demonstrated the most effective separation performance, achieving an EPM value of 0.07.

Many of the dry-cleaning techniques for fine coal show promise in separation results. However, some obstacles are encountered when considering industrial applications. These relate to dense medium recovery, product purification and capacity. In general, there is no effective method that can beneficiate the minus 6 mm coal sizes. Additionally, density cut-points vary by size which can adversely affect the separation efficiency. Ideally all size fractions should be separated at the same density cut-point to maximize coal recovery.

3.1.6.3 Magnetic separation

In recent years, desulfurization and separation methods for fine coal have become popular research topics in the dry coal preparation sector. Chemical and biological desulfurization technologies can remove inorganic and organic sulphur in coal. However, these technologies have issues, including high costs, long production cycles, and pollution. Physical desulfurization techniques can only remove inorganic sulphur and are considered more economical and practical (Çelik and Yildirim, 2000; Zhao *et al.*, 2008). Numerous studies have been conducted regarding the application of magnetic concentration methods to remove gangue mineral and pyrite from coal (Fujita *et al.*, 1981; Hucko and Maronde, 1982; Van Driel and de Kerk, 1983; Male, 1984; Zhang *et al.*, 2015; 2017; 2020). For example, a study using lignite showed a reduction in ash content to 12.3% from 35.6% in an air-jig and magnetic separator combination (Order *et al.*, 2003). Desulphurization efficiency depends on the magnetic susceptibility, density, particle size, magnetic field intensity and gradient. Jiao *et al.* (2009) investigated the relationship among these parameters in the desulphurization of fine coal. A direct relationship was observed between magnetic susceptibility and density. High-density coal exhibited opposite magnetic properties to low-density coal at the cut density of 1.6 kg/m³. As fine coal decreased in size, the diamagnetic characteristic of low-density coal weakened while the paramagnetic attribute of high-density coal increased. Yildirim *et al.* (1996) demonstrated a decrease in sulphur content from 2.49% to 0.39% for low-rank and semi-coked lignite using RERMS. Saeid *et al.* (1993) reported an ash reduction of 40% and a sulphur decrease of 10 percentage points in a 106–500 µm UK coal sample. Celik (2002) noted a decrease in ash from 39.49% to 14.2% and a product sulphur content of 0.41% from a feed of 2.09%.

While magnetic separation methods find some commercial application for shale and sulphur reduction in the +0.5 mm particle size range (Zhang *et al.*, 2017; 2020), obstacles include the need for fine comminution for optimal liberation, low feed moisture and strict feed preparation and

presentation. As such, they may not be as efficient in separating clean coal from shale, more specifically pyrite (Zhu and Zhu, 2005; Wang and Li, 2004).

It has also been proven that coal pre-treatments like pyrolysis or microwave treatment can improve the efficiency of magnetic separation (Koca *et al.*, 2000; Celik and Yildirim, 2000; Uslu *et al.*, 2003; Uslu and Atalya, 2004; Zhang *et al.*, 2015; Tripathy *et al.*, 2017; Zhang *et al.*, 2015; 2017; 2020;). Since pyrite is weakly paramagnetic and its separation from coal is difficult, it can be transformed into another form called pyrrhotite by heating. Pyrrhotite is strongly paramagnetic and can easily be separated from coal in only moderate magnetic intensities. Studies on pyrolysis prove that treatment of a lignite coal sample with pyrolysis enhances the magnetic properties of the mineral matter present (Koca *et al.*, 2000). After heat treatment and magnetic separation for a beneficiation process of Tavsanlı-Omerler lignites, total sulfur, ash and volatile matter reduced from 3.98%, 15.16% and 39.37% to 1.27%, 8.5% and 22.08%, respectively, whereas the heating value increased from 5,877 to 6,727 kcal/kg (Celik, 2002).

As heating destroys the coal, it is impossible to transform the bulk of the pyrite into pyrrhotite. The use of microwave radiation, to convert the pyrite in coal, is an effective heat treatment approach and has the advantages of fast, selective heating and uniform heat distribution (Butcher and Rowson, 1994; Uslu *et al.*, 2002; Dwari and Rao, 2007; Waters *et al.*, 2008; Ge *et al.*, 2013; Chen *et al.*, 2019). The pyrite has a higher permittivity and heats up quicker than coal. Therefore, microwave pre-processing of pulverized coal can stimulate the quick pyrolysis of the pyrite in the coal and transform it into pyrrhotite (Uslu and Atalay, 2004; Waters *et al.*, 2008; Zhang *et al.*, 2015; Zhang *et al.*, 2022). Zhang *et al.* (2017) showed that after a two-stage beneficiation process of coal (0.5–0.25 mm), including microwave and magnetic separation, the pyrite removal was 20% after 60 s and 60% after 90 s of microwave treatment.

Zhang *et al.* (2020) explored the impact of feed size, microwave pre-treatment time, and background field intensity on the desulfurization of coal through high-gradient magnetic separation. Their findings indicated that extended microwave pre-treatment time facilitated the conversion of pyrite to pyrrhotite in pulverized coal, aiding the more efficient removal of sulphur components during the magnetic separation process. Extensive studies on microwave-enhanced magnetic separation for coal desulfurization suggest that microwave treatment can heighten the magnetism of pyrite, thereby enhancing the desulfurization effectiveness during magnetic separation (Ambedkar *et al.*, 2011). Excessive pre-treatment (above 4 minutes) can cause further decomposition of the newly generated pyrrhotite into troilite (FeS) in the reaction system, resulting in a weakened magnetism of the pulverized coal. Zhang *et al.* (2018; 2015) found the same result. As the pulverized coal particle size decreases, there is a consistent increase in the desulfurization

rate. This is due to finer particles allowing for the complete decomposition of sulfur groups within the coal, leading to a larger surface area for enhanced reaction completion. With increasing background field intensity, the magnetic force on the pyrrhotite becomes larger, and the sulphur components are more easily separated from pulverized coal. Uslu and Atalay (2004) observed that utilizing a 2-T magnetic field intensity in the magnetic separation of coal (-0.15 mm size) didn't significantly decrease the sulfur content. Post-magnetic separation, the removal rates for ash and sulfur were 15.79% and 22.29%, respectively. Even with microwave heating at 850 W and 2.45 GHz, the increase in magnetic property wasn't sufficient to enhance pyrite removal (37.46%) via magnetic separation at 2 T. However, the inclusion of magnetite, known for its microwave absorption properties, notably amplified microwave heating and subsequently improved pyritic sulfur removal via magnetic separation. By incorporating 5% magnetite, sulfur content was reduced by 55.11%.

The high gradient magnetic separator and microwave desulfurization techniques for enhancing the magnetic properties of coal are still in the laboratory stage and have not yet reached commercial status. Therefore, developing an efficient and reliable method to desulfurize this type of coal is necessary.

3.1.6.4 Electrostatic separation

Much like the magnetic methods described above, most of the work on electro-static separation is developmental and only applies to very fine particle sizes (Inculet *et al.*, 1980; Masuda *et al.*, 1984; Mukherjee *et al.*, 1987; Finseth *et al.*, 1993; Dwari and Rao, 2006; Trigwell *et al.*, 2003). While very good ash reductions could be achieved, the main objective of these investigations is the removal of sulphur rather than lowering the ash for a final product. Feed sulphur contents of between 1.5–2.5% could be reduced to less than 1%, albeit in a particle size range of below 45 μm .

Tao *et al.* (2010) reported the successful application of TBS in cleaning pulverized coal by reducing 13 per cent of the ash content of feed with 90 per cent combustible recovery. They also concluded that other impurities, such as sulphur and mercury, can be removed. Dwari and Rao (2008, 2009) revealed the results of coal cleaning (-300 μm) with a cylindrical fluidized bed tribo-charger that had internal riffles. Coal was beneficiated from an ash value of 43% ash to a product with 18% and 33% ash and 30% and 67% yield. Bada *et al.* (2010) reported the successful application of TBS for cleaning two types of pulverized coal samples (-177 μm) in South Africa.

Based on the available literature, surface pretreatment of coal emerges as an effective strategy to enhance the efficiency of triboelectric separation (Ma *et al.*, 2020; Zhang *et al.*, 2021; 2022;

Xian *et al.*, 2021b). The principle behind the separation in triboelectric separation (TBS) relies on the variance in tribo-charges between different materials (He *et al.*, 2020). According to Zhang *et al.* (2016), polymethyl methacrylate was identified as the optimal material for tribo-charging, augmenting the charge difference between coal and other minerals. He *et al.* (2020) highlighted that alterations in temperature and moisture can affect the tribo-charge difference of minerals. Xian *et al.* (2021) delved into the optimal temperature and humidity conditions for triboelectric separation of coal macerals. Surface modification using kerosene, diesel, acetic acid, and sodium stearate was also noted to significantly impact the efficiency of coal triboelectric separation (Ma *et al.*, 2020). Wang *et al.* (2017) confirmed that the utilization of ethanol as a modified reagent notably amplifies the tribo-charge difference between clean coal and gangue minerals. Additionally, Li *et al.* (2016) observed a discernible enhancement in triboelectric separation results of coal fly ash following microwave heating, attributing it to alterations in the permittivity.

3.1.7 Conclusions

There are relevant economic, operability and environmental drives for the shift to processing coal on a waterless basis. Any advantages must, however, be weighed against any possible limitations including densimetric properties and coal type, particle size and distribution, moisture content, feed presentation and certain operating parameters. Implementation should also consider the desired product specification, feed preparation, and separating efficiency and costs. Much investigation has been conducted into the various methods of dry processing and many processes are commercially available for specific applications and perform relatively well.

The dry coal processing methods find use in pre-concentration operations for destoning and production in small and remote or under-developed mining sites and in areas with extremely dry or freezing conditions. These processes are most applicable to methods pertaining to the coarse coal (+6 mm) circuits with low moisture contents. Although the DE-XRT sorting method is promising for de-shaling and desulphurization, its application is still in the consolidation phase in the coal industry. These machines, however efficient, may need to be implemented in numbers to be able to meet the throughput requirements, especially as PSD reduces. This significantly increases the capital and operating costs of the plant. The air jig is favourable due to its high capacity and ability to admit a large range in feed size but only proves suitable for destoning applications and only when the fraction of near-dense material is low. The FGX air table design is applicable for coarse particles as well but usually demands the preparation of a closely sized feed with reduced moisture content. In parallel, the various air table designs (Standard, KAT and AKAFLOW) are more appropriate for processing the intermediate or fine particle sizes but require

strict preparation. The efficiency of these air table variants is also significantly affected by the presence of near-dense materials and moisture, especially in the fine coal fractions.

ADMFBs exhibit notable separation efficiency and high capacity; however, their operation costs and sensitivity to moisture due to finely sized dense medium pose challenges. In contrast, air jigs, air tables, and SEP-AIR methods operate without requiring additional dense medium processing, offering larger capacities and lower processing costs. Nevertheless, their separation efficiency remains limited due to inherent constraints in the separation mechanism. Additionally, electrostatic and magnetic separation methods necessitate specific coal features and a certain level of dissociation, resulting in limited handling capacities. Consequently, they are primarily employed for specialized objectives, such as desulfurization, due to these constraints.

Given the above, the EPM values of dry processes do not compare well with the 0.020–0.025 achievable in a typical water-based beneficiation plant, and the cut-points are also comparatively high. Dry processing still has a way to go when considering wide-scale industrial implementation.

The search for a suitable dry coal beneficiation technique for especially the arctic, arid, and remote regions is still underway. Many researchers around the world are a part of searching for a solution, whether it be a new design or improvements to the methods discussed in this paper. Much investigation needs to be done regarding the feasible dry separation of fine coal particles as well as the large-scale separation of the coarser counterparts.

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CHAPTER 4: THE POTENTIAL FOR SEP-AIR IN SOUTH AFRICA

This chapter lists the merits inherent to the SEP-AIR dry beneficiation technique, an innovation pioneered by Gormash Export in Novosibirsk Russia, in relation to its applicability within the South African coal processing sector. A compendium of the research conducted utilizing South African coal is presented, substantiating the rationale behind the ongoing laboratory investigations. The intricate facets of the laboratory-scale unit's conception and deployment are expounded upon, encompassing insights into airflow dynamics and particle behaviours.

4.1 SEP-AIR for South African coal processing

As elucidated in Chapter 1, the coal processing industry in South Africa confronts two challenges. Firstly, the industry contends with water scarcity stemming from escalating drought conditions and shifting precipitation patterns. Consequently, acquiring industrial usage licenses has become a formidable task, coupled with stringent regulations governing water pollution. Dry processing methods, discussed in Chapter 3, obviate the need for water, thereby mitigating these challenges. Additionally, these dry processes streamline post-processing procedures for water removal, rendering the dry processing facility an uncomplicated, modular, and cost-effective solution.

Furthermore, these dry processing methods offer a pragmatic solution to the industry's second quandary, which revolves around dwindling coal reserves amid sustained high demand. Specifically, dry processing methods prove particularly apt for coal processing in modest-scale mining operations and remote or underdeveloped locations where water-based coal processing is considered infeasible. Moreover, the ability to beneficiate the smaller, often neglected -6 mm coal fractions underscores the viability of dry processing methods as an avenue to address this issue.

Among the commercialized dry processing methods discussed in Chapter 3, gravity-based separators such as the air-jig, air-table variants (including FGX, Standard, AKAFLOW, and KAT), air-dense medium fluidized bed (ADMFB), and suction fluidization methods like SEP-AIR are the most relevant. However, the air jig and FGX, despite their high capacities, exhibit subpar separation efficiencies. The Standard, KAT, and AKAFLOW air tables are suitable only for intermediate and small coal fractions, offering reduced capacity.

Notably, the ADMFB distinguishes itself with superior separation efficiency and precise cut-point density. Nevertheless, its operation comes with elevated costs, primarily due to the intricate post-processing requirements for coal and dense medium recovery, which often prove inefficient in dry processing scenarios. Furthermore, the fine-sized dense medium used in the ADMFB is moisture-sensitive, diminishing its resilience in wet conditions.

In contrast, the SEP-AIR offers a slightly reduced separation efficiency or Ecart Probable Mooyen (EPM), compared to the ADMFB, ranging from 0.10 to 0.17, but without needing dense medium, mitigating the related operational issues. Moreover, this method demonstrates exceptional performance at high throughput levels, ranging from 45 to 200 mph, product yields from 85–93% and effectively accommodates particle sizes ranging from 1 to 100 mm, catering to Northern Hemisphere coal types (Stepanenko, 2016a; Stepanenko, 2016b). The SEP-AIR offers a comprehensive solution for dry processing, delivering sufficient separation efficiency and product yield at high capacity for both small and large coal fractions. Moreover, the modular and compact design, along with dust collection mechanisms, makes it suitable for small-scale and remote mining operations.

The SEP-AIR has, therefore, emerged as one of the prominent research foci in the realm of coal processing in South Africa. Nevertheless, limited studies have been published regarding the separation efficiency achieved for smaller South African coal fractions. This aspect, where the SEP-AIR exhibits an advantage over other available dry processes, serves as the primary objective of the research compiled in this thesis: to gain insights into the SEP-AIR's operation and capacity to beneficiate minus 13 mm coal fractions and determine which parameters (design and operating) affects the separation efficiency and product quality to ensure optimal separation.

Notably, two studies utilizing the SEP-AIR pilot plant located in Novosibirsk, Russia and employing South African coal as the test material sought to address this gap. These studies investigated the 6–13 mm particle size range, revealing a product yield of 87.30%, along with a reduction in ash content from 13.1% in the feed to 7.7% in the product. Furthermore, these studies elucidated an EPM value of 0.1005 and misplaced particles amounting to 7.78%. In a parallel vein, akin investigations were carried out for the 3–6 mm fraction within the same pilot SEP-AIR plant. While the improvements in ash content were similarly discernible, the quantitative assessment of EPM was not pursued with the same rigour (De Korte, 2021). To manifest the broader relevance of this research paradigm, a separate pilot SEP-AIR plant was commissioned in South Africa. In this instance, the primary thrust of the investigations was centred on optimizing the ash value obtained across different machine settings. It is important to note that the focus of the efficiency tests in this context was largely directed toward particle sizes exceeding 10 mm (De

Korte, 2021). It becomes clear that more investigation is required to understand the beneficiation potential of the SEP-AIR for minus 13 mm coal and the possible effects of design and operating parameters on the separation efficiency.

4.2 Operating principle and relevant theory

The separation mechanism employed by the SEP-AIR is predicated upon differentiation in particle density, size, or shape and the phenomenon of gas-solid fluidization. An in-depth analysis of coal density and mineral matter is presented in Chapter 2, Section 2.1.2, which underscores the notable disparity in density between unwanted gangue materials and the organic constituents of coal. Chapter 3 examines the principles of material separation contingent upon differences in density, which are influenced by gravitational forces, centrifugal effects, and friction within a fluid medium. The utilization of an appropriate medium plays a pivotal role in facilitating differential particle movement, thereby facilitating the separation process. Furthermore, particle characteristics such as size, shape, medium composition, density, and viscosity exert additional influence on the viability and extent of density-based separation.

The mechanism enables density-based separation by leveraging the contrasting densities inherent to coal and employing fluidization. Particles characterized by a density conducive to being lifted by suction forces are selectively collected as product, while those with higher density are retained as discard. This operational procedure facilitates the segregation of valuable coal particles, distinguished by their lower densities, from their denser gangue counterparts. Additionally, the separation unit establishes a semi-continuous fluidized bed. This fluidized bed exhibits distinctive pseudo-fluidic properties that contribute to the degree of stratification and, in turn, the separation of particles marked by density, size, and shape disparities.

4.2.1 Fluidization principle

Fluidization pertains to converting particulates within a bed into a fluid-like state, achieved by suspending them in an upward-flowing fluid, which may be either a gas or a liquid (Kunii and Levenspiel, 2001). This process follows the principle of buoyancy articulated by Archimedes. When an object is immersed, partially or completely, in a fluid, it encounters an upward buoyancy force equivalent to the weight of the displaced fluid. The object's behaviour, such as floating, sinking, or rising, depends on the relative strengths of the fluid's upward force and the object's weight (Luo and Chen, 2011).

Fluidization is classified into three distinct states based on the behaviour of particulates within the system. In the first state, the 'fixed state', particles remain densely packed with minimal mobility. The upward-flowing fluid percolates through the interstitial spaces between these immobile

particles. A slight increase in fluid velocity leads to bed expansion, causing particles to separate and some to vibrate within constrained regions. Upon reaching a specific fluid flow rate, each particle attains a suspended state, called 'incipient' or 'minimum fluidization', enabling free particle movement and rearrangement. Subsequently, as higher flow rates are achieved, bubbles form and the bed experiences further expansion. The final state occurs when particles are subjected to a significantly high fluid flow, resulting in the system entering a turbulent phase characterized by vigorous particulate and fluid motion (Kunii and Levenspiel, 2001). Figure 4.1 below provides a schematic of the different states of fluidization.

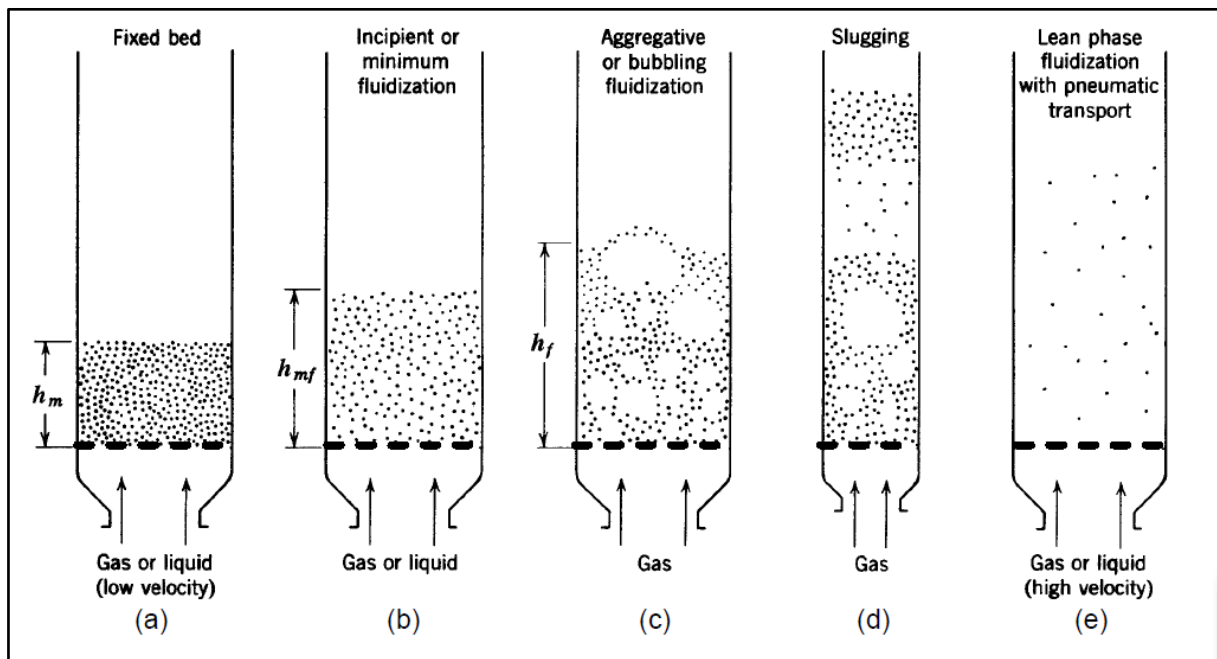


Figure 4.1: The states of fluidization (adapted from Kunii and Levenspiel, 2001)

Different behaviours are evident at fluid velocities beyond the point of incipient fluidization in liquid-solid and gas-solid systems. A gradual and uniform bed expansion with minimized flow instabilities in liquid-solid systems is usually relatively minor. Conversely, gas-solid systems show this bed expansion under specific conditions, mainly involving fine and lightweight particles fluidized by a dense gas (Kunii and Levenspiel, 2001). These systems often exhibit significant instabilities, marked by bubbling and gas channelling, when operated above the minimum fluidization point. With increased gas flow rates, particles become highly agitated, leading to more vigorous particle movement. However, the bed's expansion remains limited to the level observed at incipient fluidization.

Upon fluidizing the bed at a sufficiently elevated gas flow rate, the particles surpass their terminal velocity, causing the upper surface of the bed to vanish. Consequently, entrainment occurs, and bubble formation is not prominent, as the system experiences intense turbulent motion featuring

solid clusters and voids of gas in diverse shapes and sizes. Further escalation of the gas flow leads to a state where the fluid carries solids out of the bed (Kunii and Levenspiel, 2001).

In gas-solid fluidization systems, challenges may arise due to bubble formation and particle entrainment. Gas bubbles can merge and expand as they rise within the bed, particularly deep beds with small diameters. In such cases, these enlarged bubbles may span the vessel, influencing particle behaviour unexpectedly. Fine particles tend to flow smoothly down along the wall surrounding the ascending gas void, causing axial slugging. Conversely, in coarser particulate beds, the region above the gas void moves upward, leading to particle fall from the void, resulting in its rupture. This cyclic process creates unstable oscillatory motion, undesirable for effective fluidization (Kunii and Levenspiel, 2001).

An intriguing characteristic of a gas-solid fluidized bed is its pseudo-fluid state, which finds practical application in gravity-based separation processes. From a visual perspective, this system resembles the behaviour of boiling water and manifests fluid-like properties (Kunii and Levenspiel, 2001). For a more illustrative depiction, please refer to Figure 4.2.

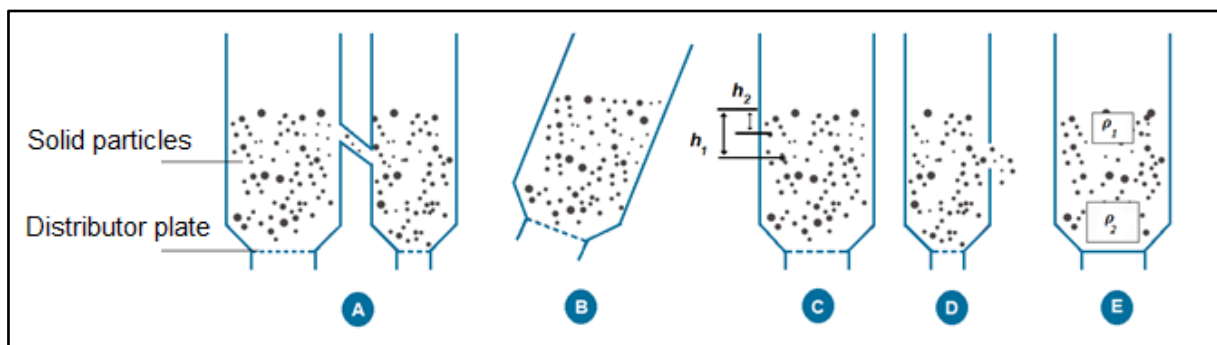


Figure 4.2: Characteristics resembling a fluidized bed (from Luo and Chen (2001); Mohanta *et al.* (2011))

Not included in Figure 4.2, another noteworthy aspect of the fluidized bed is the behaviour observed when a large, low-density object is introduced into a stably fluidized bed. In such cases, the object will float on the bed's surface. Images A and B demonstrate that interconnected fluidized beds reach equilibrium with their levels equalizing. Moreover, when these beds are tilted, the upper surface of the bed remains horizontal. Sketch C depicts the consistent pressure difference between two points within the bed and the static head between these points. It also illustrates the phenomenon of solids ejecting from a hole in the container's side, as shown in image D.

Furthermore, density-based segregation is observed in sketch E, wherein denser materials settle to the bed's bottom while less dense materials float to the surface (Mohanta *et al.*, 2011). These properties, reminiscent of liquid behaviour, manifest in a gas-solid fluidized bed.

A specific fluid velocity, often around or slightly above the minimum fluidization velocity, is observed in a well-defined and turbulence-free fluidised bed. At the incipient fluidization point, particle motion initiates due to various acting forces, notably gravity and buoyancy (Rhodes, 2008). This results in the descent of higher-density particles under gravity, while lighter particles ascend due to buoyancy effects (Choung *et al.*, 2006; Luo and Chen, 2001). The suspension's fluidic properties lead to observed density segregation within the system (Sahu *et al.*, 2009). Such a particulate bed often exhibits behaviour resembling a Bingham fluid, typically explained by the falling sphere principle in terms of rheological attributes (Chen and Wei, 2001).

For real-world scenarios, the assumption of achieving perfect separation through an ideal particle distribution is challenged due to inaccuracies in positioning both light and dense particles. This phenomenon is known as the 'displaced distribution effect' (Chen and Wei, 2005; Sahu *et al.*, 2009). Several factors contribute to this occurrence, particularly particle movement and viscosity effects. The displaced movement effect becomes more noticeable with excessively high or low gas flow rates (Chen and Wei, 2005). Hence, the separation efficiency of the system is significantly influenced by the feed air velocity. Particle size also plays a substantial role in this theory, where larger, less dense particles might sink while smaller, denser particles may float.

Naturally, gas velocity is critical for ensuring stable fluidization and effective separation within the bed. The fluid velocity must be carefully controlled to remain within the range defined by the minimum fluidization point and the bubbling velocity.

4.2.2 Minimum fluidizing velocity

The minimum fluidization point denotes the velocity at which particles shift from a densely packed bed to a fluidized state. At this juncture, particles behave fluidly, enabling free rearrangement and movement within the bed based on their density in relation to the overall fluidized system (He *et al.*, 2016a; Zhao *et al.*, 2015). Hence, the incipient fluidization point is crucial in maintaining the stability of the fluidized bed and, consequently, the efficacy of the separation process.

The velocity necessary for fluidization correlates directly with the drag force needed to suspend solid particles within the bed (Escudero and Heindel, 2011). Kunii and Levenspiel's equation (1991) are widely used to anticipate the incipient fluidization point in a system. Essential parameters for designing an efficient fluidized bed encompass particle characteristics, fluid properties, and bed geometry (Escudero and Heindel, 2011). As per Kunii and Levenspiel (1991), minimum fluidization is achieved when the drag force generated by the upward-flowing fluid equals the weight of the particles.

$$(\text{drag force created by upwards flowing fluid}) = (\text{weight of the particles}) \quad \text{Equation (4.1)}$$

$$\Delta P_b A_t = W = A_t L_{mf} (1 - \varepsilon_{mf}) [(\rho_s - \rho_g) g] \quad \text{Equation (4.2)}$$

This principle served as the basis for developing the Ergun equation, which establishes a relationship between the minimum fluidization velocity and the properties of both the medium and the particles. The minimum fluidization condition is given by:

$$\frac{\Delta P_b}{L_{mf}} = (1 - \varepsilon_{mf}) (\rho_s - \rho_g) \frac{g}{g_c} \quad \text{Equation (4.3)}$$

Which can be expanded to include minimum fluidization conditions:

$$\frac{1.75}{\varepsilon_{mf}^3 \varphi_s} \left(\frac{d_p u_{mf} \rho_g}{\mu} \right) + \frac{150(1 - \varepsilon_{mf})}{\varepsilon_{mf}^3 \varphi_s^2} \left(\frac{d_p u_{mf} \rho_g}{\mu} \right) = \left(\frac{d_p^3 \rho_g (\rho_s - \rho_g) g}{\mu^2} \right) \quad \text{Equation (4.4)}$$

$$Re = \left(\frac{d_p u_{mf} \rho_g}{\mu} \right) \quad \text{Equation (4.5)}$$

$$Ar = \left(\frac{d_p^3 \rho_g (\rho_s - \rho_g) g}{\mu^2} \right) \quad \text{Equation (4.6)}$$

Through the substitution of Equation 4.5 and Equation 4.6 into Equation 4.4, a rearrangement of Equation 4.4 yields Equation 4.7.

$$\frac{1.75}{\varepsilon_{mf}^3 \varphi_s} Re_{pmf}^2 + \frac{150(1 - \varepsilon_{mf})}{\varepsilon_{mf}^3 \varphi_s^2} Re_p = Ar \quad \text{Equation (4.7)}$$

A simplification to calculate minimum fluidization velocity is provided and named the Ergun equation:

$$u_{mf} = \frac{d_p^2 (\rho_s - \rho_g) g}{150 \mu} \frac{\varepsilon_{mf}^3 \varphi_s^2}{1 - \varepsilon_{mf}} \quad Re_{pmf} < 20 \quad \text{Equation (4.8)}$$

Where the symbols used are described as follows in Table 4.1:

Table 4.1: Description and units of the symbols used in the Ergun equation.

Symbol	Description	Unit
ΔP_b	Pressure difference	Pa
A_t	Cross-sectional bed area	m ²
W	Bed weight	N
H_{mf}	Bed height	m
U_{mf}	Minimum fluidizing velocity	m/s
d_p	Particle diameter	Pa
ρ_s/ρ_g	Particle/fluid density	Kg/m ³
g	Gravitational acceleration constant	m/s ²
μ	Dynamic viscosity	Kg/m.s
ε_{mf}	Bed voidage at minimum fluidization	-
φ_s	Particle sphericity	-
Re	Reynolds number of the particle at minimum fluidization	-

As represented by Equation 4.8, the Ergun equation demonstrates that an escalation in particle size (d_p) results in a quadratic rise in the minimum fluidization velocity. Moreover, it indicates that the bed voidage (ϵ_{mf}) is directly linked to the incipient velocity, while the minimum fluidization point is also expected to elevate with increased particle density.

4.2.3 Bubble formation

The amalgamation of gas velocity and the minimum fluidization velocity holds significant importance, as highlighted in studies by He *et al.* (2016a) and Zhao *et al.* (2016). These factors primarily dictate bubble formation within gas-solid dense medium fluidized beds, influencing separation efficiency. The presence of bubbles can yield both advantages and disadvantages, as elucidated by Luo *et al.* (2012) and Sobrino (2009):

- Small bubbles initially aid in material mixing, promoting even density distribution within the bed. Conversely, larger bubbles lead to particle remixing, hindering effective particle stratification due to entrainment and displacement.
- Small bubbles facilitate particle loosening, enhancing separation efficiency, while larger bubbles cause fluctuations in bed height, impacting stability. Smaller bubbles favour stable fluidization, fostering a well-established fluidized bed. Conversely, larger bubbles impede bed stability and hinder particle segregation (Luo *et al.*, 2012).

4.2.4 Particle classification

The minimum fluidization velocity is affected by particle properties, geometry, and fluid characteristics (Escudero and Heindel, 2011). Geldart's classification system, detailed in Kunii and Levenspiel (2001), categorizes particles into four primary groups with distinct fluidization behaviours:

- **Group A:** These particles fluidize readily with controlled bubble formation at low gas velocities. They typically have low particle densities (<1.4 SG) and small mean sizes.
- **Group B:** Particles in this group cause vigorous bubbling due to their small size range (40–500 μm) and varied densities (1.4–4.0 SG).
- **Group C:** Comprising very fine particles, fluidization is nearly impossible due to strong interparticle forces overwhelming particle-gas forces.
- **Group D:** Particles are either very large or dense, leading to the formation of large bubbles hindering fluidization, often resulting in gas channelling and back-mixing (Yang *et al.*, 2015).

4.3 Design and commissioning of a laboratory scale separating unit.

To assess the applicability of SEP-AIR to beneficiate minus 13 mm coal and determine the effects of different design and operating parameters, a laboratory-scale separation unit was designed and constructed in strict adherence to the manufacturer's prescribed specifications. This endeavour involved a collaborative partnership between the North-West University (NWU) and Gormash Export, which was aimed at the commissioning of a laboratory-scale SEP-AIR unit with primary objectives encompassing the assessment of operational efficiency and the utilization of computational fluid dynamics (CFD) modelling techniques in the context of Southern African coal particles measuring below 13 mm in size.

This section proceeds to delve into various aspects encompassing the design, dimensions, and operational parameters, while also addressing the interplay between air and particle dynamics within the separation unit. The comprehensive examination of these factors is instrumental in successfully commissioning the separation unit and identifying optimal design and operational conditions.

The SEP-AIR comprises three distinct processes, each serving specific functions: i) the feed, ii) the separating unit, and iii) the centrifugal fan. These processes will be elaborated upon in the subsequent sections.

4.3.1 Feeding process

The feeding process consists of a perforated conveyor system situated beneath the separation unit, serving two key purposes: i) the removal of fine fractions before entering the system and ii) the regulation of particle entry concerning speed, orientation and vibration. Chapter 3 addresses the essentiality of feed preparation and delves into the impact of fines, particle velocity, particle orientation and feed mass on the operational aspects of a separation unit.

Due to their size, fine particles are susceptible to misplacement due to their influence on fluidization and stratification dynamics. This susceptibility can result in product contamination and, subsequently, a decrease in product quality. Moreover, finer particles pose challenges when encountering moisture, as it can induce particle agglomeration and machinery blockages. In the laboratory experiments, fine particles are initially screened to remove undesired fractions before being manually introduced into the inlet air stream. To ensure uniform exposure to the suction force, particles are oriented into a monolayer configuration, where they form a single-particle layer spanning the conveyor plate's width.

Manufacturer specifications dictate that a feed ratio of particle size should not exceed 2:1, wherein the largest particles in the feed are twice the size of the smallest particles in the feed. This specification aligns with the theory of equal settling in particles, initially established by Rittinger in 1867, as elucidated in the work by Patil and Parekh (2011). Maintaining a small particle size ratio serves to minimize particle misplacement resulting from the influence of particle size on fluidization. For the present investigation, the coal particles are classified as either Geldart A or Geldart D types, and they are expected to fluidize relatively easily without a dense medium, but the formation of large bubbles and gas channelling and back mixing may be common.

4.3.2 Separating process

The separation process comprises four distinct sections, each tailored with specific dimensions to induce specific air and particle behaviours essential for various functions within the separation process.

- **Suction Nozzle:** This component comprises a rectangular fluidizing box above the feed conveyor. Air enters horizontally through the gaps between the box and the conveyor plate and ascends upward, inducing particle fluidization and subsequent density stratification and acting as a first separation stage on an individual particle.
- **Circular Vortex Chamber:** Positioned above the fluidizing box, this chamber's circular arrangement and specific diameter force the upward-flowing air to form a vortex that captures particles which have been fluidized to a sufficient height. This acts as the second separation stage of an individual particle. As the particle moves through the vortex, its properties can determine whether it will sink back into the fluidizing box or continue along the vortex. Additionally, the vortex chamber contributes to the establishment of a uniform airflow profile spanning the length of the separating nozzle, mitigating the occurrence of dead spots in the region furthest from the suction fan and near the unit walls.
- **Circular Connecting Pipe:** This section has a smaller diameter and specific length attached to the side of the vortex chamber, accelerating the airflow and facilitating the ejection of captured particles.
- **Cubic Collecting Bin:** Affixed to the connecting pipe, this bin features larger dimensions, reducing the velocity of captured particles and serving as a collection point for the separated product.

Particle fluidization plays a pivotal role in the separation process, and therefore, it is essential to consider the effects of particle classification and bed geometry on velocity characteristics and bubble formation, as detailed in Sections 4.2.1 to 4.2.4. Nevertheless, certain aspects of the SEP-AIR unit's design may necessitate a more robust and bubbling fluidization while maintaining an

effective density separation. This is closely linked to the positioning of the vortex chamber above the fluidizing box, which means that particles must be fluidized to a specific height to be captured into the vortex and ejected through the connecting pipe.

While consolidated trickling and hindered settling still apply to the larger density particles, a fluidized bed operated near the minimum fluidization velocity may not provide these particles with sufficient lift. Slightly higher velocities are required to maintain a suitable bed expansion. It is important to note that these conditions may enhance particle capture, but they may also introduce negative aspects associated with bubbling fluidized beds, particularly issues related to bubble coalescence and rupture, leading to an unstable oscillatory motion and particle entrapment and/or entrainment.

The particle size plays a pivotal role in determining the density at which the separation process occurs, primarily regulated by the velocity of the airflow entering the fluidizing box. The precise positioning of the fluidizing nozzle above the feeding conveyor significantly impacts the characteristics of the air within the inlets and fluidizing chamber. This, in turn, affects the velocity profile that develops in the fluidizing box, affecting the particle behaviour. However, it is important to underscore that the particle size range predominantly dictates the optimal gap height, ensuring unimpeded air and particle ingress into the inlet of the suction nozzle.

As a general guideline, an inlet gap height of approximately 1.5 times the size of the largest particle in the feed is recommended, as per guidance from the experts at Gormash Export. The gap height of the laboratory-scale unit was designed to be adjustable to effectively process different particle size ranges.

4.3.3 The centrifugal fan

The suction force is generated using a Trojan BC60 series direct-drive centrifugal fan with a power rating of 1.1 kW (Trojan 2021). This fan can reach a maximum speed of 1,000 revolutions per minute (RPM), offering a duty volume of 1,700 Am³/hr and a duty pressure of 230 Pa. This translates to an air velocity of 93.95 m/s at the maximum flow setting. The suction force is controlled by a frequency inverter that can be varied from 0–50 Hz which affects the duty volume and consequently air velocity. Figure 4.3 provides an image of the suction fan and control box (left) and a schematic (right) providing the dimensions of the suction fan.

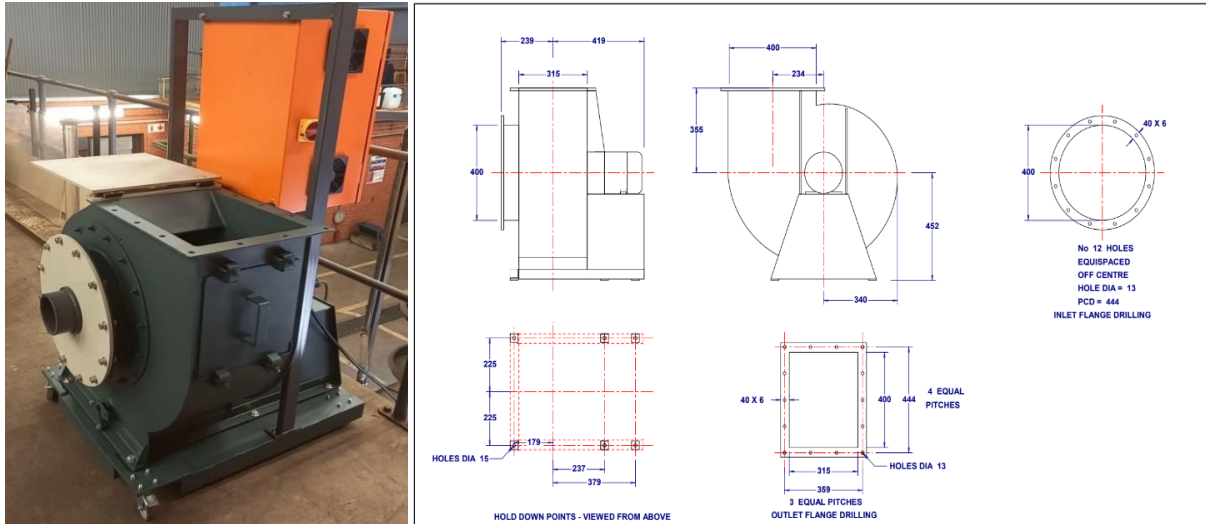


Figure 4.3: Image of suction fan and control box (left) and schematic (right) providing fan dimensions.

During laboratory-scale air and coal beneficiation tests, fan settings ranging from 10 to 50 Hz were employed, corresponding to an air velocity range of 18.79–93.95 m/s. Due to the suction nozzle's unique design and dimensions, distinct velocity profiles are observed in various sections. A more comprehensive discussion of these velocity profiles will be provided in Section 4.4.

4.3.4 The laboratory-scale unit

As previously described, the laboratory-scale unit comprises the centrifugal suction fan in conjunction with the separating unit, feeding system and collecting system. Figure 4.4 provides visual representations of the entire separation unit (on the left) and the suction nozzle (on the right), encompassing the fluidizing box, vortex chamber, and connecting pipe.



Figure 4.4: Images of the separating unit (left) and suction nozzle (right) including labelled sections.

The dimensions of the rectangular fluidizing chamber, cylindrical vortex chamber, cylindrical connecting pipe, and cubic collecting bin are detailed in Table 4.2.

Table 4.2: Dimensions of the laboratory-scale separating unit.

	Fluidizing chamber (mm)	Vortex chamber (mm)	Connecting pipe (mm)	Collection bin (mm)
Length	300	300	150	600
Width	100	-	-	600
Height	300	-	-	600
Diameter	-	160	80	-

The laboratory-scale separating unit is equipped with a feeding system, which involves a pre-screening process to eliminate coal fines. The particles are manually placed in a monolayer configuration onto the conveyor plate, positioned at the fan-side air inlet, denoted as 'FS' and located on the right side, as depicted in the left image of Figure 4.5 below. The alternate inlet, referred to as the 'other-side air inlet' and labelled 'OS', is also shown in Figure 4.5, providing a visual reference for positioning both FS and OS air inlets. Notably, the adjustable conveyor plate, shown in the left image, is set at a gap height of 10 mm between the plate and the bottom edge of the suction nozzle for particles in the range of +3.2-6.7 mm, and it is adjusted to 20 mm for particles ranging from +6.7-13.2 mm, in accordance with the guidelines given in Section 4.2.2. Furthermore, the collecting mechanism, as depicted in the right image of Figure 4.5, takes the form of a removable plate, facilitating the extraction of collected particles. Observing the tapered design at the bottom of the collecting bin is pertinent, ensuring that particles accumulate in a concentrated area for ease of removal.

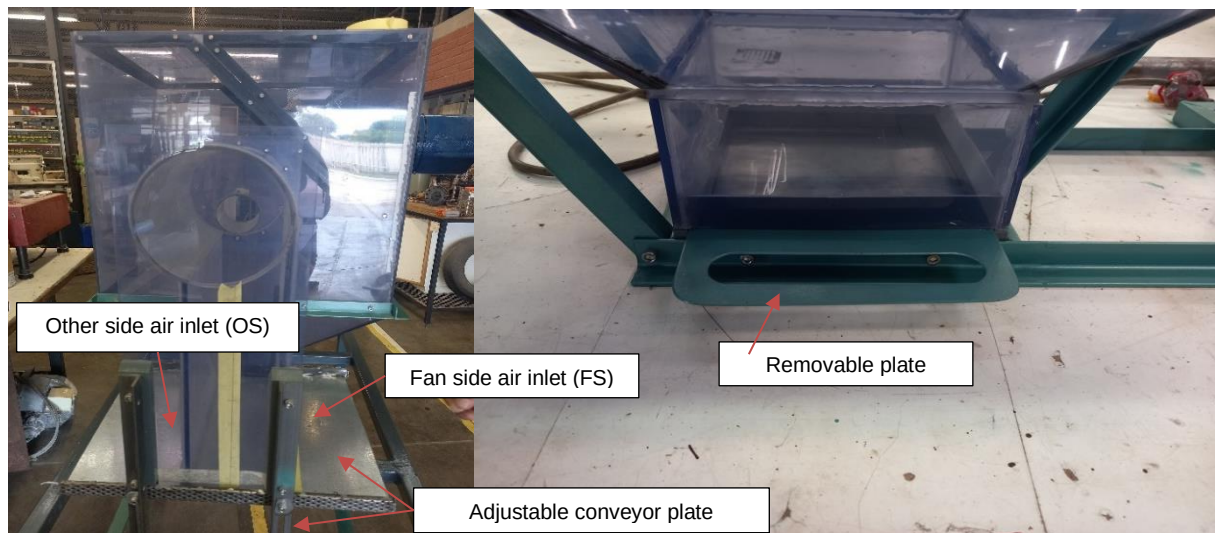


Figure 4.5: Image labelling of the air inlets and conveyor plate.

The subsequent images (Figure 4.6) provide different vantage points of the operational laboratory-scale separation unit situated at North-West University.

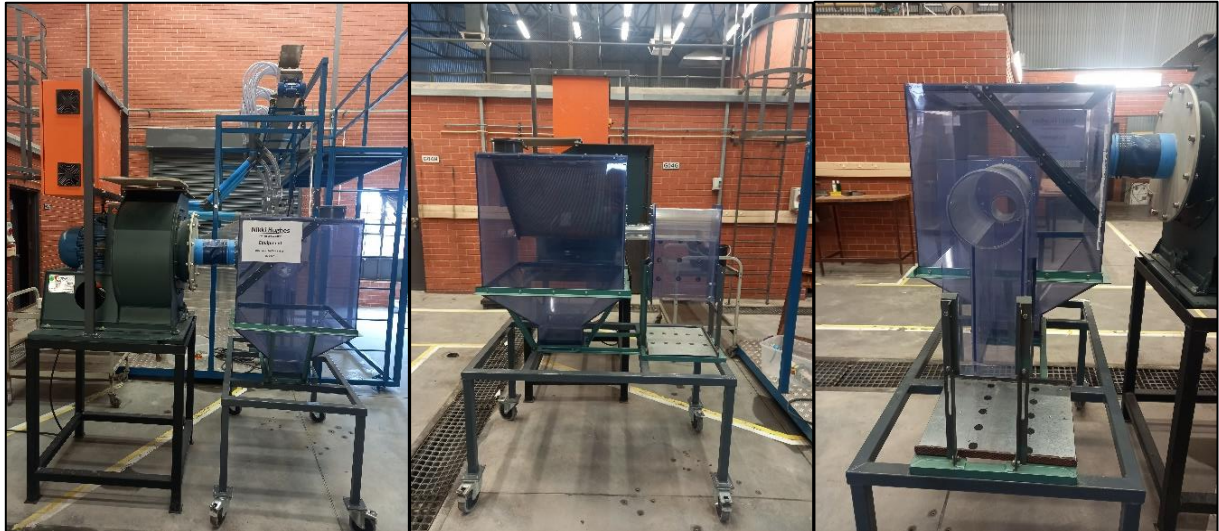


Figure 4.6: Different perspectives of the separating unit commissioned at the NWU.

4.4 Airflow behaviour

Understanding the air flow profile within different sections of the separating unit is critical, as it directly influences the separation efficiency (Kunii and Levenspiel, 2001). To achieve this understanding, a series of airflow tests were conducted on the separating unit under varying temperature and relative humidity conditions. These tests aimed to elucidate the characteristics of the airflow profile, including its speed and direction.

Air velocity measurements were systematically executed within the unit using a Testo smart probe hot-wire anemometer renowned for its accuracy, which falls within the range of 0.1–0.3 m/s for air velocity readings (Testo, 2023). These measurements encompassed a total of 40 distinct positions distributed across different segments of the unit. These segments included five locations spanning both air inlets, three positions within the connecting pipe, and nine points distributed across the fluidizing box at three distinct depths. Figure 4.7 represents the positions where velocity measurements were collected within the separating unit.

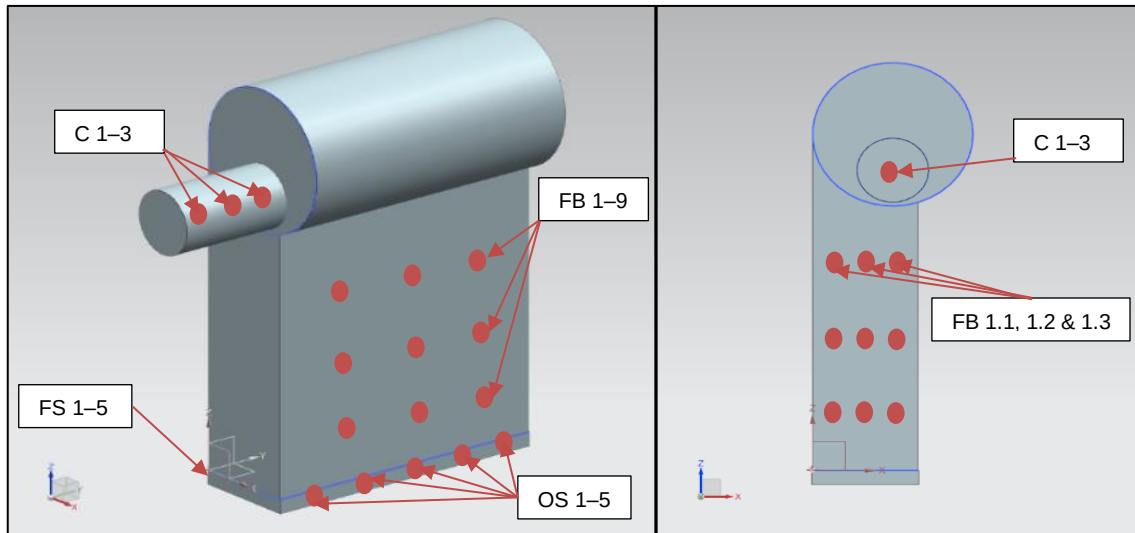


Figure 4.7: Velocity measuring points in the suction nozzle from the front and side views.

The measurement points within the air inlets were denoted as FS1–5 (fan-side) and OS1–5 (other-side), evenly spaced along the 300 mm length of the suction nozzle at 50 mm intervals. The FS measurements were oriented in the x-plane direction, while the OS measurements were oriented in the opposite direction, referred to as the minus x-plane, as depicted in Figure 4.7. In the 120 mm connecting pipe, three measurements were taken at 40 mm intervals, labelled as C1–3, along the minus y-plane direction, as illustrated in Figure 4.7. Within the fluidizing box, a total of twenty-seven velocity measurements were conducted, 9 distributed along the z-plane at three heights 85, 185 and 285 mm (labelled FB1–9) and three depths along the 100 mm width of the fluidizing box (25, 50 and 75 mm) from the fan-side wall within the x-plane designated with a decimal 1, 2 or 3.

A comprehensive dataset was amassed for ten different suction fan frequency settings, spanning from 5 Hz to 50 Hz in 5 Hz increments. Three individual velocity readings were taken for each setting in each measurement point to ensure repeatability. Low average standard deviations of 0.21, 0.13, and 0.33 were observed for the repeated velocity readings in the connecting pipe, air inlets, and fluidizing box, respectively, underscoring the high level of repeatability achieved.

To assess the stability of the velocity profile, additional measurements were recorded at one-second intervals over a one-minute duration. This meticulous monitoring process aimed to confirm the consistency of velocity readings within the system over time. An average variance of 0.29 was observed across all suction fan frequency settings, indicating that the velocity readings remained uniform and exhibited minimal temporal variation.

The determination of airflow direction was facilitated through the utilization of an s-type pitot tube in conjunction with a Fluke anemometer. It is important to note that a negative airflow reading

signified a flow direction contrary to the anticipated airflow pattern in this configuration. These measurements yielded valuable insights into the airflow direction at various positions within the suction nozzle and the potential occurrence of eddy currents.

Table 4.3 presents a concise summary of the air vectors observed at the 40 distinct positions within the separating unit, encompassing both speed and direction. The magnitude of the velocity is quantified numerically in m/s, while the direction is defined within the Cartesian plane framework, as depicted in Figure 4.7.

Table 4.3: Summary of the velocity vectors (in m/s) measured in the separating unit at different suction fan settings.

Velocity magnitude in m/s Velocity direction as either + or - in the x, y or z plane (as per cartesian plane in Fig 4.7)					
Position in suction nozzle	10 Hz	20 Hz	30 Hz	40 Hz	50 Hz
Fan-side inlet (FS1)	3.79(+x)	7.96(+x)	12.04(+x)	15.88(+x)	20.53(+x)
Fan-side inlet (FS2)	4.01(+x)	8.21(+x)	12.45(+x)	16.55(+x)	20.50(+x)
Fan-side inlet (FS3)	4.58(+x)	9.29(+x)	13.96(+x)	18.43(+x)	23.01(+x)
Fan-side inlet (FS4)	4.18(+x)	8.57(+x)	12.84(+x)	17.52(+x)	20.99(+x)
Fan-side inlet (FS5)	4.07(+x)	8.43(+x)	12.73(+x)	17.21(+x)	21.14(+x)
Other-side inlet (OS1)	-3.69(-x)	7.34(-x)	11.05(-x)	15.30(-x)	19.71(-x)
Other-side inlet (OS2)	-3.94(-x)	7.98(-x)	12.37(-x)	16.39(-x)	20.72(-x)
Other-side inlet (OS3)	-4.19(-x)	8.72(-x)	12.78(-x)	17.35(-x)	21.90(-x)
Other-side inlet (OS4)	-3.91(-x)	8.10(-x)	12.32(-x)	16.81(-x)	20.79(-x)
Other-side inlet (OS5)	-3.39(-x)	6.94(-x)	11.17(-x)	15.58(-x)	19.58(-x)
Connecting pipe (C1)	14.53(-y)	31.76(-y)	46.48(-y)	61.32(-y)	76.65(-y)
Connecting pipe (C2)	14.37(-y)	29.23(-y)	47.92(-y)	60.85(-y)	76.06(-y)
Connecting pipe (C3)	14.12(-y)	28.49(-y)	46.17(-y)	59.09(-y)	73.86(-y)
Fluidizing box (FB1.1)	0.98(±z)	2.43(+z)	3.70(+z)	5.57(+z)	8.30(+z)
Fluidizing box (FB1.2)	0.73(+z)	2.35(+z)	4.31(+z)	6.23(+z)	4.62(+z)
Fluidizing box (FB1.3)	0.80(+z)	1.41(+z)	2.09(+z)	3.33(+z)	7.06(+z)
Fluidizing box (FB2.1)	1.03(±z)	2.19(+z)	3.57(+z)	5.18(+z)	8.61(+z)
Fluidizing box (FB2.2)	1.51(+z)	3.43(+z)	5.41(+z)	6.69(+z)	7.44(+z)
Fluidizing box (FB2.3)	1.54(+z)	2.64(+z)	4.15(+z)	4.64(+z)	8.61(+z)
Fluidizing box (FB3.1)	1.52(+z)	3.16(+z)	5.02(+z)	6.78(+z)	8.54(+z)
Fluidizing box (FB3.2)	2.02(+z)	4.85(+z)	7.38(+z)	10.61(+z)	13.41(+z)
Fluidizing box (FB3.3)	1.18(+z)	3.27(+z)	5.27(+z)	8.47(+z)	10.27(+z)
Fluidizing box (FB4.1)	1.69(±z)	3.28(+z)	4.83(+z)	7.06(+z)	8.84(+z)
Fluidizing box (FB4.2)	1.65(+z)	3.09(+z)	5.20(+z)	7.40(+z)	9.53(+z)
Fluidizing box (FB4.3)	0.96(+z)	1.75(+z)	2.51(+z)	3.47(+z)	4.64(+z)
Fluidizing box (FB5.1)	1.36(±z)	3.15(+z)	4.92(+z)	6.30(+z)	7.83(+z)
Fluidizing box (FB5.2)	2.66(+z)	4.92(+z)	6.85(+z)	8.78(+z)	10.37(+z)
Fluidizing box (FB5.3)	2.25(+z)	3.81(+z)	5.55(+z)	7.75(+z)	9.85(+z)
Fluidizing box (FB6.1)	1.68(+z)	3.05(+z)	5.03(+z)	6.84(+z)	8.76(+z)
Fluidizing box (FB6.2)	1.69(+z)	3.43(+z)	5.12(+z)	7.03(+z)	9.29(+z)
Fluidizing box (FB6.3)	0.91(+z)	1.91(+z)	2.70(+z)	4.33(+z)	6.37(+z)
Fluidizing box (FB7.1)	3.27(±z)	5.86(+z)	8.66(+z)	11.75(+z)	14.27(+z)
Fluidizing box (FB7.2)	4.27(+z)	8.50(+z)	13.54(+z)	18.60(+z)	22.91(+z)

Fluidizing box (FB7.3)	1.34(+z)	3.40(+z)	4.99(+z)	6.22(+z)	9.04(+z)
Fluidizing box (FB8.1)	2.03(±z)	3.62(+z)	6.39(+z)	8.65(+z)	11.37(+z)
Fluidizing box (FB8.2)	2.79(+z)	7.00(+z)	8.94(+z)	13.59(+z)	16.30(+z)
Fluidizing box (FB8.3)	3.21(±z)	5.75(±z)	9.57(±z)	11.56(±z)	17.65(±z)
Fluidizing box (FB9.1)	3.19(+z)	4.69(+z)	7.23(+z)	9.43(+z)	12.01(+z)
Fluidizing box (FB9.2)	3.85(+z)	8.34(+z)	13.79(+z)	17.55(+z)	22.40(+z)
Fluidizing box (FB9.3)	1.36(+z)	3.70(+z)	5.07(+z)	6.76(+z)	8.22(+z)

Several observations can be gleaned from the airflow patterns depicted in Table 4.3. Firstly, the velocities recorded fall within the transitional and fully turbulent flow regimes, as indicated by their associated Reynolds numbers, which range from 4,712 to 414,549. The thresholds for laminar and critical flow of 2,800 and 4,000, respectively (Welty *et al.*, 2007) have been surpassed by the velocity readings at all 40 measuring points in the suction nozzle. The threshold for transitional flow depends on relative roughness, friction factor and variances in the inlet flows and can be determined using the Moody Chart (Welty *et al.*, 2007). The PVC construction material used for the suction nozzle has a low relative roughness (The Engineering Toolbox, 2003) and by applying a maximum friction factor of 0.02 suitable to the dimensions of the suction nozzle (Welty *et al.*, 2007), the transition zone threshold is determined at a Reynolds number of 60,000. When analysing the Reynolds numbers obtained at cross-sections of the inlets, fluidizing box and connecting pipe, different regions of transitional and turbulent flow are observed. Specifically, the connecting pipe exhibits a fully turbulent flow regime whereas transitional flow is observed in the inlets and fluidizing box except for the velocity profile attained at 40 and 50 Hz. These show a combination of transitional and turbulent flow regimes in the fluidizing box.

Notably, the air velocities within the air inlets and connecting pipe exhibit a remarkable degree of uniformity, with average variances of 0.24 m/s and 1.52 m/s, respectively. However, a striking disparity emerges within the fluidizing box, where a substantial variance of 9.88 m/s is observed. Notably, the average air speeds within the fluidizing box are higher in its lower section, specifically at positions 7, 8, and 9. This behaviour is likely influenced by the inlet gap height. Additionally, air speeds are slightly elevated on the side proximate to the connecting pipe, particularly at positions 3, 6, and 9. Moreover, as the airflow ascends from the inlet, a curvilinear pattern becomes evident. These variations can be attributed to the development of a more intricate velocity profile across the cross-sectional area of the fluidizing box. Observed during the experimental measurements is that airspeed remains largely unaffected by fluctuations in temperature and relative humidity, while consistently exhibiting an increase as the suction fan setting is elevated.

Experimental measurements acquired using the s-type pitot probe unveil the existence of variable flow directions in the vicinity of the wall, suggesting the presence of eddying currents that hinder airspeed. Furthermore, these measurements substantiate that air enters the suction nozzle

horizontally through both the fan-side (FS) and other-side (OS) inlets before ascending vertically in a curved trajectory. Subsequently, a vortex materializes within the vortex chamber, accelerates through the connecting pipe, decelerates within the collecting bin, and ultimately exits through the suction fan. To validate the obtained airflow direction, smoke tests were conducted. Videos were recorded as smoke generated from a fog machine permeated through the suction unit under different suction fan settings. These visual observations served as a confirmation of the airflow direction determined through the analytical analysis above.

A modification in the inlet gap height from 10 mm to 20 mm exhibits a minimal impact on the airspeed within both the FS and OS inlets, as indicated by the low Mean Absolute Error (MAE) of 0.91 m/s concerning an average airspeed of 12.38 m/s. A similar trend is observed within the connecting pipe, where varying inlet gap heights of 10 mm and 20 mm and an infinitely large gap (absence of a conveyor plate) do not significantly influence the measured velocities, yielding an MAE of 3.5 m/s in relation to an average velocity of 46.5 m/s.

In contrast, notable disparities become evident in the velocities within the fluidizing box when considering the three distinct inlet gap heights. Specifically, within the lower segment of the fluidized bed, encompassing measuring positions 7, 8, and 9, an MAE of 4.5 m/s is observed, corresponding to an average velocity of 13.6 m/s, representing an error margin of 35%. Within the middle section of the fluidizing box, spanning measuring positions 4, 5, and 6, a lower MAE of 2.1 m/s is discerned, in conjunction with an average velocity of 8.5 m/s, reflecting a 24% error. Meanwhile, at measuring positions 1, 2, and 3, an MAE of 1.8 m/s is documented, alongside an average velocity of 8.8 m/s, indicating a 22% error. These observations underscore the influence of varying inlet gap heights on the velocity profile that emerges within the fluidizing box, subsequently imparting discernible effects on the dynamics of the semi-fluidized particulate bed formation and the achievable separation efficiency. The location of a particle within the bed relies on the interplay of its velocity relative to the surrounding medium. This interplay is a vital element that affects separation efficiencies significantly. It depends on factors such as bed viscosity and the velocity of the medium, as elaborated in the context of misplacement effects (Kunii and Levenspiel, 2001). The heightened velocity observed with a smaller gap height facilitates the more facile fluidization of particles and contributes to the establishment of a fluidized bed that extends higher within the confines of the fluidizing box. However, it is imperative to acknowledge that this heightened velocity may also lead to the fluidization of denser particles, potentially resulting in their unintended capture within the product stream. Hence, it is crucial to ascertain the minimum fluidization velocity. Incorrect fluidization conditions can result in displacement effects, causing inefficient separation. The displacement phenomenon becomes conspicuous when the gas flow

is either excessively high or excessively low (Chen and Wei, 2005). Thus, the velocity of the incoming air significantly influences the system's separation efficiency.

4.5 Particle behaviour

Comprehending the particle behaviour within the separating unit is significant, as it exerts a direct influence on the separation efficiency attained. To gain this understanding, a series of particle tests was systematically conducted, encompassing both single-particle feed scenarios and multiple-particle feed scenarios. The single-particle feed tests, using density tracers, were designed with the specific objective of elucidating the ramifications of airflow characteristics on the motion of particles with varying sizes and densities. In contrast, the tests involving multiple-particle feeds, using a combination of density tracers and coal particles, were devised to determine the influence of particle movements on one another.

4.5.1 Theoretical minimum fluidizing velocity

Theoretical minimum fluidization velocities were determined for the two size ranges considered with particles of dimensions 3.2, 6.7, and 13.2 millimetres, across various SGs (1.4, 1.6, 1.8, and 2.0), employing the formula denominated as 'Equation 4.8' in Section 4.2.2. The tabulated data, presented in Table 4.4, furnishes the computed values for the minimum fluidization velocity.

Table 4.4: Theoretical minimum fluidizing velocities for different particle properties.

Minimum fluidizing velocity (m/s)	3.2 mm	6.7 mm	13.2 mm
1.4 SG	1.31	5.74	22.28
1.6 SG	2.50	10.96	42.54
1.8 SG	3.69	16.18	62.80
2.0 SG	4.88	21.40	83.06

The computations were executed under the presupposition of specific parameter values, notably a dynamic air viscosity of $1.8\text{E-}05$ Pa·s, an air density of $1,180$ kg/m³, the standard gravitational constant of 9.81 m/s², a particle sphericity of 0.8 , and a bed voidage of 0.5 .

Section 4.4, which pertains to airflow dynamics within the separation unit (Table 4.3), enables the determination of average inlet velocities. These velocities offer valuable insights into the initial fluidization conditions for particles subjected to a range of fan settings. Specifically, under low flow conditions (characterized by a suction fan frequency of 10 Hz), inlet velocities reach 3.88 m/s. Such velocities are deemed effective for achieving fluidization of particles with specific gravities (SG) of 1.4 , 1.6 , and 1.8 when they possess dimensions of 3.2 mm. For medium flow settings (where the fan operates at a frequency of 30 Hz, providing inlet velocities of 12.33 m/s), the conditions are conducive to the fluidization of particles with dimensions of 3.2 mm, across all SGs, as well as particles of 6.7 mm with SGs of 1.4 and 1.6 . High flow settings (with a fan

frequency of 50 Hz and inlet velocities of 20.45 m/s) can facilitate fluidization across all SGs for particles measuring 3.2 mm and 6.7 mm in size and the 1.4 SG of 13.2 mm particles.

It is imperative to underscore that the preceding observations predominantly concern the initial fluidization behaviour of particles upon their introduction into the inlet. Nevertheless, notable variations in fluidization velocities are observed within the fluidizing box, in both the vertical and horizontal dimensions. This observation implies that the dynamics of particle fluidization may undergo continuous alterations due to the fluctuating velocity profiles.

Under conditions characterized by low fan settings, specifically at 10 Hz, it becomes evident that particles measuring 3.2 mm with specific gravities (SG) of 1.8 and 2.0 are incapable of sustaining fluidization throughout any segment of the fluidizing box. Conversely, 1.6 SG particles adhere to the minimum fluidization criteria in the lower region of the fluidizing box, while 1.4 SG particles exhibit a consistent capability to maintain fluidization across the entire vertical and horizontal extent of the box. Notably, no instances of fluidization are observed for particles measuring 6.7 mm or 13.2 mm under these specified conditions.

At medium fan settings (30 Hz), the outcomes reveal that all 3.2 mm particles with SGs of 1.4 and 1.6 achieve fluidization across the entire vertical and horizontal span of the fluidizing box. However, 3.2 mm particles with an SG of 1.8 fail to undergo fluidization in segments located along the OS wall, particularly those that are situated farthest from the connecting pipe. Similarly, particles with an SG of 2.0 do not sustain fluidization in the uppermost segments of the box, as well as those positioned closest to the OS wall, furthest from the connecting pipe. In the context of 6.7 mm particles with an SG of 1.6, fluidization is confined to the lower and middle regions of the fluidizing box, whereas particles with SGs of 1.8 and 2.0 fail to exhibit sustained fluidization across the entire box. For particles measuring 13.2 mm, regardless of specific gravity, they do not achieve fluidization under the medium flow settings.

Under high fan settings (50 Hz), all densities of 3.2 mm particles, in conjunction with the 1.4 SG category of 6.7 mm particles, demonstrate the capability to maintain fluidization throughout the entirety of the fluidizing box. However, the 1.6, 1.8, and 2.0 SG categories of 6.7 mm particles exhibit fluidization solely in the lower regions of the box, specifically those closest to the FS wall and the middle sections. In the case of 13.2 mm particles, only the 1.4 SG category of particles attains fluidization in the lower and middle portions of the box, while the denser 1.6, 1.8 and 2.0 SG particle categories fail to achieve sustained fluidization.

This theoretical analysis underscores the intricate and dynamic nature of particle behaviour within the fluidizing system. It undergoes distinct alterations in response to fluctuating flow conditions,

primarily because of the distinctive velocity profiles that manifest. Evidently, particle size and density are interdependent factors that jointly influence the processes of fluidization and subsequent density-based separation.

4.5.2 Single particle behaviour

Within the context of the single tracer tests, a density tracer, characterized by specific size and density parameters, was systematically introduced into the middle of the separating unit at various suction fan settings. The primary objective was to ascertain the requisite suction force necessary to induce fluidization and subsequently capture the particle. A particle size of 8 mm was deliberately selected for the density tracers, as it occupies a central position within the range of particle sizes under consideration in this study. Additionally, three distinct SGs of 2.0, 1.6, and 1.4 were employed in conjunction with suction fan settings that spanned from 10 to 50 Hz in 5 Hz increments.

Upon introducing the density tracer, a log of qualitative observations regarding particle behaviour was documented. These observations encompassed an assessment of whether the particle exhibited movement, lifting, falling, fluidization, or ultimate capture. In addition, a timer was employed to ascertain the temporal aspect of particle capture at specific settings. These investigative procedures underwent ten iterations to evaluate their repeatability, thereby fortifying the reliability of the obtained findings. Table 4.5 summarises the observations noted for the 8 mm tracers.

Table 4.5: Particle capture rate, time and observations noted for differing density tracers at various suction fan settings.

Density (SG)	Fan setting (Hz)	Average inlet air velocity (m/s)	U_{mf} (m/s)	Particle capture rate (%)	Time (s)	Description
2.0	10–20	3.88–7.93	30.51	0	-	No particle movement
	25–45	10.21–18.53		0	-	Particle shifting on plate
	50	20.45		0	-	Particle tumbling, lifting and falling
1.6	10–15	3.88–6.08	15.63	0	-	No particle movement
	20–25	7.93–10.21		0	-	Particle shifting on plate
	30–40	12.33–16.62		0	-	Particle tumbling, lifting and falling
	45	18.53		63	27–120	Particle fluidization and capture
	50	20.45		100	2–23	Particle fluidization and capture
1.4	10–15	3.88–6.08	8.19	0	-	No particle movement
	20–25	7.93–10.21		0	-	Particle shifting on plate
	30–35	12.33–14.58		0	-	Particle tumbling, lifting and falling

	40	16.62		13	7.25	Particle tumbling, lifting and falling followed by some fluidization and capture
	45	18.53		100	3–32	Particle fluidization and capture
	50	20.45		100	1–10	Particle fluidization and capture

An 8 mm density tracer with an SG of 2.0 exhibits an interesting characteristic; it remains uncaptured within a 20-second regardless of the selected suction fan setting. Notably, the tracer manifests observable movement on the conveyor plate, shifting and tumbling. Although some lifting of the particle is evident under maximum airflow conditions, this transient ascent proves insufficient for permanent capture as a product, often culminating in the subsequent particle falling.

In contrast, the 1.6 SG tracers demonstrate a distinct behavioural pattern. Beginning at a suction fan setting of 20 Hz, corresponding to an average inlet air velocity range of 7.9 m/s, these tracers exhibit movement characterized by shifting, vibrating, and spinning. Subsequently, tracer fluidisation becomes discernible at 40 Hz (16.6 m/s). Within a time interval spanning 27 to 120 seconds, a 63% tracer capture rate is observed at 45 Hz (18.5 m/s). Under a maximum flow of 20.5 m/s, at 50 Hz, a 100% capture of these tracers is achieved within 2 to 23 seconds.

Likewise, the 1.4 SG tracers exhibit distinctive particle behaviour commencing at a suction fan setting of 20 Hz (7.9 m/s); these tracers manifest movement characterized by shifting, vibrating, and spinning. Tracer fluidization is evident at 40 Hz, corresponding to 16.6 m/s, with a 13% particle capture rate achieved within a 7-second interval. Moreover, 100% tracer capture rates are observed above 45 Hz (representing 18.5 m/s) within a total timeframe ranging from 3 to 32 seconds and at 50 Hz (20.5 m/s) within 1 to 10 seconds.

Subsequent experiments were conducted to further investigate tracers' behaviour with SGs of 1.6 and 1.4. The aim was to determine the optimal fan setting necessary to separate particles of distinct densities effectively. In the case of the 1.6 SG tracers, a series of tests was conducted at 1 Hz intervals, ranging from 46 Hz to 49 Hz. This range was selected due to the observed decrease in particle capture rate at 45 Hz and the achievement of complete particle capture at 50 Hz. Similarly, for the 1.4 SG tracers, an array of tests was executed, spanning fan settings from 41 Hz to 47 Hz, with each test conducted at 1 Hz increments. The collective findings of these experiments are summarized in Table 4.6, encapsulating the observations made.

Table 4.6: Particle capture rate, time and observations noted for differing density tracers at specific suction fan settings.

Density (SG)	Fan setting (Hz)	Particle capture rate (%)	Time (s)	Description
1.6	40 (16.6 m/s)	0	-	Particle tumbling, lifting and falling
	45 (18.5 m/s)	63	4–33	Particle tumbling, lifting and falling followed by some fluidization and capture
	46 (18.9 m/s)	71	2–105	Particle tumbling, lifting and falling followed by some fluidization and capture
	47 (19.3 m/s)	100	2–48	Particle tumbling, lifting and falling followed by some fluidization and capture
	48 (19.8 m/s)	100	12–123	Particle fluidization and capture
	49 (20.2 m/s)	100	2–40	Particle fluidization and capture
	50 (20.5 m/s)	100	2–28	Particle fluidization and capture
1.4	40 (16.6 m/s)	13	7.25	Particle tumbling, lifting and falling followed by some fluidization and capture
	41 (16.9 m/s)	25	11–32	Particle tumbling, lifting and falling followed by some fluidization and capture
	42 (17.3 m/s)	38	3–17	Particle tumbling, lifting and falling followed by some fluidization and capture
	43 (17.7 m/s)	89	2–60	Particle tumbling, lifting and falling followed by some fluidization and capture
	44 (18.1 m/s)	100	2–40	Particle fluidization and capture
	45 (18.5 m/s)	100	3–32	Particle fluidization and capture
	46 (18.9 m/s)	100	6–54	Particle fluidization and capture
	47 (19.3 m/s)	100	2–10	Particle fluidization and capture

Achieving separation between the 1.4 SG tracers and the 2.0 SG tracers proves feasible at a specific suction fan setting of 44 Hz. This success is attributed to the absence of particle fluidization or capture observed for the 2.0 SG tracers at this fan setting. Similarly, effective separation between the 1.6 SG tracers and the 2.0 SG tracers is attainable at a fan setting of 47 Hz.

However, it is noteworthy that achieving a complete separation between the 1.4 SG and 1.6 SG tracers may present challenges due to the overlap of suction fan settings. Specifically, at 45 Hz, a fan setting leads to the 100% capture of 1.4 SG tracers, approximately 63% of the 1.6 SG particles also become captured. This discrepancy suggests that a lower fan setting may be necessary for the desired separation, but such lower settings may also adversely affect the capturing of the 1.4 SG tracers. This observation underscores the critical importance of selecting a fan setting that can effectively strike a balance between achieving the desired separation and minimizing the capture of undesired tracers.

Numerous observations emerge from the above experiments. Firstly, the behaviour of tracers, particularly their trajectories and velocities upon achieving sufficient fluidization for capture, lends credence to the reinforcement of a vortex within the vortex chamber. Subsequently, this phenomenon corresponds to an increase in airspeed within the connecting pipe and an associated decrease in airspeed within the collecting bin.

Secondly, the design of the air inlet, characterized by two inlets drawing air inward towards each other, gives rise to a notable phenomenon. Specifically, it results in the suction of tracers from the entry point at the fan-side (FS) inlet, with the fluidization of these tracers being further augmented by the inflow of air from the other-side (OS) inlet. Intriguingly, under certain conditions, tracers may be expelled from the suction nozzle through the other-side (OS) inlet, a consequence of excessively high velocities relative to the specific size and density attributes of the given tracer.

Third, the fluidization of individual tracer particles is marked by turbulence, encompassing the entirety of the fluidizing box, devoid of any discernible pattern in trajectory. The tracer's behaviour closely mirrors the immediate air stream conditions it encounters. It tends to fluidize and accelerate in regions characterized by high velocities, decelerate, descend in regions characterized by low velocities, and assume swirling and tumbling motions within eddying currents. These movements persist until the tracer follows a stream that leads to its capture as a product or allows it to descend as a discard. This is corroborated by the effect of velocity on particle fluidization as described by Kunii and Levenspiel (2001) in Section 4.2.

Fourth, the interaction between tracers and the conveyor surface noticeably affects the duration required for the tracers to become energized by the airflow and initiate fluidization. An experiment involving 1.6 SG tracers, conducted at 47 Hz (19.3 m/s), with a rougher conveyor surface, produced interesting results. While the tracer capture rate remained at 100%, as observed with a smoother surface, the time taken for the capture of the first tracer decreased from 2.25 seconds to 1.47 seconds. Moreover, the overall duration for all tracers to be captured decreased from 48.37 seconds to 39.15 seconds. These findings suggest that initial particle movement on the conveyor, induced by vibration and/or a rougher surface, plays a crucial role in facilitating efficient particle fluidization.

Additionally, it was noted that gently nudging the tracers further expedited their initial movement and fluidization by overcoming surface friction. This insight underscores the potential role of particle interaction, where particles engage in nudging and colliding with one another, as a factor that may aid in the fluidization process. However, it is essential to acknowledge that particle interactions may also have adverse effects, as the forces from collisions can alter a particle's trajectory.

4.5.3 Multiple particle behaviour

From the results obtained for the single particle separation density of the 8 mm tracer particles, a fan setting of 44 Hz relating to an average inlet velocity of 18.1 m/s is required for a 1.4 SG cut (See Table 4.6). To determine the separation density of a multiple particle system, thirty-two 8 mm tracers, eight of each 1.2, 1.4, 1.6 and 2.0 SG, were mixed into 300 g of +6.7-13.2 mm coal particles and fed to the separating unit at suction fan settings spanning 35–44 Hz at certain increments. Mass balances (pertaining to coal and tracers) and Helium pycnometry (pertaining to coal) were conducted on the product and discard streams to determine product yield and density and tracer counting to determine the cut-point density. Table 4.7 provides a summary of the results.

Table 4.7: Results of the combined coal and density tracer tests at various suction fan settings

Fan setting (Hz)	Product yield (%)	Product density (SG)	Cumulative number of tracers
35 (14.7 m/s)	25	1.42	4 (1.2 SG)
40 (16.6 m/s)	66	1.41	8 (1.2 SG) 3 (1.4 SG)
42 (17.3 m/s)	85	1.51	8 (1.4 SG) 6 (1.6 SG)
44 (18.1 m/s)	91	1.49	8 (1.6 SG)
Discard	9	2.03	8 (2.0 SG)

An examination of the data presented in Table 4.7 reveals that the most favourable product yield is achieved when the suction fan operates at 44 Hz. Notably, the coal product in question possesses a density of 1.5 SG, and all eight 1.6 SG tracers are detected within the resulting product. This observation strongly suggests the influence of multi-particle interactions on the density of the separated product. From this, it becomes apparent that lower suction fan settings can lead to an effective density-based separation. For instance, when the fan operates at 40 Hz, a product density of 1.4 SG is attained, and no capture of 1.6 SG particles is observed. However, this gain in separation efficiency comes at the cost of reduced product yield. Furthermore, PSD tests consistently reveal that the product obtained at lower fan settings contains a smaller cut-point particle size (D_{50}), likely contributing to the lower yields observed. This underscores the interplay of particle size and density in shaping the quality of the separated product. Notably, a series of repeatability tests corroborate these findings, demonstrating consistent product density, yield, and PSD results.

The above finding aligns with the conclusion from Section 4.4.1, which posits that particle interactions might indeed enhance separation efficiency. Furthermore, in the context of a system involving multiple particles, a semi-fluidized bed materializes within the lower regions of the fluidizing box. A fluidized particulate bed acts as a pseudo-fluid with its properties, such as

density, and therefore aids in the density stratification of individual particles. This phenomenon facilitates particle elevation or flotation and the capture process. Consequently, this elucidates the higher product density observed at identical fan settings in the case of the multiple-particle systems as compared to the single-particle system.

Additional tests were conducted to investigate the effects of multiple particles on the beneficiation process further. These assessments primarily revolved around productivity tests aimed at determining the impact of varying mass loadings on the system's performance.

Optimal operating conditions were ascertained when 150 grams of coal particles within the +3.2-6.7 mm size range and 250 grams of coal particles spanning the +6.7-13.2 mm size category were introduced. At these settings, the system exhibited its best performance. However, when the system was overloaded with a mass twice as large, the ensuing results depicted product and discard yields of 14% and 86%, respectively, in stark contrast to the corresponding 60% and 40% figures achieved under optimal loading conditions with the same suction fan settings.

This overloading scenario manifests a cascade of effects, notably an augmented number of particles congregating on the conveyor plate, leading to entrapment and subsequent obstruction of the airflow. This negatively impacts the fluidization of particles, resulting in heightened particle misplacement. Notably, in the case of the +3.2-6.7 mm PSD, 77% of the particles in the product stream gravitate toward the lower end of the PSD, signifying inadequate fluidization conditions within the system, with a propensity for capturing smaller particles.

Conversely, underloading the system (one-third of the optimal feed mass) also engenders a decline in productivity, yielding product and discard proportions of 32% and 68%, respectively. A reduced number of particles stemming from underloading hinders the formation of a stable semi-fluidized bed within the fluidizing box. This, in turn, creates a scenario where particles behave as isolated entities, leading to a more haphazard and less efficient capture process while needing higher velocities to attain capture. Intriguingly, the underloaded system does not exhibit significant particle size separation, with both product and discard PSDs closely aligned.

An additional facet of the multiple particle system pertains to the residence time of particles within the suction nozzle. To further confirm the improved fluidization observed in multiple particle systems, productivity tests were executed on the +3.2-6.7 mm coal particles, subjecting them to the suction nozzle for varying residence times, ranging from 20 to 120 seconds in 20-second intervals. The 150 g feed contained 65% of minus 4.75 mm coal particles as determined from the PSD. An overview of the outcomes is presented in Table 4.8.

Table 4.8: Results of the productivity tests conducted at different residence times.

Residence time (s)	Product Yield (%)	Discard Yield (%)	% < 4.75 mm particles (product)
20	19	81	72
40	41	59	66
60	41	59	63
80	36	64	63
100	55	51	52
120	57	43	61

The data presented in Table 4.8 shows a notable trend: an enhancement in product yield is discerned as residence time increases. This phenomenon can be attributed to the extended duration, which allows particles the opportunity to attain proper fluidization, interact with each other and the unit walls, and be effectively captured. In contrast, it is worth noting that there are no discernible trends observed in the percentage of particles smaller than 4.75 mm obtained at varying residence times and in comparison to the feed. This observation suggests that while a clear distinction exists in terms of particle size separation alongside density separation between the product and discard, residence time does not appear to exert any discernible influence on particle size obtained in the product and discard streams.

4.6 Conclusion and Recommendations

As gathered in the sections above, much can be gleaned from the effects of air and particle behaviour on the potential and extent of density separation within a laboratory-scale SEP-AIR unit. The results from the experiments detailed in this chapter aided in determining the best operating conditions for coal efficiency tests. Specifically, correct mass loading, residence time, and suction fan settings are needed for specific density cuts. Furthermore, these results helped focus the airflow conditions and particle properties that are needed to model the separating unit using CFD accurately. It is, however, recommended that future investigations extend to the effects of these factors on coal separation efficiency as the current experiments, outside of the tracer tests, focused on airflow and product yield. The chapters that follow address modelling the airflow and particle behaviour with CFD and the results of the efficiency tests conducted on +3.2-3.7 mm and +6.7-13.2 mm particles.

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CHAPTER 5: CFD SIMULATION OF AIRFLOW (PAPER 2)

This chapter introduces a Computational Fluid Dynamics (CFD) analysis of airflow dynamics within the suction nozzle of a laboratory-scale separation unit resembling the SEP-AIR configuration. The included paper, titled “CFD evaluation of the airflow characteristics in an air-gravity separation unit using suction fluidization and vortex capturing,” undertakes a comparative examination between simulated and experimental airflow data acquired across varying speeds: low, medium, and high. Additionally, the paper elucidates the nature of airflow patterns and behaviours. Within this chapter, a dedicated section is allocated to the simulation of particle dynamics within the suction nozzle, facilitating observation of their interactions within the context of the airflow attributes.

5.1 Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) is a branch of physics dedicated to investigating fluid mechanics and the forces influencing their behaviour. CFD relies on the application of the Navier-Stokes equations, which elucidate the interrelationship among pressure, velocity, density, and temperature within a moving fluid (Rouse, 2016).

This discipline employs numerical techniques, mathematical models, and software tools to address and evaluate challenges associated with fluid flow. It harnesses the latest advancements in computer hardware and sophisticated programming methodologies to simulate interactions between fluids and surfaces as dictated by boundary conditions. Consequently, CFD provides valuable insights into flow patterns that would be otherwise challenging, costly, or even unfeasible to investigate through traditional methodologies. Nonetheless, it is essential to acknowledge that CFD simulations do not offer results with absolute certainty, primarily owing to potential imprecision or speculative assumptions in the input data. Moreover, the mathematical models utilized for addressing the given problem may exhibit limitations, and the precision of outcomes remains constrained by the computational capabilities at one's disposal. (Rouse, 2016).

Siemens NX-12 and STAR CCM+ have been chosen as the CFD software tools for the simulation within the scope of this study. Initially, a 3D rendering of the geometry of the separation unit is constructed to scale using NX-12. The STAR CCM+ software utilizes this 3D rendering to conduct fluid dynamics simulations. The STAR CCM+ program follows a three-step procedure to create a simulation.

- The first step involves generating a surface and volume mesh over the geometry and defining the corresponding boundary conditions. The mesh divides the geometry's surface and volume into several 3D cells.
- The second step entails solving the governing equations that describe the fluid flow and related phenomena. These equations are numerically solved for each mesh cell in three dimensions. The solution of the previous cell is used as the initial value for the next.
- The final step revolves around achieving convergence to a solution that accurately represents the simulated fluid dynamics. Once the entire mesh is solved, the simulation is iterated until the solutions converge.

5.1.1 Meshing

A mesh is a discretized representation of the computational domain employed by physics solvers to obtain numerical solutions (Siemens, 2023). Achieving an appropriate grid resolution for surface and volume is a critical prerequisite for solving any CFD problem. Various meshing strategies are available, each offering distinct advantages and applications. Before the meshing process, the 3D rendering is exported as para-solid files from NX-12 and subsequently imported into STAR-CCM+ as a surface mesh. Parts within the rendered assembly are allocated to specific regions, with each part surface assigned to a corresponding boundary. Inlet and outlet regions are identified by specific types and boundary conditions.

For surface meshing, two models are relevant: the surface wrapper and surface remesher. The former wraps the initial surface to create a closed, manifold, and water-tight geometry of sufficient quality for generating surface and volume meshes (Fernandez, 2019). The latter retriangulates the surface while adhering to a specified target edge length. Additionally, it can selectively exclude surfaces or boundaries, thus preserving the original triangulation from the imported mesh (Fernandez, 2019; Siemens, 2021a).

There are five models applicable to volume meshing: Trimmer, polyhedral mesher, tetrahedral mesher, advancing layer mesher, and thin mesher (Fernandez, 2019; Siemens, 2021). Trimmer and thin meshers are employed for external aerodynamic flow and thin geometries. Polyhedral and tetrahedral meshers generate volume meshes with polyhedral and tetrahedral cells, respectively. Of these, the polyhedral mesher has proven to be numerically stable and accurate compared to the tetrahedral mesh, while also resulting in a reduced number of cells (Symscape, 2013; Fernandez, 2019; Siemens, 2023). Various optional volume meshing models can be integrated to further refine surface and volume meshes for specific purposes, including the prism layer mesher, extruder, generalized cylinder mesher, shelling mesher, and embedded thin

mesher (Fernandez, 2019; Siemens, 2023). Figure 5.1 provides images of a tetrahedral mesh (top left), polyhedral mesh (top right) and polyhedral mesh with a prismatic layer (bottom centre).

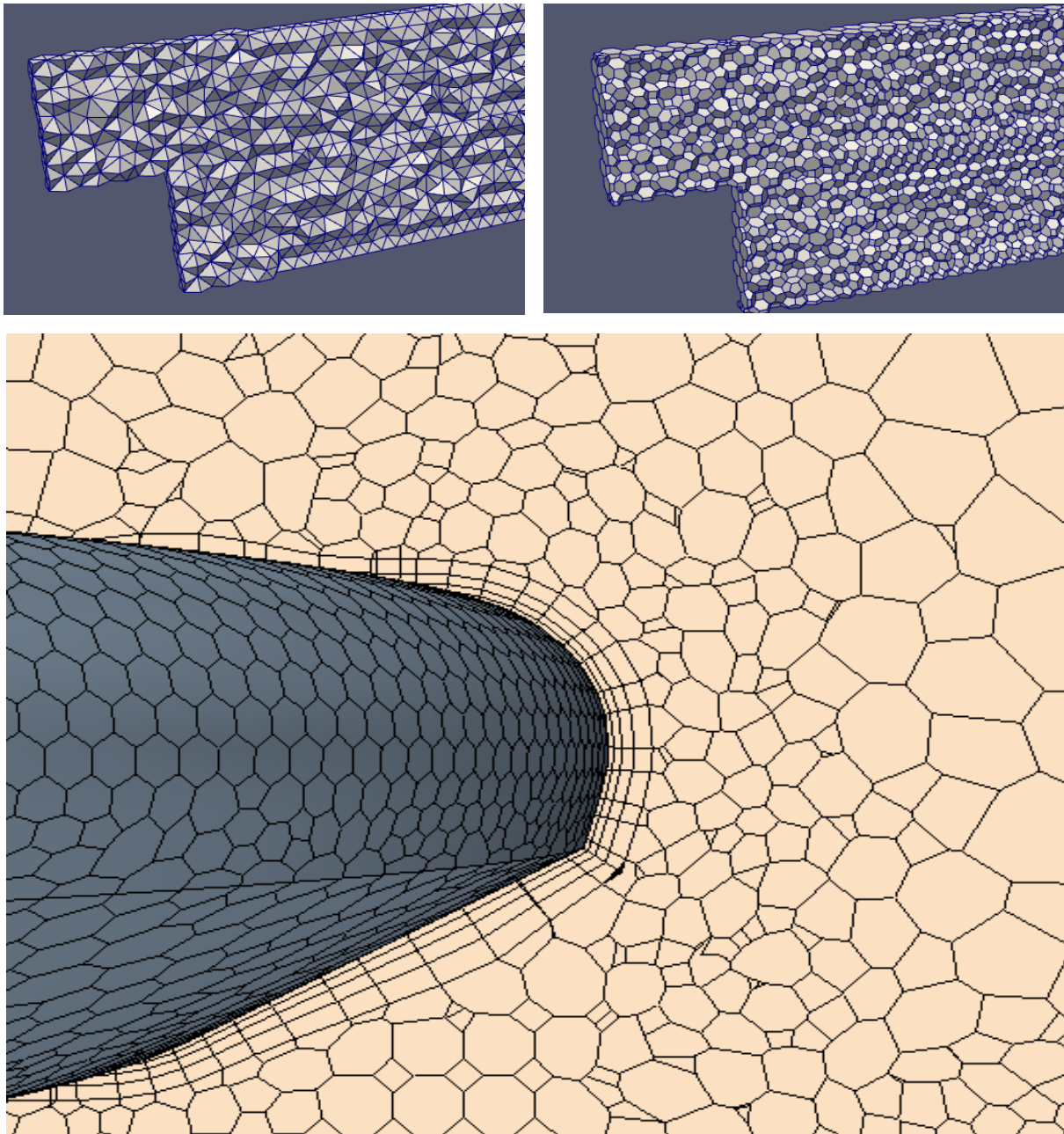


Figure 5.1: Tetrahedral mesh (top left), polyhedral mesh (top right) and polyhedral mesh with prismatic layer (bottom centre) from Symscape (2013).

As delineated in the preceding paragraphs and visually depicted in Figure 5.1, a mesh partitions the geometric volume into multiple cells. The dimensions of these mesh cells assume a pivotal role in ensuring the accurate representation of the geometry while circumventing the generation of an excessively fine mesh, which, in turn, could impair computational efficiency (Siemens, 2021a). Consequently, there arises a need to judiciously refine the mesh, encompassing considerations such as cell shape and size, the incorporation of additional prismatic layers, or the

identification of specific regions within the geometry necessitating a finer mesh for enhanced geometric fidelity (Siemens, 2021a).

5.1.2 Continua

A continuum is a foundational concept for delineating the composition of different sections within a simulation. Frequently, one of these sections comprises a gas, fluid or solid. Simulations can incorporate multiple continua, interacting with one another, each composed of a set of physics and mathematical models supported by associated assumptions. The pivotal consideration lies in the judicious selection and combination of these models and refinements aimed at accurately representing real-world phenomena.

In the context of model selection, it is instructive to reference the work of Fernandez (2019) and Siemens (2021b). Several categories encapsulate various aspects of the continua.

- **Spatial Dimensions:** Space models primarily facilitate the computation and access of mesh metrics. The choice of this model hinges upon whether a two-dimensional or three-dimensional simulation is requisite.
- **Time:** Time models encompass solvers responsible for controlling the iteration and time-stepping processes. Available models comprise steady, implicit unsteady, explicit unsteady, and harmonic balance. Steady conditions apply to flow scenarios independent of time, where only spatial derivatives are discretized. Implicit and explicit unsteady options dictate the way flow equations are solved. Implicit methods necessitate iterative solution procedures, whereas explicit methods offer straightforward solutions if all variables are known. The harmonic balance model is reserved for instances marked by rapid and periodic flows.
- **Motion:** Motion signifies the alteration in the position of an object concerning a specific frame of reference. In STAR-CCM+, three options are available: mesh displacement in real-time, moving reference frame in steady-state, and harmonic balance flutter. These options are pertinent when mesh vertices require real-time displacement, when solving for a moving component, or when dealing with blade vibrations in the context of the harmonic balance model.
- **Material:** Material models manage the thermodynamic and transport properties of substances such as gases, fluids, or solids. STAR-CCM+ offers three material models: single-component material, multi-component material, and multi-phase mixture material. Single-component material models cater to pure substances in their fundamental states: gas, liquid, and solid. Multi-component models address situations involving multiple materials in the same state, while multiphase models handle mixed flows of two or more states.

- **Flow:** STAR-CCM+ provides segregated and coupled flow models for fluids and gases. The coupled solver concurrently addresses the governing equations for the flow field, whereas the segregated solver tackles equations separately and exchanges information between equations after each iteration. The coupled solver is preferred in scenarios where stiff equations prevail, necessitating minimal input changes for substantial solution variations (Johansson, 2021).
- **Equation of State (EOS):** An EOS relates state variables describing the state of matter under specific physical conditions, such as pressure, volume, temperature, or internal energy (Koretsky, 2004). Within STAR-CCM+, the EOS model computes density and its derivatives concerning temperature and pressure. The choice between constant density, ideal gas, or real gas is available. The real gas model allows for various applicable EOSs, including van der Waals, Redlich-Kwong, and Peng-Robinson (Koretsky, 2004).
- **Viscous Regime:** The viscous or flow regime classifies flow structures into laminar, transient, or turbulent. Viscosity and turbulence often play critical roles in fluid flow scenarios. Models for turbulent flow encompass K-epsilon, K-omega, Reynolds stress, and Spalart-Allmaras.
- **Optional Models:** Numerous optional models are available to enhance flow accuracy and facilitate convergence. These models serve to refine and tailor the simulation to specific requirements.

5.1.3 Boundary and initial conditions

In NX-12, the geometry assembly is exported as para-solid files into STAR-CCM+, which is represented as a surface mesh. Parts within the assembly are associated with specific regions, each part surface being assigned a corresponding boundary. These boundaries can typically be categorized as inlets, outlets, symmetry planes, or walls (Siemens, 2021b). These boundaries are spatially defined by the geometry parts from which they originate and are physically associated with their assigned continuum. The roles of unit walls, inlets, and outlets are clearly defined within the geometry.

STAR-CCM+ provides a range of boundary conditions, including velocity inlet, mass flow inlet, stagnation inlet, free stream, wall, outlet, and pressure outlet (Kathiravan, 2020b). The choice of boundary conditions, particularly the combination of inlet and outlet conditions, can exert a significant influence on the outcomes of simulations. Guidelines for boundary condition selection of a general flow phenomenon are available from Recktenwald (n.d) and Simscale (2023).

Initial conditions pertain to the actual values associated with the boundaries and may include parameters such as velocity, mass flow, or pressure. These initial conditions serve as the starting

point for the iterative solution process. The careful selection of initial conditions is imperative as they impact the convergence, robustness, stability, and computational efficiency of the iterative method, as well as the accuracy of the final solution (Siemens, 2021b). Furthermore, in many numerical simulations and optimization problems, the choice of initial conditions can offer valuable physical insights, allowing the simulation to align with real-world conditions (Siemens, 2021b). In practice, these initial values are often derived from experimental data obtained from physical replicas of the conditions under study.

5.1.4 Solution and Convergence

Simulations are conducted with the overarching objective of achieving a converged solution to the governing physics equations. Pursuing convergence is vital to ensuring the attainment of a physically meaningful outcome. An indispensable tool in this quest is continuously monitoring simulation results, a process that can be realized through several means (Siemens, 2021b).

One commonly employed technique involves the observation of residual plots generated during solver execution. These residuals serve as monitors, tracking the degree of satisfaction of the discretized equations. Convergence is signified by a decline in residuals from an initial value of unity, followed by an oscillation around a reduced value. The residuals represent the discrepancies between the solved discretized equations and their respective values and are calculated by root-mean-square averaging (Siemens, 2023). By default, the residuals of the continuity equation, the x-, y-, and z-momentum equations, and the turbulent kinetic energy and turbulent dissipation rate, are continuously monitored and plotted. Ensuring each of these residuals decreases to a value below $1\text{E-}03$ is a guideline provided by Symscap (2012). Additionally, the convergence status can be assessed by monitoring specific physical quantities of interest. When these pertinent physical quantities have stabilized to approach an asymptotically constant value, it indicates a converged simulation (Siemens, 2021b).

It is imperative for a simulation to possess a well-defined criterion for terminating iterations. In a steady-state simulation, the automatic termination criterion is often contingent upon reaching a maximum prescribed number of iterations. In unsteady simulations, the termination criterion is associated with the number of outer and inner iterations and the passage of physical time. Alternatively, users can establish their termination criteria by employing monitors that track the solution and halt iterations upon achieving specific predefined solution values, particularly in the context of steady-state conditions. Furthermore, multiple stopping criteria can be configured (Siemens, 2021b).

5.1.5 Governing equations

In fluid dynamics, three physical principles govern, leading to the development of the fundamental governing equations, also termed conservation equations (Fernandez, 2019; Welty *et al.*, 2008).

- The law of conservation of mass (continuity equation)
- Newton's second law of motion (momentum equation)
- First law of thermodynamics (energy equation)

These are detailed below according to the work by Fernandez (2019) and Welty *et al.* (2008).

Continuity equation:

By invoking the first foundational principle of physics within the context of a finite control volume, which remains stationary in space, we focus on a specific point along the control surface. At this point, the flow velocity is denoted as 'V', and the elemental surface area is represented by the vector 'dS'. Additionally, 'dV' signifies an elemental volume contained within the confines of the control volume. Equation 5.1 illustrates the principle of mass conservation within a moving fluid, describing that a constant mass is observed at any point in the flow regime.

$$\frac{\partial}{\partial x} \iiint \rho dV + \iint \rho \mathbf{V} d\mathbf{S} = 0 \quad \text{Equation (5.1)}$$

Momentum equation:

Newton's second law—which provides a relationship between force, mass and acceleration—can be reformulated in a broader and more general manner as follows:

$$\mathbf{F} = \frac{d}{dt} (m\mathbf{V}) \quad \text{Equation (5.2)}$$

On the left side of the equation, the force affecting the fluid within the volume 'V' originates from body forces (such as gravitational or electromagnetic forces acting on the fluid from a distance) and surface forces (pressure and shear stress on the surface 'S'). On the right side, the temporal change in fluid momentum within the fixed control volume includes two main elements: the net flow of momentum across the surface 'S' leaving the control volume and the time-dependent alteration of momentum due to unsteady flow fluctuations within volume 'V'. Therefore, when Newton's second law is applied to the context of fluid flow, it can be expressed as:

$$-\iint p d\mathbf{S} + \iiint \rho \mathbf{f} dV + \mathbf{F}_{viscous} = \frac{\partial}{\partial t} \iiint \rho \mathbf{V} dV + \iint (\rho \mathbf{V} \cdot d\mathbf{S}) \mathbf{V} \quad \text{Equation (5.3)}$$

This can be reformulated as a set of partial differential equations that establish the interrelations among flow-field properties at any given point within the flow.

$$\begin{aligned} \frac{\partial(\rho\mu)}{\partial t} + \nabla \cdot (\rho\mu\mathbf{V}) = -\frac{\partial p}{\partial x} + \rho f_x + (F_x)_{viscous} \frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v\mathbf{V}) = -\frac{\partial p}{\partial y} + \rho f_y + (F_y)_{viscous} \frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w\mathbf{V}) \\ = -\frac{\partial p}{\partial z} + \rho f_z + (F_z)_{viscous} \frac{\partial(\rho w)}{\partial t} \end{aligned} \quad \text{Equation (5.4)}$$

Here, the subscripts 'x', 'y', and 'z' attached to 'f' and 'F' represent the respective x, y, and z components of both body and viscous forces. By considering an infinitesimally small moving fluid element with a fixed mass and applying Newton's second law in the form of $F = ma$, we can arrive at the expressions labelled Equation 5.5 and named the Navier-Stokes equations which provide the momentum equations in x-, y- and z-direction, respectively and describes the flow of incompressible fluids.

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \quad \text{Equation (5.5)}$$

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} \quad \text{Equation (5.5)}$$

$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \quad \text{Equation (5.5)}$$

Energy equation:

In analysing incompressible flow, the continuity and momentum equations suffice. However, in dealing with compressible flow, including an additional fundamental equation, namely the energy equation, becomes essential for a comprehensive characterization of the system.

The foundation of the energy equation rests upon the first law of thermodynamics, a fundamental physical principle stating that energy can be neither created nor destroyed and is defined in the following way:

$$\delta q + \delta w = de \quad \text{Equation (5.6)}$$

Here, δq and δw denote incremental quantities of heat and work, both of which constitute forms of energy that, when introduced into the system, result in a modification of the internal energy, denoted as 'de'. This fundamental principle, when applied within a control volume, can be directly transposed into the following expressions:

$$\iiint q\rho dV + \dot{Q}_{viscous} - \iint p\mathbf{V} \cdot d\mathbf{S} + \iiint \rho(\mathbf{f} \cdot \mathbf{V})dV + \dot{W}_{viscous} = \frac{\partial}{\partial t} \iiint \rho \left(e + \frac{V^2}{2} \right) dV + \iint \rho \left(e + \frac{V^2}{2} \right) \mathbf{V} \cdot d\mathbf{S} \quad \text{Equation (5.7)}$$

$$\frac{\partial}{\partial t} \left[\rho \left(e + \frac{V^2}{2} \right) \right] + \nabla \cdot \left[\rho \left(e + \frac{V^2}{2} \right) \right] \mathbf{V} = \rho q - \nabla \cdot (p\mathbf{V}) + \rho(\mathbf{f} \cdot \mathbf{V}) + \dot{Q}'_{viscous} + \dot{W}'_{viscous} \quad \text{Equation (5.8)}$$

Turbulence models:

Turbulent flows exhibit inherent irregularities, rendering a deterministic approach to turbulence problems unfeasible. Consequently, the treatment of turbulent flows relies on the application of statistical methods. Three approaches to turbulence modelling are available in STAR-CCM+ namely, models that give close to the Reynolds-Averaged-Navier-Stokes (RANS) equations, large eddy simulation (LES) and detached eddy simulation (DES) (Fernandez, 2019).

Within the framework of Reynolds-Averaged Navier-Stokes (RANS), the Navier-Stokes equations governing the instantaneous velocity and pressure fields undergo a decomposition into mean and fluctuating components. This decomposition yields equations for the mean quantities that closely resemble the original equations. However, a notable addition is introduced in the momentum transport equation, namely the inclusion of the Reynolds stress tensor:

$$T_t = \rho v'v' = -\rho \begin{bmatrix} u'u' & u'v' & u'w' \\ u'v' & v'v' & v'w' \\ u'w' & v'w' & w'w' \end{bmatrix} \quad \text{Equation (5.9)}$$

Two fundamental approaches are available for expressing the Reynolds stress tensor in relation to the mean flow parameters: turbulent-viscosity models and Reynolds-stress models. Turbulent viscosity models employ the concept of turbulent viscosity to define the Reynolds stress tensor as a function determined by mean flow properties. Examples of such models encompass the Spalart Allmaras, K-epsilon, and K-Omega models (Fernandez, 2019).

The K-Epsilon model, introduced by Launder and Spalding (1974), falls into the category of two-equation models. This model is the most utilized comprehensive turbulence model and is integrated into the majority of commercial CFD software. Transport equations are solved for two turbulence parameters, namely turbulent kinetic energy (κ) and rate of dissipation of turbulent kinetic energy (ϵ) (Versteeg and Malalasekera, 2007).

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right] + 2\mu_t E_{ij} E_{ij} - \rho \epsilon \quad \text{Equation (5.10)}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right] + C_1 \frac{\varepsilon}{k} 2\mu_t E_{ij} E_{ij} - C_2 \varepsilon \rho \frac{\varepsilon^2}{k} \quad \text{Equation (5.11)}$$

The K-Omega turbulence model introduced by Wilcox (1998) is also a two-equation model, calculating the turbulent kinetic energy (κ) and the specific rate of dissipation of the turbulence kinetic energy into internal thermal energy (ω), which is defined as the quotient of κ and ε (Wilcox, 2008).

$$\frac{\partial(\rho\kappa)}{\partial t} + \frac{\partial(\rho\kappa u_j)}{\partial x_j} = \rho P - \beta^* \rho \omega \kappa + \frac{\partial}{\partial x_j} \left[\left(\mu + \sigma_\kappa \frac{\rho\kappa}{\omega} \right) \frac{\partial \kappa}{\partial x_j} \right], P = \tau_{ij} \frac{\partial u_i}{\partial x_j} \quad \text{Equation (5.12)}$$

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho\omega u_j)}{\partial x_j} = \frac{\alpha\omega}{k} \rho P - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[\left(\mu + \sigma_\omega \frac{\rho\kappa}{\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + \frac{\rho\sigma_d}{\omega} \frac{\partial \kappa}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad \text{Equation (5.13)}$$

The Spalart-Allmaras model represents a one-equation approach, addressing the transport equation for turbulent viscosity (ν_t). While it exhibits distinct limitations in its applicability as a general turbulence model, the model has demonstrated notable success within the specific domain of aerodynamic and turbomachinery flows for which it was designed (Fernandez, 2019).

In the case of Reynolds-stress models, transport equations for individual Reynolds stresses are solved. The Reynolds Stress Transport (RST) model necessitates the solution of seven additional equations: three for Reynolds shear stresses, three for Reynolds normal stresses, and one for dissipation.

Reynolds stress equation models rely on the transport equation for kinematic Reynolds stress, represented as (Anderson and Anderson, 2012):

$$\frac{DR_{ij}}{Dt} = D_{ij} + P_{ij} + \Pi_{ij} + \Omega_{ij} - \varepsilon_{ij} \quad R_{ij} = \langle u'_i u'_j \rangle = -\frac{\tau_{ij}}{\rho} \quad \text{Equation (5.14)}$$

Where the rate of change of R_{ij} plus its transport by convection is equal to the sum of the transport by diffusion, pressure-strain interactions, rotation, and rate of production minus the rate of dissipation. The six partial differential equations obtained from the above equation describe the behaviour of six independent Reynolds stresses. Employing the RST model entails a notable computational burden and often requires a higher number of iterations to achieve convergence. The RST model excels in its ability to account for the influence of streamline curvature, swirl, rotation, and abrupt variations in strain rate in a manner that aligns more closely with physical reality compared to one- or two-equation models. As a result, it finds application in the computational analysis of cyclone flows, swirling flows in combustors, rotating flow passages, and stress-induced secondary flows within ducts (Fernandez, 2019).

Within the framework of large-eddy simulation (LES), the simulation explicitly captures the larger three-dimensional unsteady turbulent motions while simultaneously applying modelling techniques to account for the effects of smaller-scale motions. This modelling approach amalgamates aspects of Reynolds-averaged Navier-Stokes (RANS) in regions characterized by steady flow while transitioning to LES in unsteady and separated flow regions. By virtue of its capacity to explicitly represent the substantial unsteady large-scale motions, LES is anticipated to offer enhanced accuracy and reliability in comparison to Reynolds-stress models, particularly for flows characterized by significant large-scale unsteadiness (Fernandez, 2019).

Detached eddy simulation (DES) is a hybrid modelling methodology that artfully integrates elements of Reynolds-averaged Navier-Stokes (RANS) simulation in certain sections of the flow while seamlessly transitioning into large-eddy simulation (LES) in other regions. This approach effectively leverages the strengths of both RANS and LES, offering a RANS-based simulation to accurately represent boundary layers and an LES-based simulation to capture the intricacies of unsteady separated flow regions, thus providing the user with a comprehensive and versatile modelling framework (Fernandez, 2019).

5.1.6 Summary

The foundational equations in fluid dynamics comprise six fundamental equations: continuity, three momentum equations, energy, and, when relevant, an EOS. These equations calculate variables such as pressure, velocity, and temperature. The EOS equation relates temperature, pressure and composition to density, making it possible to solve for a density variable. Additionally, turbulence models introduce supplementary equations, including turbulent kinetic energy (κ) and dissipation rate (ϵ) (as for the K-Epsilon model), κ and the specific dissipation rate (ω described as the quotient of κ and ϵ) in the K-Omega model, and turbulent viscosity in the Spalart-Allmaras model. Reynolds stress models involve seven additional transport equations, three Reynolds shear stresses, three Reynolds normal stresses and one for dissipation.

These equations are simultaneously solved in three dimensions for each mesh cell within the imported geometry using a designated solver, undergoing iterative computations until reaching either convergence or termination. Figure 5.2 illustrates the convergence process, exemplifying an initial reduction and eventual stabilization of residuals or errors over 4,400 iterations for all six transport equations (continuity, momentum in x-, y-, and z-directions, turbulent dissipation (Tdr), and turbulent kinetic energy (Tke)).

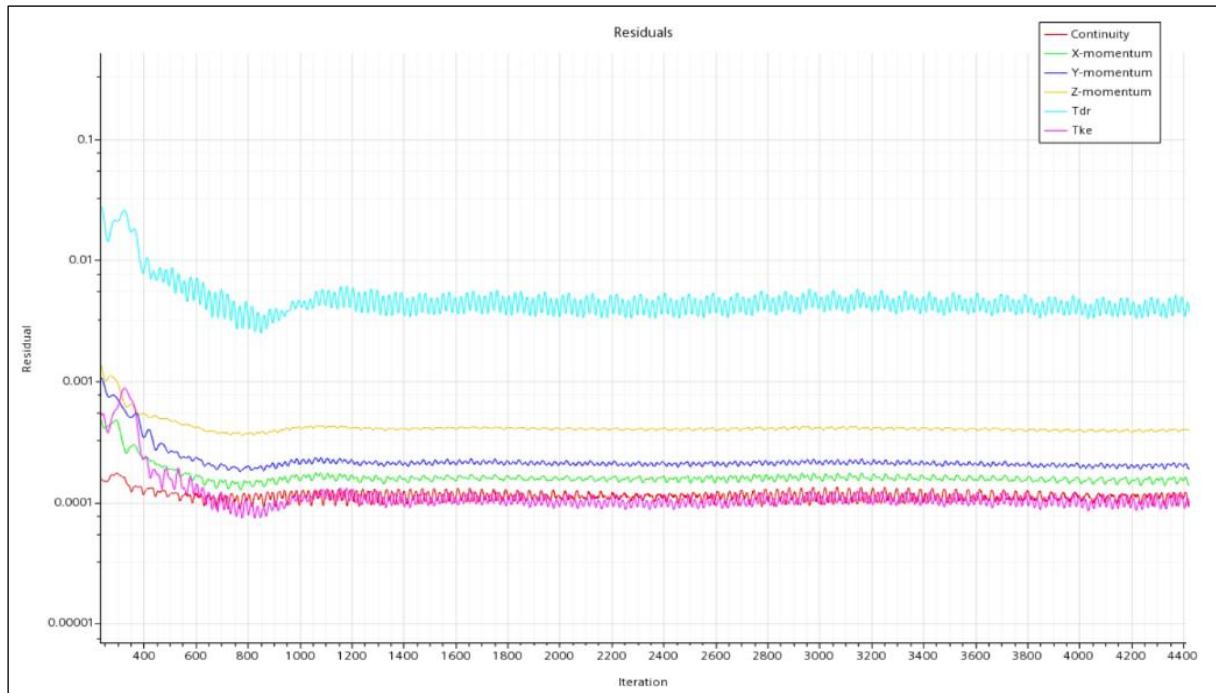


Figure 5.2: Example of residual graph for K-Epsilon Turbulence Model from STAR-CCM+.

5.2 CFD evaluation of the airflow characteristics in an air-gravity separation unit using suction fluidization (Paper 2)

Contributions by authors

Miss N. Hughes undertook this study as a postgraduate student, operating under the guidance of Prof. M. le Roux and Prof. Q.P. Campbell. The scope and rationale of the study were delineated by Prof. le Roux and Prof. Campbell. The experimental configuration adhered to manufacturer specifications, a design orchestrated by Miss Hughes, in collaboration with technical support staff from North-West University. Miss Hughes assumed responsibility for executing the experimental procedures, encompassing data acquisition and subsequent analysis. She further oversaw the CFD simulation and its alignment with experimental data, operating under the mentorship of Mr. van der Merwe. The resultant findings and their ensuing discourse were products of consultations between Miss Hughes, Prof. le Roux, Prof. Campbell, and Mr. van der Merwe. After these deliberations, the work underwent meticulous revision and refinement, priming it for publication in a peer-reviewed journal. The composition of the manuscript was attributed to Miss Hughes, enriched through the editorial contributions of Prof. le Roux and Mr. van der Merwe.

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CFD evaluation of the airflow characteristics in an air-gravity separation unit using suction fluidization

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5.2.1 Abstract

In this study, different sections of the suction nozzle of a laboratory-scale SEP-AIR unit was subjected to different air velocity assessments. Subsequently, computational fluid dynamics (CFD) modelling was utilized to gain insight into the airflow profile and associated properties. The investigation focused on three distinct airflow intensities achieved at low, medium, and high suction fan settings of 10, 30 and 50 Hz within four sections of the suction nozzle namely, fan-side (FS) inlet, other-side (OS) inlet, connecting pipe and fluidizing box. The experimental and simulated velocities are provided in the following table:

	Low flow (10 Hz)		Medium flow (30 Hz)		High flow (50 Hz)	
Velocity (m/s)	Exp	Sim	Exp	Sim	Exp	Sim
Fan-side (FS) inlet	4.13	4.23	12.37	12.43	21.27	22.53
Other-side (OS) inlet	3.82	4.11	11.94	13.16	20.54	23.88
Connecting pipe	14.34	13.97	46.86	42.97	75.52	78.07
Fluidizing box	0.73–4.27	0.16–4.14	2.51–13.79	0.30–11.70	4.62–22.91	0.71–20.50

The comparison between the modelled and experimental velocities reveals a significant level of agreement, as evidenced by high coefficients of determination (R^2) which provide an indication of the extent to which the experimental variable explains the variation in the response variable. However, some deviations were observed in the predicted variables, as indicated by the root mean square error (RMSE), which indicates the predictive capability of the regression model in estimating the value of the response variable. The RMSE must be observed in the context of the actual airflows, which it represents in that if the RMSE is significantly lower than the observed airflow, the predictive capability of the regression model is considered accurate.

Specifically, for the low flow system of 10 Hz, the R^2 and RMSE values were determined as 0.95 and 1.13 m/s respectively. Similarly, for the medium flow system of 30 Hz, the R^2 and RMSE

values were found to be 0.93 and 4.09, respectively. Lastly, for the high-flow system, the R^2 and RMSE values were obtained as 0.94 and 6.78, respectively. The comparison of the RMSE to the average observed velocity in the inlets and connecting separating units indicates that the predictive capability of the model is good, with minimal deviation in the predicted and observed variables. The similarity between the RMSE and the velocities in the fluidizing box shows a lower accuracy of the predicted values in this section.

Keywords: CFD, suction fluidization, airflow characteristics, turbulence, vortex flow

5.2.2 Introduction

Air-based gravity separators have garnered considerable attention within the context of coal beneficiation due to the urgent challenges posed by water scarcity, pollution, dwindling coal reserves, remote and small-scale mining operations and the processing of fine materials. Among the various processes available, the FGX air table (De Korte, 2013), Air Dense Medium Fluidized Bed (ADMFB) (Peters *et al.*, 2021; Peters *et al.*, 2020; Hughes *et al.*, 2017) and negative pressure fluidization (De Korte, 2021) has particularly captivated researchers in the South African coal processing industry.

Negative pressure fluidization employs a system design that harnesses the power of an induced draft fan to generate an adequately forceful airflow, thereby inducing fluidization and subsequent segregation of particles based on their size, density, and shape. Extensive exploration of different process designs is evident in the existing literature. For instance, Moszko *et al.* (2016) investigated a process called 'AMSEP' for coal processing of mine-originating wastes, Stepanenko (2016) examined and commercialized the SEP-AIR for a variety of ore processing based on particle size, shape and density, and Stanczyk *et al.* (2020, 2021) explored the negative pressure pneumatic separator (NPPS) for hard coal beneficiation.

This study adopts a design akin to the SEP-AIR and seeks to comprehend the airflow characteristics by conducting experiments and utilizing computational fluid dynamics (CFD) modelling to establish a velocity profile. Gaining an understanding of the airflow within the separation unit can provide valuable insights for assessing the suitability and applicability of the SEP-AIR for coal beneficiation. Furthermore, this information can guide the optimization of the process for specific applications, ensuring its effectiveness and efficiency.

5.2.2.1 The importance of airflow characteristics

In a system where air functions as the fluidizing medium, a comprehensive understanding of airflow behaviour and patterns assumes paramount importance in evaluating the suitability and

applicability of the process. The characteristics of airflow directly impact the fluidization properties, thereby influencing the movement of particles (Rhodes, 2008) and the separation efficiency obtained (Kunii and Levenspiel, 2001). Obtaining insights into these characteristics can facilitate optimized system design, determination of process scale, and establishment of operating parameters that ensure appropriate air flow direction, speed, and distribution. As a result, proper movement and stratification of particles are ensured, leading to enhanced separation efficiency, recovery rates, reduced energy consumption, and safe operation (Kunii and Levenspiel, 2001). Moreover, comprehension of airflow characteristics enables troubleshooting and identification of root causes behind inefficient or uneven separation, particle misplacement, and blockages, which may contribute to operational issues.

5.2.3 Description of the laboratory-scale separation unit and function

To examine the properties, behaviour, and patterns of airflow, a laboratory-scale separating unit was designed, constructed, commissioned and optimized—following the manufacturer's specifications. This section presents a description of the unit's geometry and a summary of the anticipated airflow patterns and particle movement within. The processing unit comprises the following sections: i) feed, consisting of a manual conveyor system for particle entry; ii) separating unit, where the fluidization and separation of the particles occur; and iii) centrifugal fan, providing the suction force required. The separating unit is composed of four distinct compartments, namely: (1) rectangular fluidizing box, (2) cylindrical vortex chamber, (3) cylindrical connecting pipe, and (4) cubic collection bin. Figure 5.3 is a schematic of the compartments, numbered from 1 to 4 in sequential order.

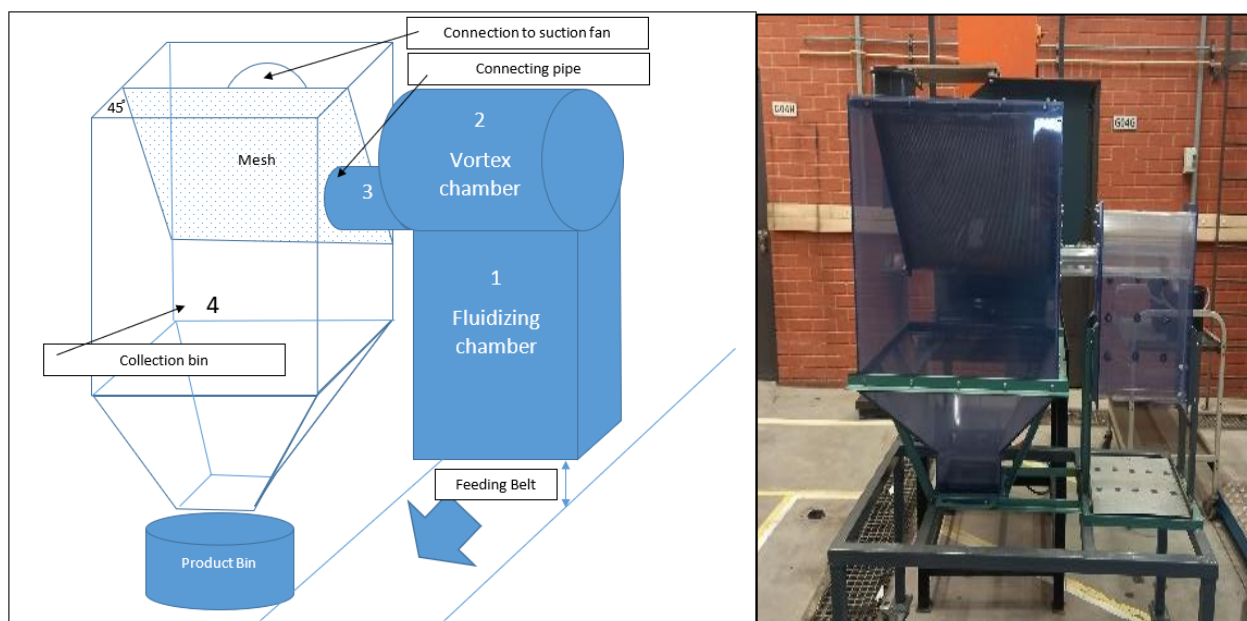


Figure 5.3: Schematic (left) and image (right) of the separating unit with components labelled.

Table 5.1 provides information regarding the geometry of the fluidizing box, collection bin, vortex chamber and connecting pipe.

Table 5.1: Dimensions of the laboratory scale separating unit.

	Fluidizing box (mm)	Collection bin (mm)	Vortex chamber (mm)	Connecting pipe (mm)
Length	300	600	300	150
Width	100	600	-	-
Height	300	600	-	-
Diameter	-	-	160	80

Each compartment within the system is specifically designed to exhibit distinct airflow patterns, thereby serving a particular function. Due to the draft induced by the suction fan, air enters horizontally from the environment over the feed belt and into the fluidizing box. Subsequently, it progresses into the vortex chamber, where the circular arrangement induces the formation of a vortex. As the cyclic airflow proceeds from the vortex chamber to the connecting pipe, which possesses a smaller circular cross-section, it accelerates in accordance with Bernoulli's principle. Upon entering the larger collection bin, the air decelerates once again and exits through the suction fan.

The combination of the vortex chamber and connecting pipe functions as a 'particle capturing' mechanism, whereby the circulating air seizes fluidized particles at the fluidizing box height, accelerating them for collection in the product bin. Additionally, the vortex chamber contributes to the establishment of a uniform airflow profile spanning the length of the fluidizing box, mitigating the occurrence of dead spots in the region furthest from the suction fan. The positioning of the fluidizing box above the feeding conveyor also influences the properties of the air within the air inlets. Decreasing the gap size leads to an increase in air velocity, potentially affecting the velocity profile within the fluidizing box. Nevertheless, the particle size range predominantly determines the appropriate gap height, ensuring unobstructed particle flow into the inlet of the fluidizing box. As a general guideline, a gap height of no less than 1.5 times the size of the largest particle in the feed is recommended (A.I. Stepanenko, CEO of Gormash Export, personal communication, September 2019).

A straightforward particle feeding system is employed to introduce particles into the separation nozzle at a predetermined load and velocity. The draught power is produced through a Trojan BC60 series direct-drive centrifugal fan, with a power capacity of 1.1 kW. This fan has the capability to attain a peak rotational speed of 1,000 revolutions per minute (RPM), providing a throughput of 1,700 Am³/hr and a pressure rating of 230 Pa. This results in an air speed of 93.95 m/s when operating at maximum flow. The suction strength is modulated by a frequency inverter,

offering adjustable settings within a range of 0–50 Hz, which, in turn, influences the throughput and, consequently, the airspeed.

5.2.4 Model development

The primary focus of this study revolves around the airflow patterns within the suction nozzle (compartments 1, 2, 3 and feeding belt in Figure 5.3), a three-dimensional assembly including the feed conveyor plate, air inlets, fluidizing box, vortex chamber, connecting pipe and air outlet was created utilizing Siemens NX-12. This geometry was used to define the boundaries for the simulation of airflow patterns in STAR-CCM+ and is visually depicted with compartments, inlets and outlets labelled in Figure 5.4.

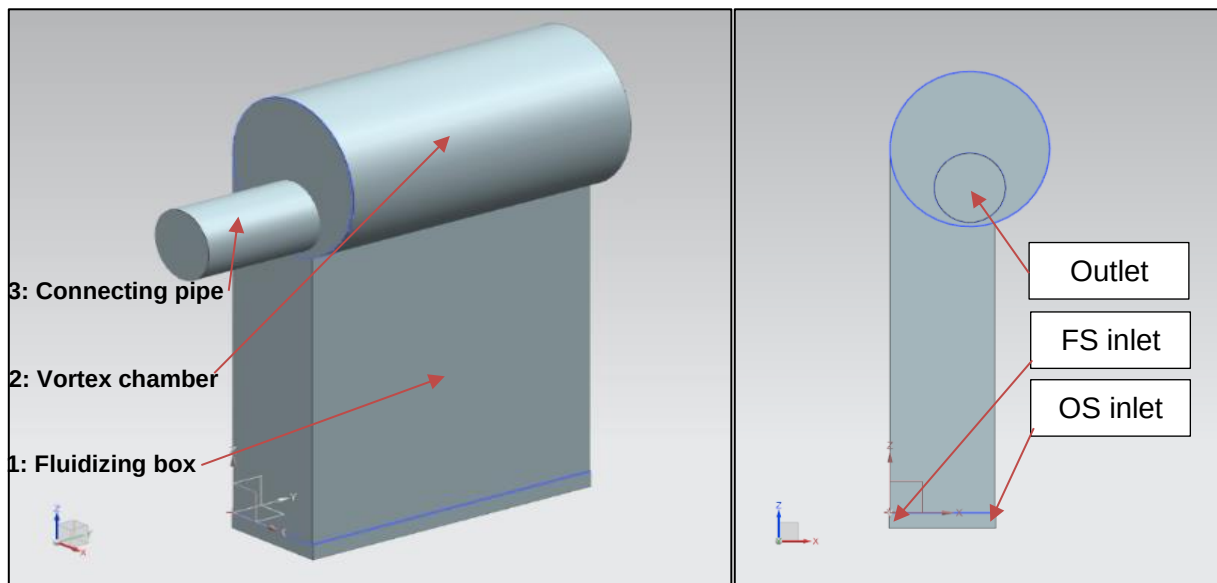


Figure 5.4: Suction nozzle assembly constructed in NX-12, trimetric view with compartments labelled (left) and front view with inlets and outlet labelled (right).

5.2.4.1 Meshing and boundary conditions

Various meshing strategies are available, each offering distinct advantages and applications. In this study, the assembly was exported as para-solid files from NX-12 and subsequently imported into STAR-CCM+ as a surface mesh. Parts within the assembly were assigned to specific regions, with each part surface assigned a corresponding boundary. The inlet and outlet regions, as illustrated in Figures 5.4 and 5.5, were designated with a specific type and boundary condition, namely velocity inlet and pressure outlet, respectively. The outer surface of the suction nozzle and the bottom of the feeding belt were deemed walls.

For surface meshing, a surface remesher was employed. This remesher ensures the generation of a high-quality discretized mesh suitable for CFD simulations. It accomplishes this by re-triangulating the surface based on a specified edge length, while also allowing for the omission

of selected surfaces and preserving the original features of the imported mesh. To generate the volume mesh, the polyhedral mesher option was chosen. This method constructs a volume mesh composed of polyhedral-shaped cells. It has proven to be numerically stable and accurate compared to the tetrahedral mesh, while also resulting in a reduced number of cells. Additionally, the prism layer mesher, an optional feature, was employed. It adds prismatic cell layers adjacent to wall boundaries, aiding in the prediction of flow characteristics such as drag force and pressure drop. Furthermore, it refines the mesh around regions with sharp edges or small openings, where flow descriptions become more complex (Siemens, 2023).

A base size of 5 mm was selected for the mesh cells yielding 144,129 cells, 867,278 cell faces and 703,627 cell vertices. Figure 5.5 illustrates the resulting mesh generated for the suction nozzle using the meshing strategy with polyhedral and prismatic cells visible, as well as the velocity inlets and pressure outlet (portrayed in orange) and wall (portrayed in grey).

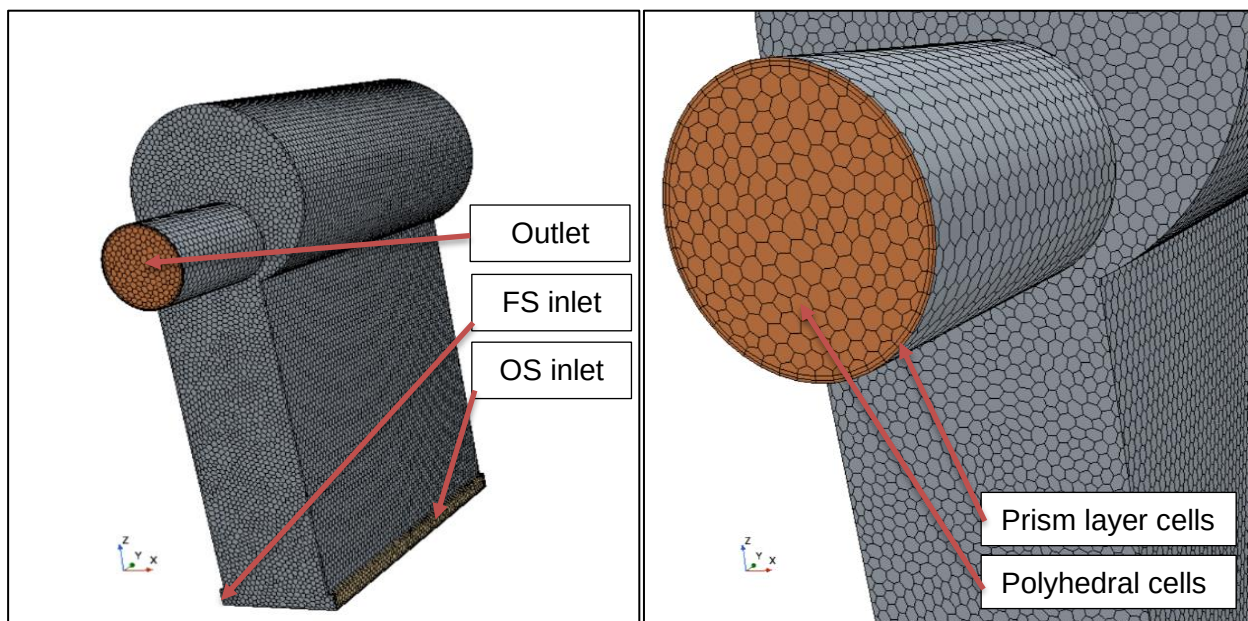


Figure 5.5: Resulting mesh with cells, inlets, outlet and walls visible.

5.2.4.2 Governing equations

The governing equations employed by Siemens' STAR-CCM+ for solving fluid dynamics problems encompass physics models that account for various factors such as space, time, motion, material properties, turbulence and the three fundamental conservation equations: (1) continuity, (2) momentum, and (3) energy. Within each of these categories, STAR-CCM+ offers numerous models, providing a vast array of choices and combinations. The selection of an appropriate combination of physics models is crucial to ensure that the simulation accurately captures the essential physics relevant to the specific problem being investigated. The diagram

presented in Figure 5.6 provides an overview of the chosen combination of physics models specifically selected for the current study.

Space	Three dimensional
The three-dimensional spatial model is implemented on three-dimensional meshes, wherein all spatial directions hold significance.	
Time	Steady state
The steady-state time model is utilized when discretizing spatial derivatives. In accordance with the methodology outlined in literature, the steady-state time model is deemed appropriate for the study.	
Material	Single component gas
The single-component material models are employed for the modeling of pure substances in their fundamental states, namely gas, liquid, and solid.	
Equation of state	Constant density
The constant density EOS can be used for single-phase flows, non-reactive flows and incompressible flows where $Mach < 1$.	
Fundamental equations	Conservation
The conservation of mass, momentum and energy equations are applied.	
Turbulence	Reynolds-Average-Navier-Stokes (RANS)
- The Reynolds Stress turbulence is widely acknowledged for highly swirling or strongly segregated flow. - K-Epsilon is the most utilized comprehensive and robust turbulence model	
Optional	Optional models selected
- Gradients - Exact wall distance and two-layer All y+ wall treatment	

Figure 5.6: Physics models selected for the STAR-CCM+ simulation (made from information from Symscape, 2012; Anderson, 2017; Fernandez, 2019; Ferziger, 2020; Siemens, 2023).

5.2.4.3 Solution algorithm and convergence

As stated previously, the outlet of the connecting pipe was configured as a pressure outlet, with boundary condition pressure values of -125 Pa, -1150 Pa, and -3000 Pa for the low, medium, and high flow systems respectively. These pressure values were acquired from the laboratory-scale unit through physical measurements of pressure in the connecting pipe using a Fluke 922 airflow and manometer. This information serves to provide the simulation with the magnitude of the suction force boundary condition observed at various flow intensities. Velocity values obtained through physical measurements were also included in the air inlets and pressure outlets as initial conditions to aid the numerical calculations and convergence.

In STAR-CCM+, convergence assessment is typically conducted using residual monitors and specified coefficients for velocity, force, or pressure. Residuals denote discrepancies between solved discretized equations and are computed via root-mean-square averaging (Siemens, 2023). Continuity equation residuals, x-, y-, and z-momentum equations, turbulent kinetic energy, and turbulent dissipation rate are monitored and plotted by default. Simulation convergence is confirmed when these residuals decrease below $1E-03$ (Symscape, 2012). Final convergence is ascertained by monitoring pressure values in the connecting pipe, considering convergence is achieved when pressure stabilizes and varies by less than 0.1 Pa per iteration.

5.2.5 Experimental method

A series of physical airflow tests were carried out within distinct sections of the separating unit to examine the actual airflow behaviour and compare it with the model-generated results. The primary focus of these experiments was to assess airspeed and flow direction, as these factors play a critical role in determining the adequacy of suction force required to transport specific particles.

Air velocity measurements using a Testo 440 smart probe anemometer were conducted at various positions within the unit, including 40 different locations. These measurements encompassed 5 locations spanning both inlets each (50, 100, 150, 200 and 250 mm along the 300 mm length), 3 locations spanning the connecting pipe (40, 80 and 120 mm along the 150 mm length), and 9 locations covering the area of the fluidizing box (50, 150 and 200 mm along the 300 mm length and 85, 185 and 285 mm along the 300 mm height) at 3 different depths (25, 50 and 75 mm along the 100 mm width). The measurements were taken for 10 suction fan settings and 10 readings were recorded for repeatability. Figure 5.7 provides a schematic of the unit, indicating the points where air velocity measurements were taken.

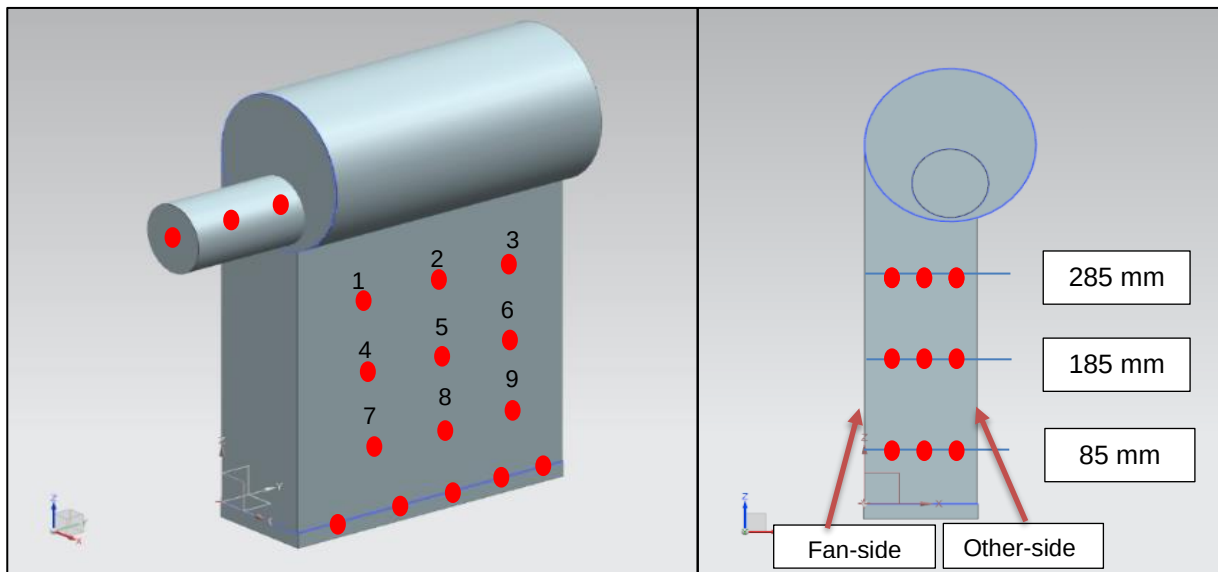


Figure 5.7: The points within the suction nozzle where velocity readings were measured (left and right) and the horizontal cross-sections across the height of the fluidizing box (right).

To assess the variability of the velocity profile over time, additional measurements were captured every second over a duration of one minute. This monitoring process aimed to determine the extent to which the velocity readings within the system vary over time. An s-type pitot tube, in conjunction with a Fluke 922 anemometer, was employed to determine the direction of airflow. In this configuration, a negative airflow reading indicated a flow opposite to the intuitively expected airflow direction. These measurements provided valuable insights into potential eddying currents

and facilitated a comparison between the velocity vectors obtained from the simulation and the measured airflow direction.

5.2.6 Results

The velocities obtained from the experiments were carefully examined to assess their repeatability and variability. Subsequently, the velocity readings were compared to the simulation results at three different flow intensities (low 10 Hz, medium 30 Hz, and high 50 Hz). This comparison was conducted using parity plots in conjunction with statistical measures such as the coefficient of determination (R^2) and root mean square error (RMSE).

5.2.6.1 Experimental airflow values, direction and repeatability

Table 5.2 presents the mean magnitudes of velocity and associated Reynolds numbers observed in specific regions of the separating unit for each flow intensity (10, 30 and 50 Hz) considered. The mean velocity in both inlets, the connecting pipe and three horizontal cross-sectional slices of the vertical z-plane (Figure 5.7) at different heights (85, 185 and 285 mm) along the fluidizing box is provided in Table 5.2. The flow direction is also depicted as an axis on the Cartesian plane (as illustrated in Figure 5.7). Moreover, standard deviation values are provided to assess the variability of the measured velocity values.

Table 5.2: The mean velocity magnitudes and standard deviation observed at different suction fan settings.

Position	Mean velocity (m/s)	Standard deviation	Direction cartesian plane	Reynolds number	Flow regime
Low flow system (10 Hz)					
Fan-side (FS) inlet	4.13	0.26	+x	7,992	Transitional
Other-side (OS) inlet	3.82	0.01	-x	7,904	Transitional
Connecting pipe	14.34	0.17	-y	80,148	Turbulent
Fluidizing box (FB)					
85 mm (from inlet)	2.61	1.01	$\pm z$	18,206	Transitional
185 mm (from inlet)	1.74	0.63	$\pm z$	10,678	Transitional
285 mm (from inlet)	1.44	0.62	$\pm z$	8,129	Transitional
Medium flow system (30 Hz)					
Fan-side inlet	12.80	0.64	+x	26,167	Transitional
Other-side inlet	11.94	0.70	-x	24,277	Transitional
Connecting pipe	46.86	0.76	-z	249,058	Turbulent
Fluidizing box					
85 mm (from inlet)	8.69	3.07	$\pm z$	56,200	Transitional
185 mm (from inlet)	4.75	1.28	$\pm z$	30,706	Transitional
285 mm (from inlet)	4.54	1.39	$\pm z$	29,406	Transitional
High flow system (50 Hz)					
Fan-side inlet	21.27	0.92	+x	42,983	Transitional
Other-side inlet	20.54	0.84	-x	40,717	Transitional
Connecting pipe	75.52	1.20	-y	405,255	Turbulent
Fluidizing box					
85 mm (from inlet)	14.91	5.06	$\pm z$	96,462	Turbulent
185 mm (from inlet)	8.39	1.73	$\pm z$	54,266	Transitional

285 mm (from inlet)	8.54	2.25	$\pm z$	55,250	Transitional
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The low standard deviations observed in the inlets and connecting pipe indicate the repeatability and accuracy of the recorded velocity readings in these regions. However, larger standard deviations are noticeable in the velocity measurements within the fluidizing box. This variation can be attributed to the development of a more intricate velocity profile in the fluidizing box than can be described by an average velocity across a horizontal plane. Mean velocity or standard deviation calculations alone over the horizontal plane do not adequately capture this complexity. Specifically, consistently higher velocities are observed axially along the centre of the fluidizing box, while lower velocities are found closer to the walls. Experimental measurements obtained using the s-type pitot probe reveal a variable flow direction in the near-wall region, suggesting the presence of eddy currents that impede the airspeed. Moreover, the top horizontal plane exhibits higher velocities toward the side of the connecting pipe, indicating the exit effect of the vortex located just above. Notable is that the velocities obtained in the different sections of the suction nozzle all relate to Reynolds numbers exceeding the conditions for laminar and critical flow (2,800 and 4,000, respectively), and thus, the airflow within the unit can be considered transitional or turbulent (Welty *et al.*, 2007). By using the Moody Chart (Welty *et al.*, 2007) in combination with the low relative roughness of PVC (The Engineering Toolbox, 2003) and calculated friction factor of 0.02, a Reynolds number of 60,000 can be considered as the threshold for transitional flow. Hence, regions of transitional and turbulent flow are observed in different sections of the suction nozzle. Specifically, transitional flow occurs in the inlets for all three suction fan settings. In the 10 Hz and 30 Hz systems, transitional flow is observed in the fluidizing box whereas a combination of transitional and fully turbulent flow is noted in the high-flow (50 Hz) system. The flow regime for the connecting pipe is fully turbulent for all three suction fan settings (10, 30 and 50 Hz).

Table 5.3 offers a horizontal cross-sectional view in the z-direction, specifically at distances of 8.5 cm, 18.5 cm, and 28.5 cm from the inlet within the fluidizing box (visible by the lines in the right image of Figure 5.7). This table presents the velocity data obtained from the 27 measurement points, providing valuable information regarding the observed velocity profile. In Figure 5.7, we can discern the locations of the 9 measurement points in the image on the left and the corresponding positions, categorized into three distinct depths and three elevations in the image on the right.

Table 5.3: Velocity in the fluidizing chamber at different horizontal planar views in the z-direction

Low flow sytem					Medium flow system					High flow system				
	x/y	1	2	3		x/y	1	2	3		x/y	1	2	3
Z plane	3	0,80	1,54	1,18	Z plane	3	2,09	4,15	5,27	Z plane	3	7,06	8,61	10,27
28,5 cm	2	0,73	1,51	2,02	28,5 cm	2	4,31	5,41	7,38	28,5 cm	2	4,62	7,44	13,41
Top	1	0,98	1,03	1,52	Top	1	3,70	3,57	5,02	Top	1	8,30	8,61	8,54
		4	5	6			4	5	6			4	5	6
Z plane	3	0,96	2,25	0,91	Z Plane	3	2,51	5,55	2,70	Z Plane	3	4,64	9,85	6,37
18,5 cm	2	1,65	2,66	1,69	18,5 cm	2	5,20	6,85	5,12	18,5 cm	2	9,53	10,37	9,29
Middle	1	1,69	1,36	1,68	Middle	1	4,83	4,92	5,03	Middle	1	8,84	7,83	8,76
		7	8	9			7	8	9			7	8	9
Z plane	3	1,34	3,21	1,36	Z Plane	3	4,99	9,57	5,07	Z Plane	3	9,04	17,65	8,22
8,5 cm	2	4,27	2,79	3,85	8,5 cm	2	13,54	8,94	13,79	8,5 cm	2	22,91	16,30	22,40
Bottom	1	3,27	2,03	3,19	Bottom	1	8,66	6,39	7,23	Bottom	1	14,27	11,37	12,01

When examining the velocity data for the low flow system presented in Table 5.3, the initial nine data points pertain to velocities within a horizontal plane situated 28.5 cm above the air inlet. The designations "1," "2," and "3" in the x-direction represent the depths of these points, positioned at 2.5 cm, 5.0 cm, and 7.5 cm from the fan-side wall, respectively. Likewise, the designations "1-3" in the y-direction denote the locations spanning 50 cm, 150 cm, and 250 cm across the width of the fluidizing box. The second cross-sectional slice is situated 18.5 cm from the inlet, featuring measuring points designated as 4, 5, and 6 at depths of 1, 2, and 3. Measuring points 7, 8, and 9, corresponding to depths 1, 2, and 3, apply to the slice positioned at 8.5 cm. These measurement points remain consistent for both the low and medium flow systems and are also represented in Figure 5.7.

Observed in the depictions provided in Table 5.3 are the consistently higher velocities in the middle of the fluidizing box for low, medium and high flow systems at all three heights. Velocities in measuring point 3.2 are higher because of the connecting pipe speeding up the air just above. The lowest velocities are observed in the region farthest from the connecting pipe. A consistently higher velocity is observed in the other-side wall at 150 cm across the width of the fluidizing box. This indicates that the velocity profile develops a curvilinear s-shape, entering the fluidizing box and leaning towards the other-side wall before swirling into a vortex.

The variance of the velocity readings, measured at one-second intervals over a one-minute duration at specific locations within the fluidizing box, exhibit a range of 0.02–0.60, 0.10–0.79, and 0.21–0.79 for the low, medium, and high-flow systems, respectively. Variance provides an indication of the extent to which values deviate from the mean. These low variances signify

minimal variations in velocity readings over time, indicating a high level of homogeneity in the measured velocities over time.

5.2.6.2 Comparison of observed and simulated data

To compare the simulated velocities with the experimental velocities, point vectors were employed in STAR CCM+™ to ascertain the speed and direction of the airflow. These vectors were placed at identical positions as the 40 measuring points within the suction nozzle in the experimental setup.

Parity plots, along with their associated coefficient of determination (R^2) and root-mean-squared-error (RMSE), were utilized to describe the correlation between the observed and simulated velocities. These statistical measures provide valuable insights into the agreement between the two sets of velocities.

The R^2 value indicates the extent to which the experimental variable elucidates the variation in the response variable while the RMSE serves as an indicator of the predictive capability of the regression model in estimating the value of the response variable. A high R^2 value, accompanied by a low RMSE value, indicates a strong correlation between the observed and predicted values. It is, however, essential to assess the RMSE in relation to the average magnitude of the observed values. A RMSE value that is significantly lower than the average observed value, which the regression model is trying to predict, is considered good. By considering the context of the average observed values, a more comprehensive evaluation of the predictive accuracy can be achieved (Wheeler, 2021).

5.2.6.3 Simulated airflow for the low-flow system

Figure 5.8 displays a parity plot illustrating the comparison between the simulated velocities and the experimental velocities in the low-flow (10 Hz) system. The corresponding statistical values obtained from this analysis are as follows: an R^2 value of 0.95 and an RMSE value of 1.13.

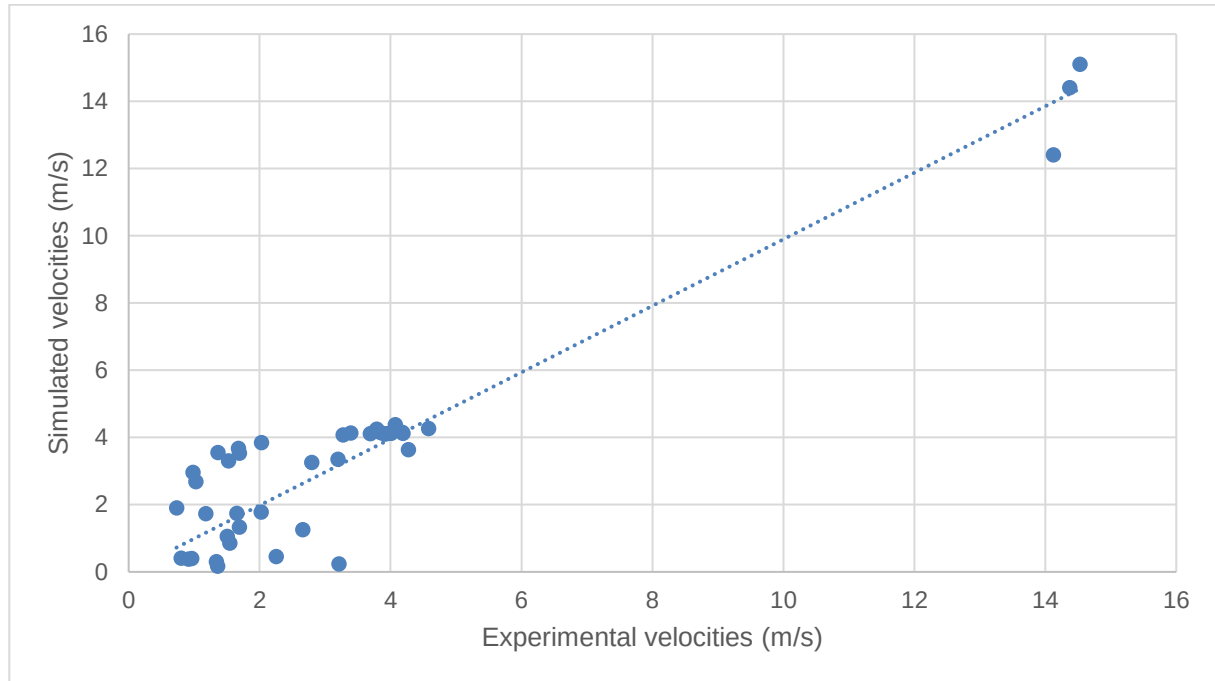


Figure 5.8: Parity plot comparing the simulated and experimental velocities in the low flow system.

Table 5.4 presents a summary of the average velocity magnitude and direction in the low flow system for both the modelled and experimental data in the inlets and connecting pipe. Additionally, a velocity magnitude range is provided for the fluidizing box, considering the observed variations in velocity along the width and height of the box.

Table 5.4: Comparison of the ranges of velocity magnitude and direction between the experiment and simulation for the different sections of the suction nozzle in the low flow system.

	Experimental velocity		Simulated velocity	
	Direction	Range of magnitude (m/s)	Direction	Range of magnitude (m/s)
Fan-side (FS) inlet	+x	4.13	+x	4.23
Other-side (OS) inlet	-x	3.82	-x	4.11
Connecting pipe	-y	14.34	-y	13.97
Fluidizing box	$\pm z$	0.73–4.27	$\pm z$	0.16–4.14

Based on Figure 5.8, Table 5.4, and the corresponding statistics, the modelled and observed velocity ranges for the low flow system are generally in good agreement. Most velocity magnitudes and directions exhibit alignment between the two datasets, indicating a satisfactory level of agreement. However, notable disparities are apparent, primarily within the fluidizing box, particularly in the near-wall regions, where both magnitude and direction of velocities show significant deviations.

The RMSE value of 1.13 m/s, obtained from the analysis, is considerably smaller than the average velocities observed in the inlets (4.13 and 3.82 m/s) and connecting pipe (14.34 m/s). However, it is comparable to the average velocity observed in the fluidizing box (1.19 m/s) with an absolute

error of 0.06 m/s, suggesting a relatively lower level of agreement in that region where the predictive capability of the model may not be as accurate. When focusing on the connecting pipe, an RMSE of 3.15 m/s is observed, which is much lower than the average observed velocity of 14.34. Similarly, a RMSE of 0.6 m/s is observed for the inlets. This indicates accurate predictions of the velocity readings in these sections of the suction nozzle.

5.2.6.4 Simulated airflow for the medium flow system

Similarly, the parity plot comparing the simulated and the experimental velocities obtained in the medium flow (30 Hz) system is provided in Figure 5.9. The R^2 and RMSE are 0.93 and 4.09, respectively.

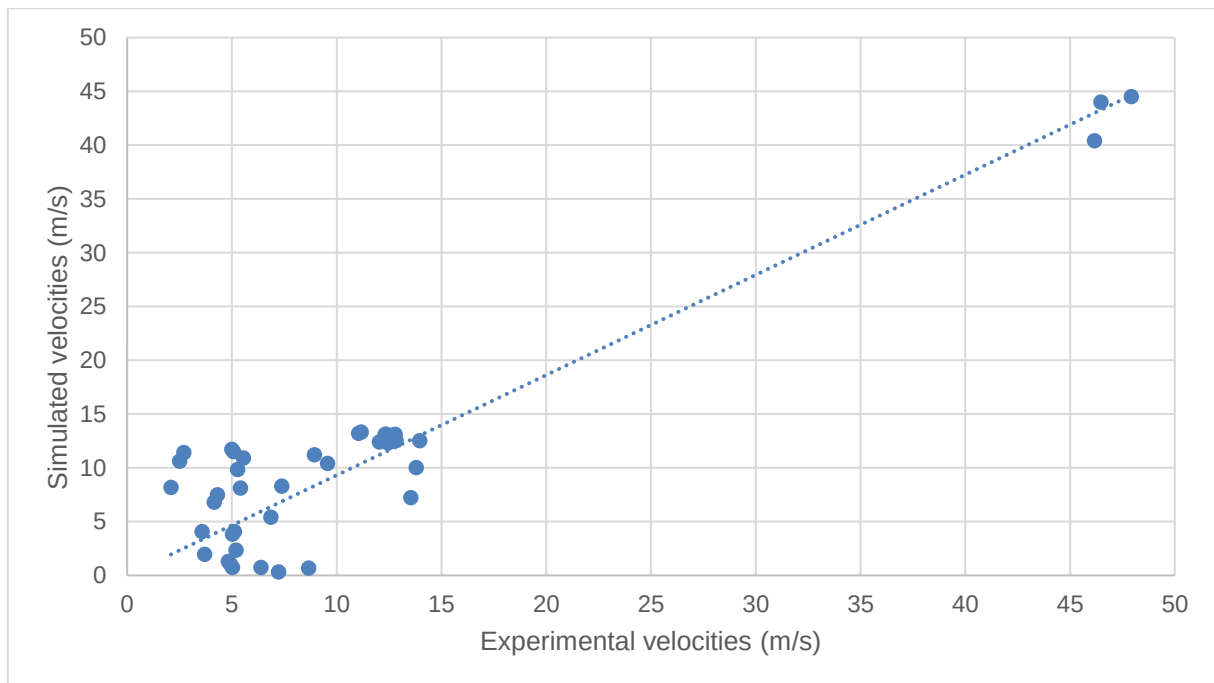


Figure 5.9: Parity plot comparing the simulated and experimental velocities in the medium flow system.

The average velocity magnitude and direction in the medium flow system for both the modelled and experimental data are summarized in Table 5.5 for the fan-side and other-side inlets, connecting pipe and fluidizing box.

Table 5.5: Comparison of the velocity magnitude and direction ranges between the experiment and simulation for the different sections of the suction nozzle in the medium flow system.

	Experimental velocity		Simulated velocity	
	Direction	Range of magnitude (m/s)	Direction	Range of magnitude (m/s)
Fan-side (FS) inlet	+x	12.37	+x	12.43
Other-side (OS) inlet	-x	11.94	-x	13.16
Connecting pipe	-y	46.86	-y	42.97
Fluidizing box	$\pm z$	2.51–13.79	$\pm z$	0.30–11.70

The data portrayed in Figure 5.9 and Table 5.5, along with corresponding R^2 and RMSE, indicate good agreement between the modelled and observed velocity ranges. The velocity magnitudes and directions in the inlets and connecting pipe exhibit alignment between experimental and simulated results. Like the low-flow system, disparities primarily occur in the near-wall regions of the fluidizing box.

The analysis revealed an RMSE value of 4.09 m/s, which differs from the higher average velocities recorded in the inlets (12.37 and 12.43 m/s) and the connecting pipe (46.86 m/s). However, it corresponds to the average velocity observed in the fluidizing box (5.79 m/s) with an absolute error of 1.7 m/s. This suggests a comparatively lower level of agreement in that specific area, indicating potential limitations in the model's predictive accuracy for this region. An RMSE of 4.56 m/s was observed for the connecting pipe, considerably lower than the average observed velocity of 46.86 m/s. Similarly, an RMSE of 0.72 m/s was noted for the inlets with velocities around 12 m/s. This indicates precise predictions of velocity readings in these sections.

5.2.6.5 Simulated flow for the high-flow system

The comparison between simulated and experimental velocities in the medium flow system is provided by the parity plot in Figure 5.10. The corresponding statistics are as follows: an R^2 value of 0.94 and an RMSE value of 6.78.

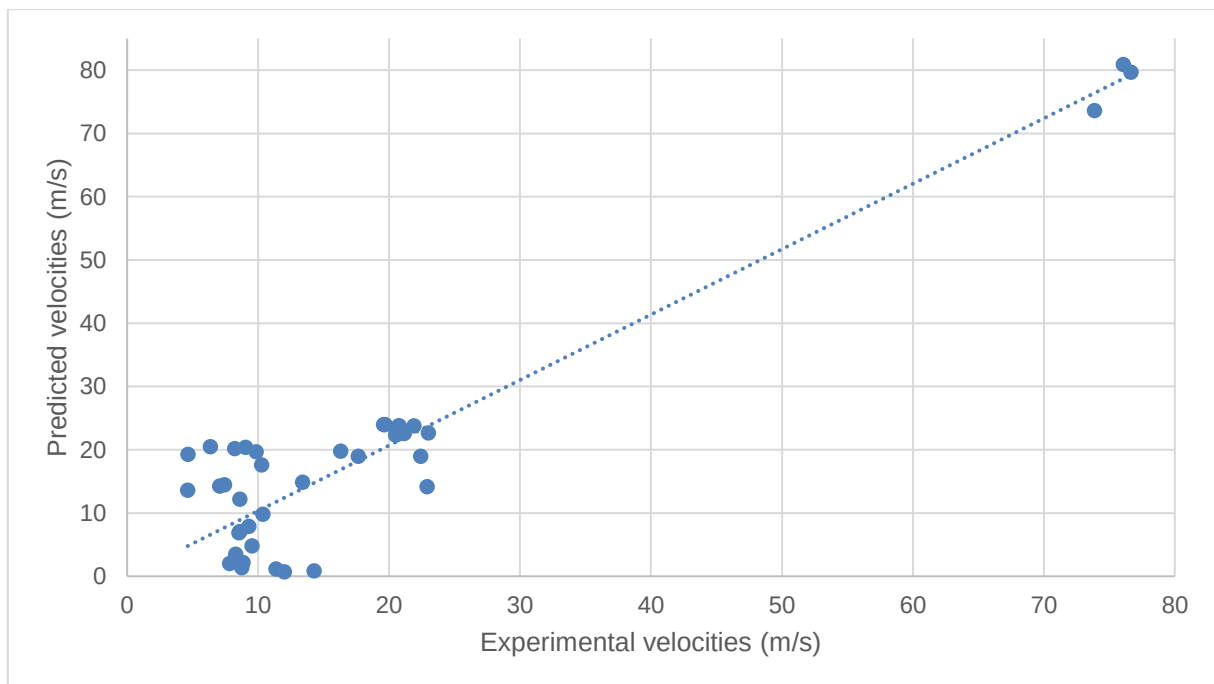


Figure 5.10: The parity plot compares the simulated and experimental velocities in the high flow system.

Table 5.6 provides modelled and experimental data for velocity magnitude and direction in the fan-side inlet, other-side inlet, connecting pipe, and fluidizing box.

Table 5.6: Comparison of the ranges of velocity magnitude and direction between the experiment and simulation for the different sections of the suction nozzle in the high flow system.

	Experimental velocity		Predicted velocity	
	Direction	Range of magnitude (m/s)	Direction	Range of magnitude (m/s)
Fan-side (FS) inlet	+x	21.27	+x	22.53
Other-side (FS) inlet	-x	20.54	-x	23.88
Connecting pipe	-y	75.52	-y	78.07
Fluidizing box	$\pm z$	4.62–22.91	$\pm z$	0.71–20.50

A satisfactory level of agreement is observed when considering the data and statistical measures obtained for the high-flow system. Disparities primarily occur in the near-wall regions of the fluidizing box as in the low and medium flow systems.

A RMSE value of 6.78 m/s was obtained, significantly smaller than the average velocities observed in the inlets (21.27 m/s and 20.54 m/s) and the connecting pipe (75.52 m/s). However, it aligns with the average velocity observed in the fluidizing box (9.49 m/s) with an absolute error of 2.71 m/s, indicating a lower level of agreement in that specific region, potentially reflecting limitations in the model's predictive accuracy for this area. Specifically focusing on the connecting pipe, an RMSE of 3.80 m/s was observed, notably lower than the average observed velocity of 75.52 m/s. Similarly, an RMSE of 1.20 m/s was noted for the inlets with velocities around 20 m/s. This suggests accurate predictions of the velocity readings in these sections.

5.2.6.6 Visual representations of the simulated results

Figures 5.11, 5.12, and 5.13 exhibit the results of the CFD simulations conducted on the low, medium, and high flow systems, respectively. These figures present cross-sectional illustrations of the suction nozzle, depicting vector streamlines in the side view (x-direction, A1) and front view (y-direction, B1), which effectively illustrate the speed and direction of the velocity. Additionally, scalar images of the same cross-sectional perspectives (A2 and B2) are included to emphasize regions with reduced flow.

The images labelled C1 and C2 depict velocity vectors and velocity scalars at each of the 40 points where physical airflow measurements were taken to facilitate a comparison. These visual representations provide valuable insights into the flow patterns that develop within the suction nozzle, with particular attention given to flow speed and direction. These insights help identify potential dead spots and eddying currents within the system.

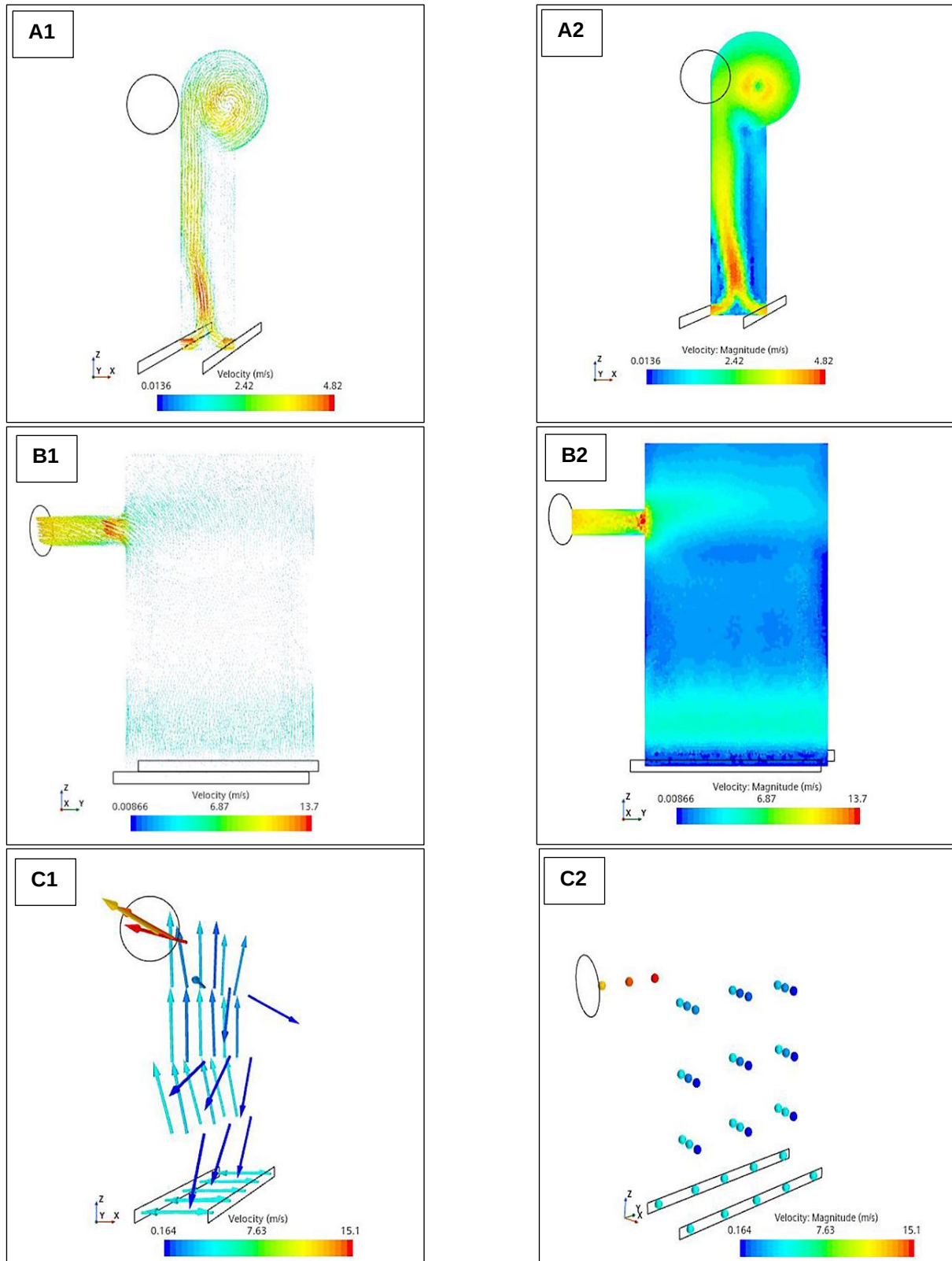


Figure 5.11: CFD simulation results portraying planar views of velocity vectors (A1, B1 and C1) and velocity scalars (A2, B2 and C2) of the airflow in the suction nozzle for the low flow system.

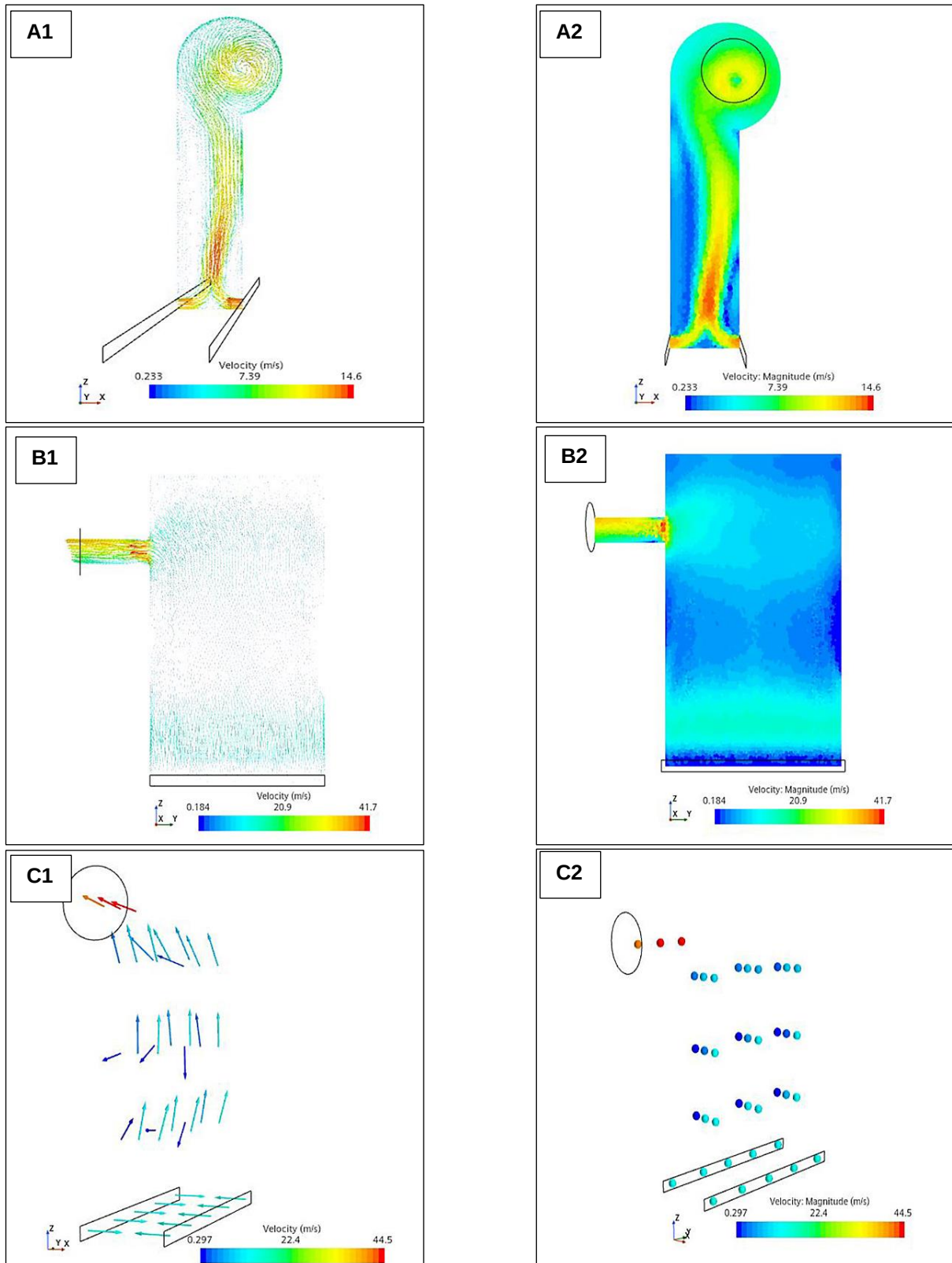


Figure 5.12: CFD simulation results portraying planar views of velocity vectors (A1, B1 and C1) and velocity scalars (A2, B2 and C2) of the airflow in the suction nozzle for the medium flow system.

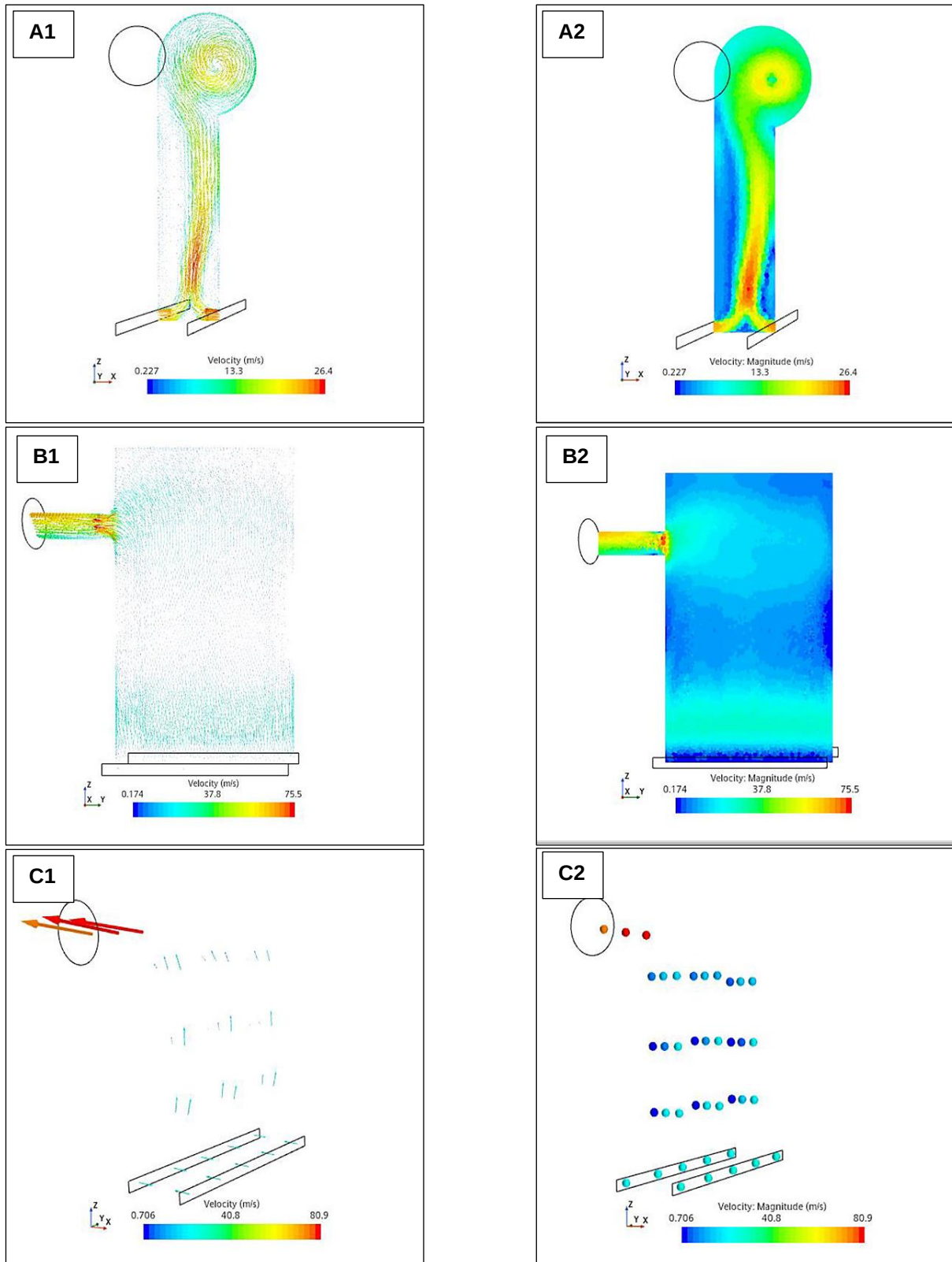


Figure 5.13: CFD simulation results portraying planar views of velocity vectors (A1, B1 and C1) and velocity scalars (A2, B2 and C2) of the airflow in the suction nozzle for the high flow system.

For the low flow system, represented in Figure 5.11, it is evident that the inlet flow initially progresses horizontally (visible in schematic A1 and C1) and then curves upward in the centre of the fluidizing box tending towards the fan-side (FS) (schematic A1). The development of a circular vortex flow can be observed in the vortex chamber (A1) and exits through the connecting pipe (B1). Variations in airspeed and changes in flow direction are apparent, indicating regions of fast (red) and slow (blue) airflow (figures A1, A2, B1 and B2) as well as areas where the flow direction alters (A1, B1 and C1). The arrows in C1 are vectors of the measuring points and indicate the direction of flow. Noteworthy is that these vectors are portrayed in relation to the velocity scalar to which they respond; hence, a large difference in velocities will result in a large difference in arrow size. Additionally, the presence of potential dead spots becomes apparent as visible with darker blue regions in A2, B2 and C2. Moreover, eddying currents are noted by the vector arrows observed in A1. Consistent with the experimental findings, these eddying currents, low-flow regions, and dead spots are predominantly observed near the walls of the unit. Similar views are provided for the medium and high flow systems in Figures 5.12 and 5.13, respectively.

An intriguing observation is that the model exhibits a distinct velocity profile for the low-flow system, contrasting with the medium and high-flow systems. The latter systems display a noticeable s-shape flow profile that is absent in the low-flow system. In contrast, the experimental velocities for all three flow systems demonstrate the pronounced s-shape airflow pattern as visible in Table 5.7. This profile contributes to the formation or intensification of eddying currents, regions with low flow, and dead spots near the walls. The development of a unique profile can be attributed to the way the air is drawn through the vortex chamber and connecting pipe, as well as the design of the air inlets and the shape of the unit. Furthermore, similar regions with low flow are observed in the region below where the fan-side and other-side inlets meet in the middle of the fluidizing box and the vicinity where the vortex flow interacts with the upward airflow current (this is noted with the dark blue regions in image A2).

5.2.7 Discussion

Across all three flow intensities (low, medium, and high), the model demonstrates accurate predictions regarding the magnitude and direction of velocities within both inlets and connecting pipe. This is evidenced by the high R^2 values and the corresponding low RMSE statistic specific to these sections. However, less precise predictions are observed for the velocities simulated in the fluidizing box. The desired high R^2 values, coupled with the undesired high RMSE values relative to the average velocity in the fluidizing box, indicate that the model's predictions in this region are inadequate. Nonetheless, it is noteworthy that these predictions consistently exhibit a constant bias, as evidenced by the high R^2 values. Despite the suboptimal performance of the

predictions, the predictor strongly influences the observed value. The underlying issue lies in the model's inability to fully capture this influence within the fluidizing box (Wheeler, 2021). Interestingly, the absolute error of the RMSE and average velocity in the fluidizing box increases with increasing suction fan setting. This indicates that the model more accurately predicts the velocities at the higher flow settings.

An important observation is that both the observed and simulated data exhibit consistent trends of higher and lower air speeds developing across the length, width, and height of the fluidizing chamber. However, there are notable disparities between the modelled and experimental velocities in specific regions. The model consistently tends to overestimate the velocity near the other-side wall, while simultaneously underestimating the velocity at the fan-side wall. In contrast, the experimental velocities demonstrate the highest values in the centre of the fluidizing chamber. Moreover, slightly higher inlet velocities are consistently observed in the modelled flow for the other-side inlet when compared to the experimental flows obtained.

These observations suggest that the model produces a more pronounced s-shape velocity profile compared to the experimental data. Since the formation of the s-shape flow profile is attributed to the development of a vortex in the vortex chamber and connecting pipe, it appears that the model fails to fully capture the complex interactions between the vortex and the upward-flowing air. Simulating the interaction between an upward uniform suction flow and a vortex presents several challenges due to the complex nature of the flow phenomena involved. Some reasons why it is difficult to accurately simulate this interaction include:

- **Turbulence modelling:** The experimental velocities correspond to Reynolds numbers exceeding 2,800, indicating that the flow can be classified as transitional or fully turbulent. Turbulence is a highly intricate phenomenon that poses significant challenges in achieving accurate modelling (Wilcox, 2006). Numerous turbulence models have been developed, each with its own set of assumptions and limitations. In this study, two turbulence models, namely the K-Epsilon and Reynolds Stress models, were investigated. A comparison of these models resulted in an R^2 value of 0.99 and an RMSE value of 0.24, indicating excellent agreement. Based on its capability to simulate highly swirling or strongly separated flows, the Reynolds Stress model was selected as the preferred turbulence model (Fernandez, 2019). However, it is important to acknowledge that the velocities exhibit regions that fall within the transitional flow regime. These regions may introduce additional complexities, as different mathematical formulas are employed for these conditions. Additional or more specific physics models may be required to accurately model transitional conditions along with refined meshing and specific changes to the

solution algorithm settings (Johansson, 2022). Similar observations are made by Wang and Chen (2009), however, the authors state that RANS models were good for simple transitional flows but not complicated ones, which clarifies the accuracy of the Reynolds Stress model in determining the inlet flows even though they are considered transitional and the difficulty in predicting accurate velocities for the complex flow profile of the fluidizing box. The fact that model accuracy increases with increased flow intensity in the fluidizing box and exhibits good predictive capability in the connecting pipe can be linked to the flow leaning toward fully turbulent flow when higher velocities are present and the RANS model being able to better determine the flow.

- Grid resolution and numerical stability: Resolving the fine-scale features of the vortex and the flow field is crucial for capturing the detailed interactions (Oberkampf and Roy, 2010). However, simulating these fine-scale features requires a high grid resolution, which can be time-consuming and require high-speed computing power. Additionally, maintaining numerical stability becomes challenging when dealing with sharp flow discontinuities or high gradients associated with vortex structures (Ferziger *et al.*, 2020; Tsoutsanis *et al.*, 2015). Moreover, refined meshing is one suggestion for areas of transitional flow (Johansson, 2022; Wang and Chen, 2009).
- Vortex dynamics: Vortices are dynamic structures that can undergo deformation, merging, or splitting depending on the flow conditions (Saffman, 1992). Capturing the accurate evolution of the vortex structure and its interactions with the surrounding flow is a complex task (Zhou *et al.*, 2020). Simulating the intricate details of vortex dynamics, such as the formation of secondary vortices, vortex shedding, or vortex breakdown (van Jindelt *et al.*, 2016), requires robust numerical methods and high-resolution simulations (Mimeau and Mortazavi, 2021).

5.2.8 Conclusion and Recommendations

In general, the simulated velocities exhibit good agreement with the experimental velocities measured in the suction nozzle, except for notable disparities in the velocity magnitudes observed within the fluidizing chamber. These findings provide a comprehensive understanding of the velocity profile, encompassing air speed and flow direction. Such insights are valuable for understanding particle movement within the separating unit, facilitating optimal system design, establishing operating parameters, and troubleshooting. However, further research efforts should be dedicated to the following areas:

- Simulation and model: To improve the accuracy of velocity predictions within the fluidizing box, it is advisable to explore not only turbulence models specifically tailored to capture

the interaction between the upward airflow and the vortex, but also models accurate for the transition flow regime. Combining different turbulence and transitional models, refining the meshing models and changing specific solution algorithm settings in that specific region may also prove beneficial.

- Unit design: The current design of the inlet and vortex chamber contributes to the development of a pronounced snaking airflow profile, resulting in significant dead spots and eddying currents within the fluidizing chamber. This suboptimal velocity profile may not be conducive to effective particle fluidization. To address this, a potential improvement involves slightly tapering the inlet outward at a 45-degree angle, allowing the velocity profile to develop uniformly across the entire width of the fluidizing chamber and mitigating the low-flow regions near the walls. Additionally, incorporating a lip in the suction nozzle section where the vortex interacts with the upward-flowing air may help reduce the negative influence of the vortex on the velocity profile within the fluidizing chamber.

Addressing these aspects related to simulation and model refinement, as well as unit design optimization, can achieve a more accurate representation of velocity profiles in the fluidizing chamber, leading to improved performance and efficiency in particle fluidization processes.

5.3 CFD simulation of particle flow

As mentioned in Section 5.1, CFD using STAR-CCM+ has the capability to model complex scenarios involving multi-component and multi-phase flows. In the context of multi-component systems, these encompass combinations of distinct chemical species homogeneously mixed at the molecular level. Conversely, multi-phase flows entail scenarios in which different immiscible phases coexist (Siemens, 2021b). In the context of the present investigation, which is centred on the phenomenon of density separation of coal particles within an air medium, it can be aptly characterized as a multi-phase system, with coal particles constituting the solid phase and air serving as the gaseous medium.

Multi-phase dynamics typically centres on two distinct approaches: the Eulerian multi-phase (EMP) approach and the Lagrangian multi-phase (LMP) approach. The distinguishing factor between these two approaches lies in their respective conceptualization of the phase. In the EMP approach, the observer conceptualizes particles, bubbles, or droplets as a continuous medium flowing through a fixed volume. On the other hand, in the LMP approach, the observer traces the trajectories of discrete parcels of particles (or individual particles) as they traverse through both space and time (Vesting *et al.*, 2021b).

In the EMP modelling approach, conservation equations for mass, momentum, and energy are individually addressed for each phase, which necessitates the solution of an augmented number of equations. The interactions between phases are contingent upon the contact area shared between them. Consequently, the length scales of the respective phases become a critical consideration, regardless of whether they manifest as dispersed or stratified flows. The LMP model is a sub grid model specifically designed for simulating dispersed phases as they traverse through a continuous phase. This approach entails the solution of equations of motion for representative parcels of the dispersed phase, modelled as injectors, as they propagate through the system. LMP is particularly advantageous when the predominant flow within the system is primarily governed by the continuous phase, and the dispersed phase constitutes a relatively small fraction of the total mass. (Vesting *et al.*, 2021).

5.3.1 Lagrangian multi-phase simulation of particles

Complementing the airflow model expounded upon in Section 5.2, the Lagrangian Multiphase (LMP) modelling methodology was employed to replicate particle behaviours within the separation unit, utilizing the STAR-CCM+ software platform. This simulation endeavour entailed the analysis of particle trajectories, velocities, and residence times, with the objective of elucidating the dynamics of particle motion, speed, and retention throughout distinct segments of the suction

nozzle while discerning any emerging patterns for a comparison with the single and multiple particle tracer tests conducted (as described in Chapter 4, Section 4.5).

Figure 5.14, presented herewith, showcases graphical representations of particle trajectories within the suction nozzle. The simulated conditions involved particles with a diameter of 6.7 mm and a specific gravity of 1.6, introduced into the system at a rate of 5.0 particles per second, alongside a suction fan operating at a frequency of 45 Hz. These parameters correspond to an airflow velocity of 19.8 m/s at the fan-side (FS) inlet, a pressure outlet of -3000 Pa, and a residence time of 120 seconds. In Figure 5.14, images designated as A and B provide front views from the other-side (OS) air inlet and the fan-side (FS) air inlet, respectively. Images denoted as C and D offer side views from the connecting pipe side and a contrasting perspective, respectively.

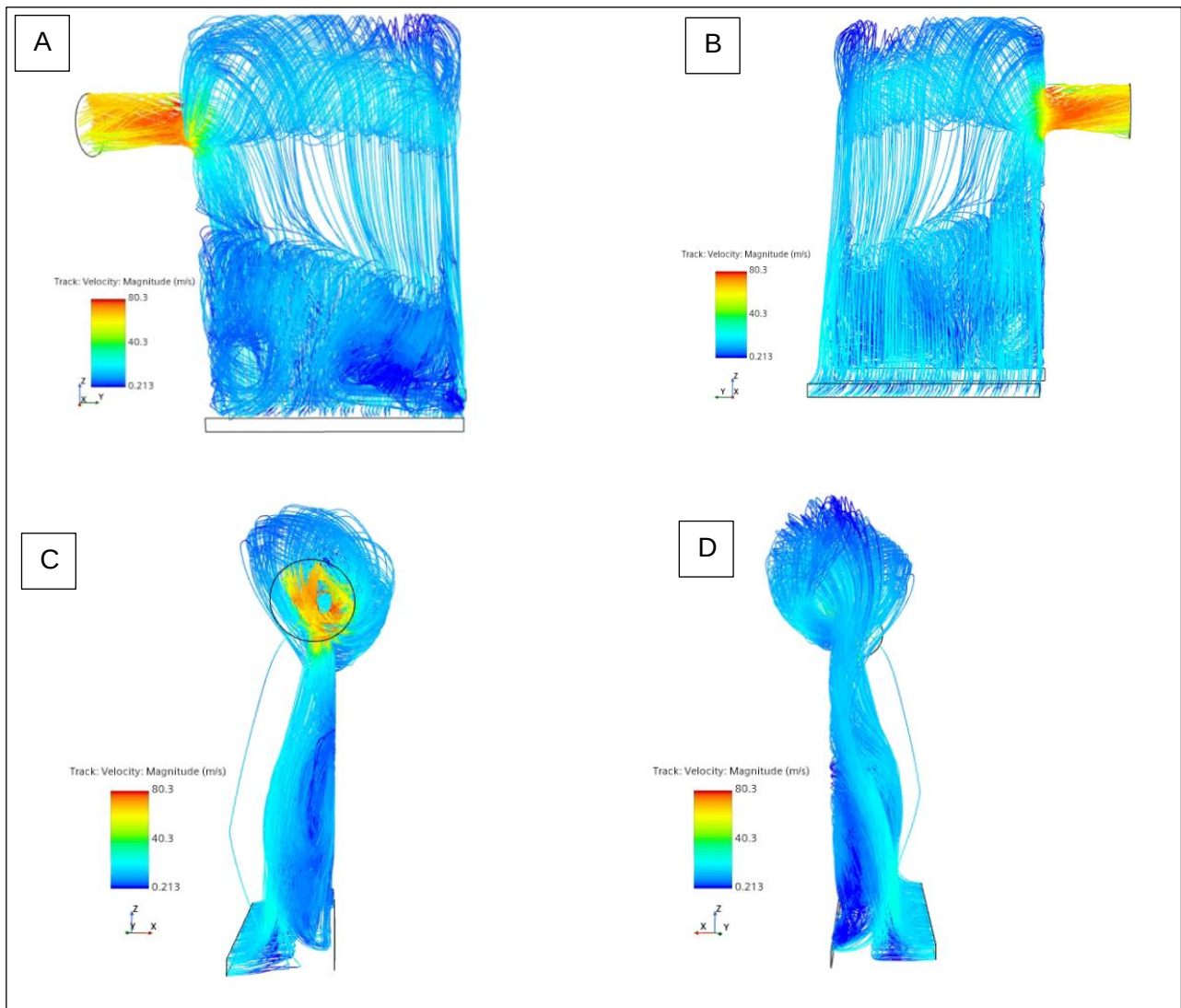


Figure 5.14: OS (A), FS (B) and side views (C and D) of the suction nozzle illustrating particle velocity tracks.

As discernible from the diverse perspectives of the suction nozzle presented in Figure 5.14, the particles enter horizontally from the FS inlet at a velocity of 19.8 m/s, and their behaviour subsequently manifests into three distinct patterns. First, a subset of particles ascends, exhibiting a slight curvature toward the OS wall, maintaining a velocity of 19.8 m/s. These particles enter the vortex chamber, circulate therein at similar speeds, and ultimately exit through the connecting pipe, attaining elevated velocities ranging from 40–80 m/s.

A second group of particles continuously circulate within the lower portion of the fluidizing box towards the OS wall and either lift to be captured or remain in the fluidized state. This alludes to the semi-fluidized bed observed to form in the lower part of the fluidizing box in multiple particle systems. The circulating motion of the particle tracks may be indicative of a vigorously bubbling type of fluidization that may aid the particles that are lifting into the vortex chamber.

Lastly, some particles, upon entry into the system, remain confined to the conveyor plate with minimal movement and do not become entrained within the fluidized flow. It is noteworthy that no instances of particles captured within the vortex returning to the fluidizing box are observed. This absence of particle re-entry may be attributed to the optimized airflow characteristics selected, which appear to align with the specific particle properties inherent to this simulation.

Notably, these different simulated behaviours are evident among particles possessing identical properties. This observation underscores the pivotal role played by the air velocity profile within the fluidizing box in shaping particle trajectories. Consequently, it becomes evident that particle attributes, such as size, shape, and density, while influential, do not singularly dictate the fluidization and separation characteristics. Additional factors, including the air velocity profile, are equally instrumental in determining the observed particle dynamics within the system. This finding is corroborated by the theory of fluidization of particles as described in Section 4.2 from the works of Kunii and Levenspiel (2001).

Figure 5.15 provides magnified views of the particle tracks in the fluidizing box (A and B), vortex chamber (C) and an image of the front OS view with solid particles displayed (D).

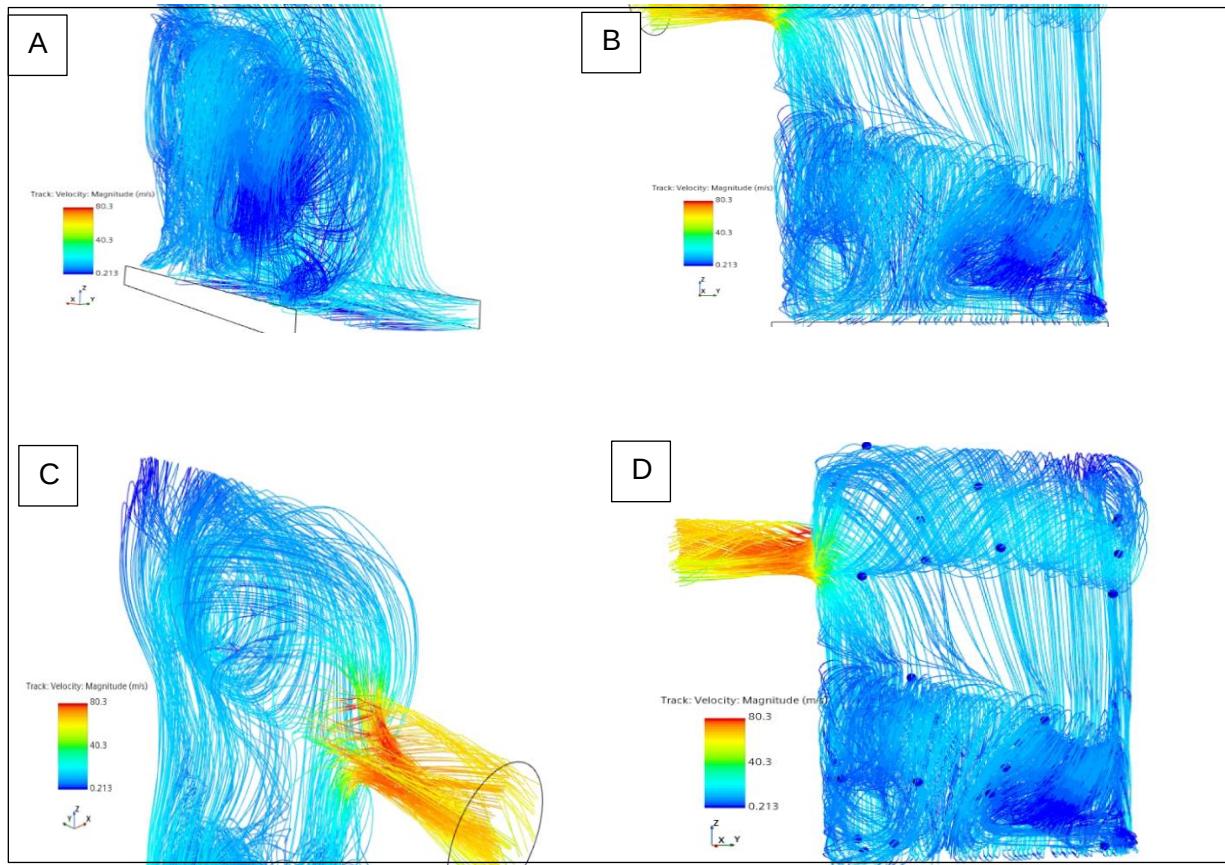


Figure 5.15: Magnified views of the particle tracks in the fluidizing box (A and B), vortex chamber (C) and an image of the front OS view with solid particles visible (D).

The simulated particle behaviours closely mirror the observations made during the particle tracer tests, which were conducted and comprehensively detailed in Chapter 4, Section 4.5. In the context of the tests, the trajectory of a single particle as it traversed the fluidized box appeared to exhibit random motion. However, the particle tracks generated through simulation reveal that this apparent randomness can be categorized into three distinct behaviours for particles of identical properties. These behaviours include: i) particles remaining in a vibrating state on the conveyor plate, ii) particles engaging in a circulating fluidization pattern within the fluidizing box, and iii) particles ascending and subsequently being captured within the vortex chamber before being expelled through the connecting pipe. Moreover, comparable behaviours were identified between the simulation results and the outcomes of the individual particle tracer tests. These observations align with the specific aspects of horizontal particle entry, the circulation of particles within the vortex chamber, and the subsequent acceleration to exit through the connecting pipe.

The individual particle tracer tests, conducted under identical airflow conditions and with particles possessing matching properties, revealed a capture rate of 63% within 27–120 seconds. The observed particle movements corresponded closely with the behaviours. Specifically, it was observed that 25% of the particles entering the system remained on the conveyor plate for

durations ranging from 5 to 115 seconds before undergoing fluidization. However, only half of this subset ultimately transitioned into a fluidized state and was subsequently captured. Furthermore, circulating motion, encompassing lifting, falling, and spinning, was evident in 75% of the particles. This observation further shows that approximately 7% of the particles remained fluidized without being captured within the vortex. This consistent alignment between the tracer test results and the simulated particle tracks underscores the notion that certain particles either remain stationary on the conveyor plate or enter a circulating fluidized state, either before or in the event of capture within the vortex, as previously indicated by the simulation results and visible in the particle tracks. Figure 5.16 provides a track of the residence time.

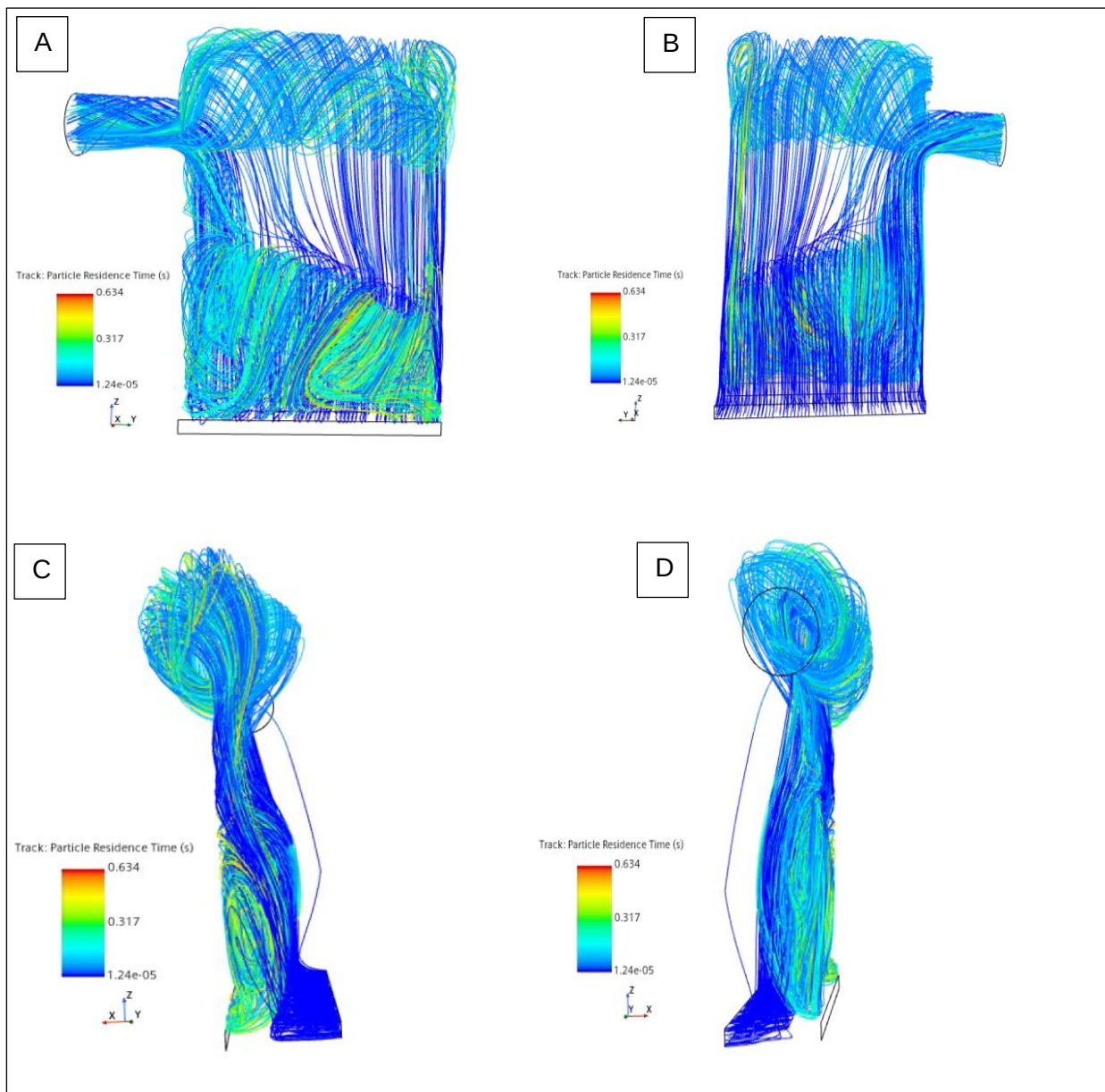


Figure 5.16: OS (A), FS (B) and side views (C and D) of the suction nozzle illustrating particle residence time tracks.

As depicted in Figure 5.16, the simulated particle tracks pertaining to residence time are presented in the same perspectives as Figure 5.14. Images designated as A and B provide front views from the other-side (OS) air inlet and the fan-side (FS) air inlet, respectively. Images denoted as C and D offer side views from the connecting pipe side and a contrasting perspective, respectively. These visualizations offer a notable insight: particles within the system exhibit continuous motion regardless of their position. None of the particles linger in any position within the suction nozzle for a duration exceeding 0.63 seconds. This observation underscores the dynamic nature of particle interactions, not only among themselves but also with the unit walls, as expounded upon in Chapter 4, Section 4.

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CHAPTER 6: DRY BENEFICIATION OF +6.7-13.2 MM COAL (PAPER 3)

Within this chapter, the included paper titled “Air-gravity beneficiation of +6.7-13.2 mm Southern African coal using a combination of suction and vortex fluidization” furnishes insights into the capacity of the laboratory-scale separation unit resembling SEP-AIR to effectively beneficiate small coal particles ranging from 6.7 mm to 13.2 mm in size, also referred to as pea-size. The paper illuminates the underlying process characteristics that dictate the mechanics of this separation mechanism.

6.1 Air-gravity beneficiation of +6.7-13.2 mm Southern African coal using a combination of suction and vortex fluidization (Paper 3)

Contribution by authors

As a postgraduate student, Miss N. Hughes undertook this research project under the mentorship of Prof. M. le Roux and Prof. Q.P. Campbell. The study's scope and rationale were established by Prof. le Roux and Prof. Campbell. The experimental setup adhered precisely to manufacturer specifications and was devised by Miss Hughes in collaboration with technical support personnel from North-West University. Miss Hughes was responsible for executing the experimental procedures, entailing data collection and subsequent analysis. The outcomes and ensuing discussions resulted from comprehensive consultations involving Miss Hughes, Prof. le Roux and Prof. Campbell. Following these consultations, the work underwent a meticulous revision process, refining it for potential publication in a peer-reviewed journal. The primary composition of the manuscript was authored by Miss Hughes, benefiting from the editorial input of Prof. le Roux.

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Air-gravity beneficiation of +6.7-13.2 mm Southern African coal using a combination of suction and vortex fluidization

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6.1.1 Abstract

This study focused on the laboratory-scale beneficiation of +6.7-13.2 mm coal using a SEP-AIR unit that integrates suction fluidization and vortex capturing. The investigation utilizes three coal samples: WB1, WB2 (from the Waterberg coalfield in Limpopo, South Africa), and MOAT (from the Moatize coalfield in Tete, Mozambique), yielding respective separation efficiencies (EPMs) of 0.25, 0.05, and 0.04. Yields of 81%, 81%, and 82% were achieved for WB1, WB2, and MOAT, respectively. Improvements were observed in product ash values: WB1 decreased from 36% in the feed to 26% in the product, WB2 decreased from 20% to 10%, and MOAT decreased from 17% to 12%. Calorific values increased from the feed's 22, 28 and 30 MJ/kg for WB1, WB2 and MOAT, respectively, to 26 MJ/kg for WB1 and 32 MJ/kg for both WB2 and MOAT.

In tandem with the variation in coal qualities tested, various air flow settings were explored. Analysis of Variance (ANOVA) tests yielded certain insights, underscoring the dominant role of coal feed quality in separation efficiency and ensuring product quality. Conversely, air speed notably impacted product yield, with higher air speeds correlating to increased yields. However, adjustments to the airspeed had a limited influence on product quality.

Keywords: Air-gravity separation, suction fluidization, beneficiation, small coal.

6.1.2 Introduction

Coal plays a pivotal role in global energy production, and its significance for economic development cannot be overstated. To enhance its quality and mitigate environmental impacts, coal necessitates processing to eliminate gangue minerals (van Houwelingen and De Jong, 2004; Fu *et al.*, 2019). This endeavour enhances coal quality, curbs greenhouse gas emissions, and diminishes transportation and waste disposal expenses.

Presently, coal preparation predominantly relies on the more effective wet separation methods, which, however, demand substantial water usage and incur high operational costs (Davaasuuren *et al.*, 2016). However, numerous countries, including China, India, South Africa, Russia, and

Turkey, confront water scarcity issues, rendering industrial water use approval increasingly challenging (Lv *et al.*, 2018; Zhou *et al.*, 2019; Zhu *et al.*, 2019). Consequently, regions with remote, underdeveloped, arid conditions or extended freezing periods might find wet processing infeasible. Hence, the exploration of alternative dry beneficiation processes gains traction.

Dry beneficiation techniques offer distinct advantages over wet methods, making them appealing to the coal industry. These advantages include addressing water scarcity, incurring lower capital and operational costs, reducing transportation expenses, minimizing environmental impacts tied to water usage and pollution, and facilitating coal mining in arid areas (Von Ketelhodt and Bergmann, 2010; Jambal *et al.*, 2022) as well as remote or under-developed regions.

Given the emphasis on economic and environmental aspects, there has been a surge in research endeavours aimed at addressing the shortcomings of dry coal beneficiation, including efficiency, capacity, and yield. Extensive investigation has revitalized previously disregarded methods, such as pneumatic concentrators (Weinstein and Snoby, 2007; Chavaldi *et al.*, 2016; Davaasuren *et al.*, 2016; Wotruba *et al.*, 2010) and sensor-based sorters (Manoucherchi, 2003). Advanced techniques, including fluidized bed separators such as the FGX (De Korte, 2013), and air dense medium fluidized bed (ADMFB) (Chen and Yang, 2003; Zhang *et al.*, 2014; Hughes *et al.*, 2017; Peters *et al.*, 2020; Zhang *et al.*, 2020; Diedericks *et al.*, 2022), suction fluidization treatments such as the SEP-AIR (Stepanenko, 2016a; Stepanenko, 2016b), AMSEP (Moszko, 2016) and Negative Pressure Pneumatic Separator (NPPS) (Stanzcyk, 2020; Stabczyk *et al.*, 2021), and winnowing (Morgan *et al.*, 2019, 2020, 2021; Sakhre *et al.*, 2018), have emerged, underscoring the ongoing pursuit of optimized dry beneficiation approaches.

6.1.3 Background and motivation

Among the emerging dry beneficiation techniques, the SEP-AIR process is a promising solution for the challenges inherent in dry coal beneficiation. Analysis of Northern Hemisphere coal types highlight that the SEP-AIR method effectively handles coal particles between 1 to 100 mm, attaining substantial processing capacities of 45 to 200 tph. Notably, this process achieves high product yields, ranging from 85% to 95%, alongside D_{50} densities spanning 1.78 to 1.90 and Ecart Probable Mooyen (EPM) efficiencies ranging from 0.1 to 0.17 (Stepanenko, 2016a; Stepanenko, 2016b). These outcomes align with the objectives of enhancing dry processing approaches, particularly refining processing for finer grinds, while maintaining elevated capacities and yields. The EPM and cut-point density align with the ranges seen in other dry processing methods. Furthermore, the notable absence of a supplementary dense medium requirement, as observed in the case of certain competitive methods, establishes the SEP-AIR as a cost-effective and

efficient approach. Additionally, the SEP-AIR has been intentionally tailored to tackle concerns like dust management and susceptibility to moisture (Stepanenko, 2016a; De Korte, 2021).

Some investigations have been carried out regarding South African coal beneficiation using the SEP-AIR method, leading to enhancements in product quality and resulting in yields spanning from 85% to 93%. The EPM ranges from 0.1 to 0.17, while cut-point densities vary between 1.78 and 1.92. These studies encompass diverse particle size ranges, ranging from 1 mm to 50 mm. For instance, a study focused on particles within the 6.0–13.0 mm size range yielded an EPM of 0.1, 87.3%, and a cut-point density of 1.92 (De Korte, 2021). This article builds on the latter study and specifically examines the SEP-AIR's capacity to beneficiate Southern Hemisphere coal types between +6.7 and 13.2 mm.

6.1.4 Experimental

To evaluate the feasibility of utilizing a suction fluidization technique akin to the SEP-AIR approach in coal beneficiation, a set of efficiency tests was conducted using a laboratory-scale apparatus. The investigation concentrated on coal particles ranging from 6.7 to 13.2 mm in size and three different coal qualities WB1, WB2 and MOAT.

6.1.4.1 Process description

The SEP-AIR uses suction fluidization with air as a medium in combination with vortex particle capturing. Particles are subjected to an upward suction force and undergo fluidization and stratification based on specific attributes such as size, shape, and density. Particles possessing the requisite fluidization characteristics are entrapped by the vortex formation and subsequently accelerated and guided toward the collection point, forming the desired product. Conversely, particles that fail to be ensnared by the vortex formation remain within the fluidizing chamber and are subsequently discharged as discard material (Stepanenko, 2016a; Stepanenko, 2016b).

6.1.4.2 Equipment

The separation apparatus comprises three main sections: i) the feed section, incorporating a manual conveyor for particle introduction; ii) the separation unit, where particle stratification and separation are enacted; and iii) the centrifugal fan, responsible for generating the suction force and subsequent airflow for the separation medium. The separation unit is further subdivided into four sections, each tailored to fulfil a distinct function:

- i. The fluidizing box, a rectangular prism that facilitates upward airflow, inducing particle fluidization (Number 1 in Figure 6.1).

- ii. The vortex chamber, a circular conduit attached to the fluidizing chamber, prompting vortex formation to capture sufficiently fluidized particles (Number 2 in Figure 6.1).
- iii. The connecting pipe, a narrower circular conduit linked to the vortex chamber, expedites the vortex and propels the captured particles (Number 3 in Figure 6.1).
- iv. The collection bin, a rectangular prism, serves to gather the particles expelled from the connecting pipe (Not portrayed in Figure 6.1).

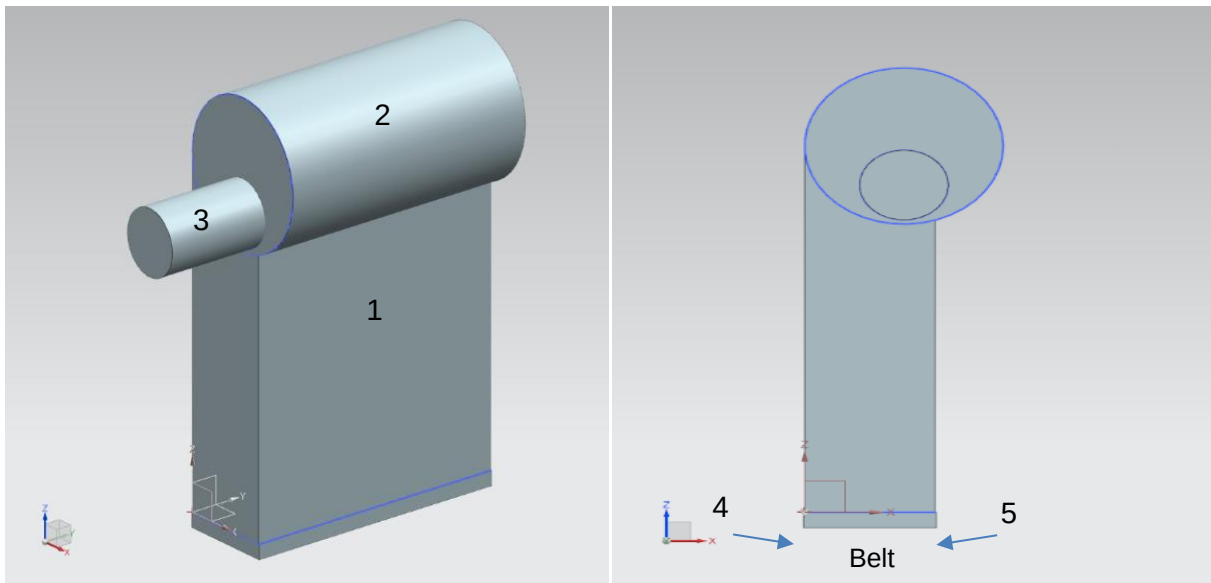


Figure 6.1: Schematic of the laboratory-scale suction nozzle from a trimetric view (left) and front view (right).

Figures 6.1 illustrates the components of the apparatus, including the fluidizing box (1), vortex chamber (2), connecting pipe (3), and air inlets (referred to as ‘fan-side’ – number 4 and ‘other-side’ – number 5). The suction fan draws air horizontally through the inlets on both the fan-side and other-side. This incoming air ascends within the fluidizing box, generating a vortex within the chamber. The airflow gains momentum as it traverses the connecting pipe. Ultimately, the airflow exits into the collection bin (Depicted in Figure 6.2).

Particles are introduced beneath the suction nozzle and become fluidized in the fluidizing box. Among these particles, those reaching an adequate elevation become entrapped within the vortex and are subsequently propelled through the connecting pipe into the collection bin, constituting the desired product. Conversely, particles that do not attain fluidization continue past the suction nozzle and are designated as discard.

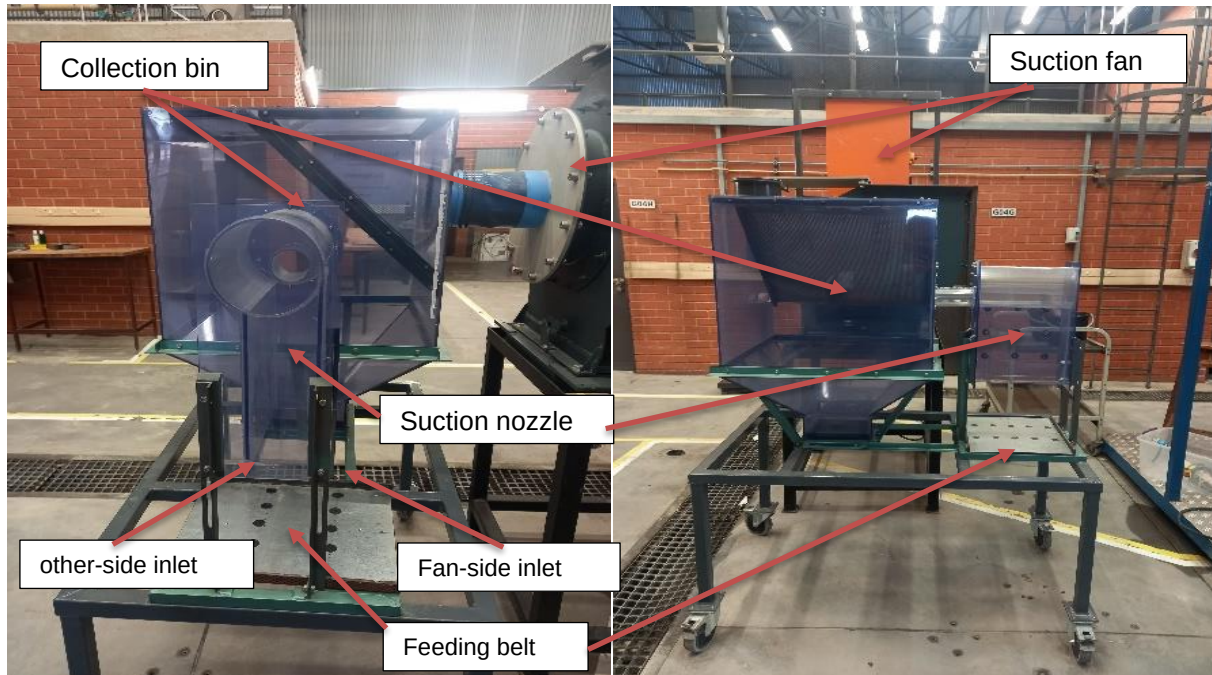


Figure 6.2: Separating unit with suction nozzle, feeding belt, suction fan and collecting bin labelled.

The fluidization characteristics within the suction nozzle, comprising the fluidizing box, vortex chamber, and connecting pipe, predominantly derive from the aerodynamic behaviour of the airflow within the system. This airflow is sustained through the coordination of the suction fan and the elevation of the fluidizing chamber relative to the conveyor setup. To ensure optimal operational efficacy, the elevation of the fluidizing chamber is determined based on the particle size spectrum, necessitating it to be at least 1.5 times greater than the largest particle encompassed within that specific size range (A.I. Stepanenko, CEO Gormash Export, personal communication, September 2019). In the context of the investigated particle size range, spanning +6.7-13.2 mm, the inlet height was 20 mm.

6.1.4.3 Materials

The present study employed three distinct coal qualities: two derived from different sampling sites in the Waterberg coalfield in Limpopo, South Africa, denoted as WB1 and WB2, and one sourced from the Moatize coalfield in Tete, Mozambique, referred to as MOAT. The coal samples underwent a series of preparation steps, including air drying for the sample to reach inherent moisture, crushing, and sieving, to yield dry samples with a particle size range of +6.7-13.2 mm. To assess the quality of the feed samples in terms of moisture content, ash value, and calorific value, proximate and bomb calorimetric analyses were performed. Furthermore, the feed coal's particle size distribution (PSD) was evaluated using sieving, and the density distribution was determined using the standard float and sink tests. The findings from these initial analyses are presented in Table 6.1.

Table 6.1: Feed quality of the WB1, WB2 and MOAT coal samples under consideration.

Analysis on an air-dried basis	WB1 +6.7-13.2 mm	WB2 +6.7-13.2 mm	Moatize +6.7-13.2 mm
Moisture content (%)	1.47	1.79	1.49
Ash value (%)	36.20	19.63	16.52
Calorific value (MJ/kg)	21.78	28.33	29.56
D ₅₀ cut-point PSD (mm)	9.3	9.7	7.3
D ₅₀ density (kg/m ³)	1630	1470	1440
Near dense material (%)	30	75	80

All three samples demonstrate comparable quality in terms of moisture content. Figure 6.3 visually illustrates the disparities in PSD among the WB1, WB2, and MOAT coal samples. The WB1 and WB2 samples exhibit similar particle size distributions (PSD), as visible by the D₅₀ particle sizes of 9.3 mm and 9.7 mm, respectively, as shown in Table 6.1. Conversely, the MOAT sample displays a greater proportion of smaller particles, as evidenced by its significantly smaller D₅₀ particle size of 7.3 mm (Table 6.1 and Figure 6.3).

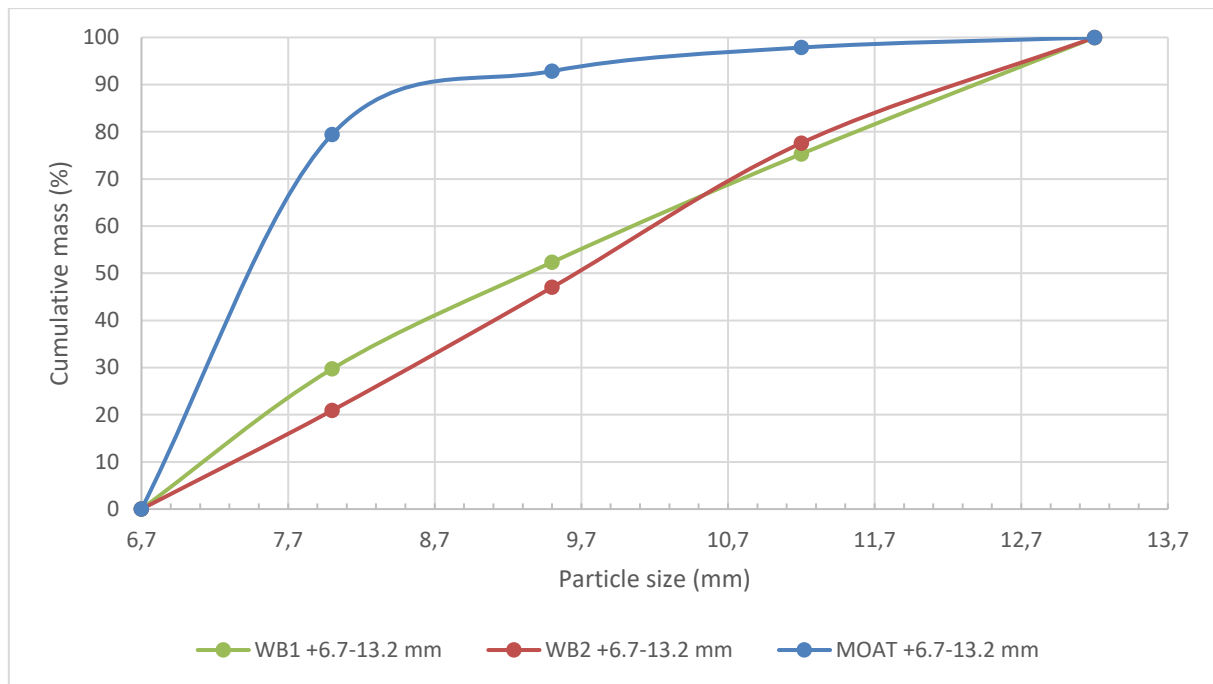


Figure 6.3: Comparison of the PSDs in the feed for the WB1, WB2 and MOAT coal samples.

Both the WB2 and MOAT samples demonstrate similar density distributions with D₅₀ density cut-points of 1470 kg/m³ and 1440 kg/m³ along with 75% and 80% near dense material, respectively. In contrast, the WB1 sample possesses a higher D₅₀ density cut-point of 1630 kg/m³ and a significantly less near-dense material of 30%. A similar trend is observed with the ash and calorific values; the WB2 and MOAT yield similar values of 19.63% and 28.32 MJ/kg, and 16.52% and 29.56 MJ/kg, for ash- and calorific-value respectively, whereas the WB1 sample has a higher ash number of 31.20% and lower corresponding calorific value of 21.78 MJ/kg.

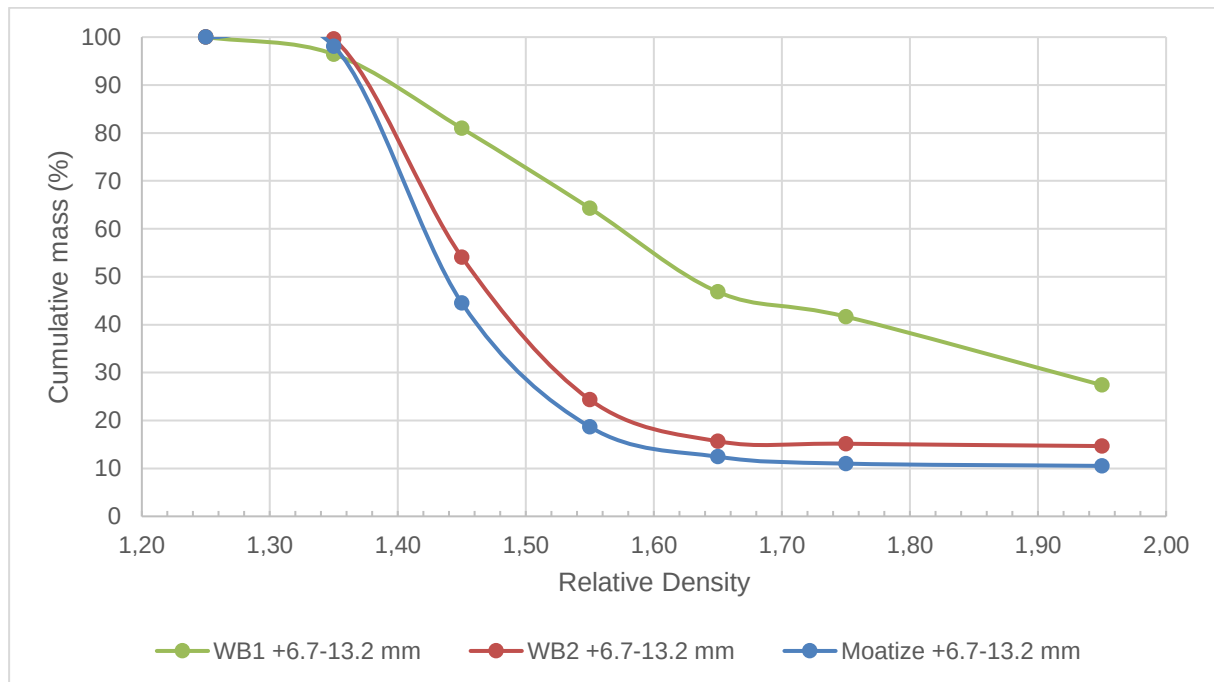


Figure 6.4: Comparison of the density distributions in the feed for the WB1, WB2 and MOAT coal samples.

6.1.4.4 Efficiency tests, significance and repeatability

To evaluate the attained degree of segregation, a series of efficiency tests were executed on the WB1, WB2, and MOAT coal specimens, encompassing five distinct airflow settings. Selected parameters were scrutinized, including the density distribution of the retained product and the rejected fraction, the EPM, organic efficiency and misplaced particles, all determined from the standard float sink analysis.

Additionally, determinations of ash value by proximate analysis, calorific value by bomb calorimetry, and particle size distribution (PSD) by sieving for both the retained product and the rejected fraction were undertaken to glean insights into potential enhancements in quality. Moreover, the single-factor and two-factor Analysis of Variance (ANOVA) tests (Kenton, 2023) were executed to assess significant differences among means in a comparative analysis of relevant variables. The ANOVA test produces two statistics: the p-value and the f-value, indicating statistical significance between data groups' means. These measures were used to ascertain the significance of changing variables like coal feed quality and airspeed. Statistical significance is assumed if the p-value is smaller than the predetermined alpha value of 0.05 and the f-value is larger than the f-critical value, which is also calculated in the ANOVA (Kenton, 2023).

The assessment of replicability for efficiency tests involves analysing the sample mean, standard deviation (SD) and 95% confidence interval (CI) pertaining to product yield and EPM as well as

D₅₀ density and D₅₀ particle size for both retained and rejected fractions. This evaluation employs three repeated tests on the WB2 coal specimen.

Table 6.2: Product quality and process efficiency variables demonstrating repeatability.

Analysis on an air-dried basis	Test 1	Test 2	Test 3	Mean	SD	95% CI
Product yield (%)	54.4	49.2	47.2	50.27	3.03	42.52–57.45
Product D ₅₀ density (kg/m ³)	1440	1440	1440	1440	0.00	1440–1440
Discard D ₅₀ density (kg/m ³)	1490	1600	1480	1523	0.06	1523–1523
Product D ₅₀ size (mm)	8.7	9.0	8.9	8.7	0.12	8.6–8.8
Discard D ₅₀ size (mm)	10.9	11.3	10.9	11.0	0.19	10.8–11.3
EPM	0.05	0.05	0.05	0.05	0.00	0.05–0.05
Particles misplaced to the product (%)	8.1	11.0	11.2	10.1	1.46	8.5–11.8
Particles misplaced to the discard (%)	63.9	42.3	74.0	60.1	13.24	45.1–75.1

The results, presented in Table 6.2 above and Figures 6.5 and 6.6 below, demonstrate that the low standard deviation values and good 95% CIs emphasize the separation unit's consistent capacity to deliver uniform qualities of retained product and discarded fraction while keeping certain operating parameters constant. However, misplacement of the product and discard seem to differ even under similar operating conditions.

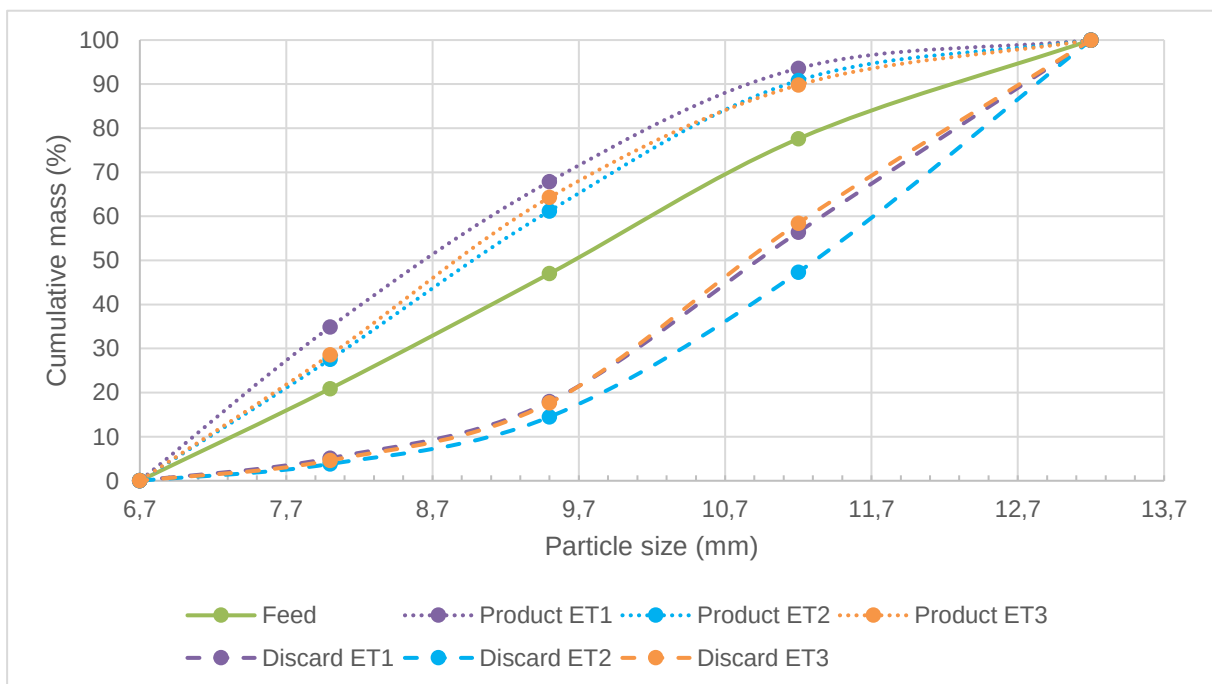


Figure 6.5: Comparison of PSD for the feed, product and discard of repeated efficiency tests (ETs) with WB2.

Figure 6.5 demonstrates repeatability concerning the particle size distribution (PSD) of both the product and discard. This observation is substantiated by the congruent D₅₀ particle sizes, as presented in Table 6.2, alongside standard deviations, and confidence intervals of 0.12 and 0.19 and 8.6–8.8 mm and 10.8–11.3 for the product and discard's PSD, respectively. Furthermore, a consistent particle size separation is evident, as the products obtained from all three repeatability tests consistently exhibit lower PSDs than the feed, while the discard PSDs manifest higher

values than the feed. This observation underscores the propensity of smaller particles to be directed towards the product stream and larger particles to be directed to the discard stream.

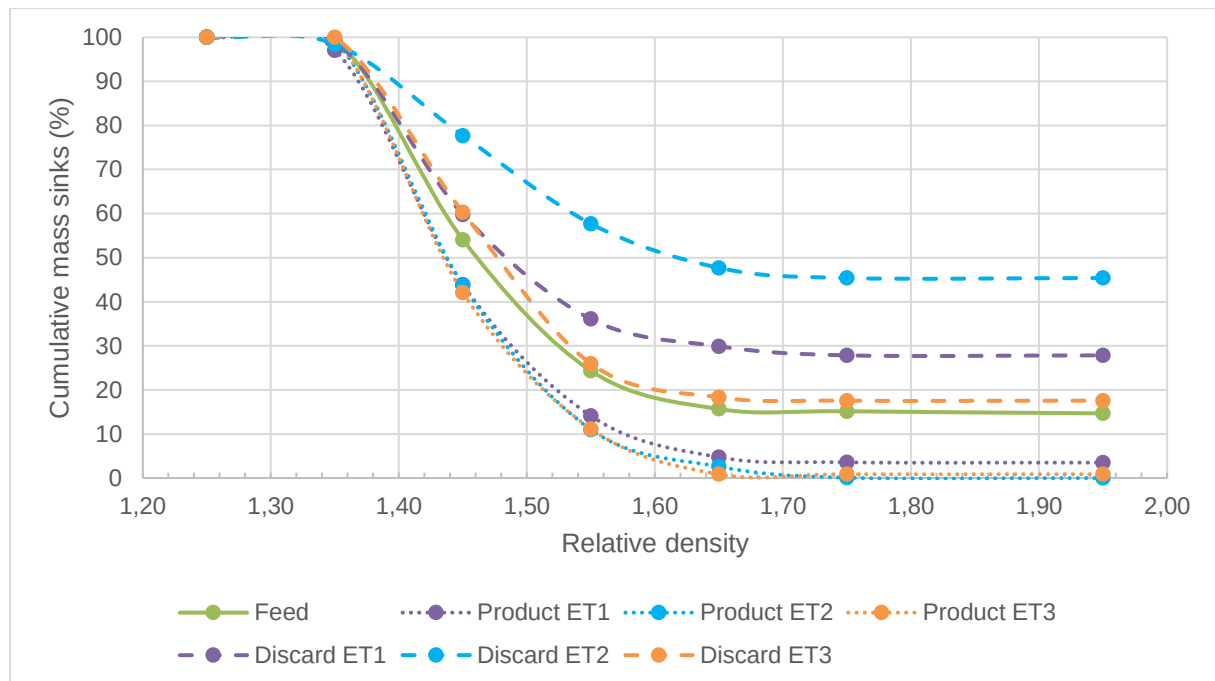


Figure 6.6: Comparison of density profile for the feed, product and discard of repeated efficiency tests (ETs) with WB2.

The density distributions of the product from the three repeated tests exhibit close alignment, as depicted in Figure 6.6, with an average standard deviation of 0.9 for the density distribution and a standard deviation of 0.00 and 0.06 and 100% confidence intervals for the D_{50} densities of the product and discard, respectively. While the D_{50} densities of the three discarded fractions display a low observed standard deviation, Figure 6.6 reveals distinguishable variations within the density profiles, indicating an average standard deviation of 8.2 for the entire density profile. This observation suggests potential disparities in discard density under comparable operational conditions while enabling the attainment of consistent and enhanced product quality. This phenomenon could be associated with misplaced particles, which also exhibit a substantial standard deviation of 13.24 and CI of 45.1–75.1% for the discard fraction. However, the repeat tests demonstrate a comparable number of particles erroneously incorporated into the product for the three repeat tests (standard deviation of 1.46 and CI of 8.5–11.8%).

6.1.5 Results

This section presents the outcomes of efficiency tests conducted on WB1, WB2, and MOAT coals. These tests assess potential improvements in separation efficiency and consequent product quality arising from alterations in both air speed and feed coal quality. The investigation incorporates five distinct suction fan settings. Table 6.3 elucidates in-depth particulars regarding

the fan configurations, encompassing mean velocities at the fan-side inlet, other-side inlet, and interconnecting conduit.

Table 6.3: Suction fan setting and corresponding fan-side, other-side and connecting pipe velocities.

Fan setting (frequency)		Fan-side inlet velocity (m/s)	Other-side inlet velocity (m/s)	Connecting pipe velocity (m/s)
1	30 Hertz (Hz)	12.79	11.86	46.86
2	35 Hertz (Hz)	15.00	14.16	52.87
3	40 Hertz (Hz)	17.09	16.16	60.42
4	45 Hertz (Hz)	18.83	18.24	67.97
5	50 Hertz (Hz)	21.01	19.90	75.52

The investigation's findings are exhibited in Table 6.4, which clearly expositions the attributes concerning feed, product, and discard quality and process efficiency. This analysis spans the five distinct suction fan configurations (described in Table 6.3) for the WB1, WB2, and MOAT coal specimens.

Table 6.4: Efficiency test results obtained at different suction fan settings for WB1, WB2 and MOAT coal.

Analysis on an air-dried basis	WB1+6.7-13.2 mm										
		30 Hz		35 Hz		40 Hz		45 Hz		50 Hz	
	Feed	P ^a	D ^b	P	D	P	D	P	D	P	D
D ₅₀ PSD (mm)	9.3	7.5	9.7	7.6	10.6	8.5	10.6	9.3	10.6	9.3	-
D ₅₀ SG ^c	1.63	1.46	1.63	1.50	1.64	1.53	1.95	1.63	1.95	1.63	-9
AV ^d (%)	36.20	18.59	38.68	22.55	37.63	26.03	69.32	33.36	61.55	36.20	-9
CV ^f (MJ/kg)	21.78	28.74	20.80	27.18	21.22	25.80	8.70	22.90	11.77	21.78	-9
Yield (%)	-	12.35	87.65	8.84	91.16	80.84	19.14	95.92	4.08	100	0.00
EPM	-	0.11	-	0.12	-	0.25	-	0.25	-	0.25	-
MP ^e (%)	-	35.71	22.60	27.27	39.23	47.40	0.00	49.01	0.00	46.83	0.00
Analysis on an air-dried basis	WB2+6.7-13.2 mm										
		30 Hz		35 Hz		40 Hz		45 Hz		50 Hz	
	Feed	P	D	P	D	P	D	P	D	P	D
D ₅₀ PSD (mm)	9.7	7.3	9.5	7.8	9.8	8.8	10.9	9.5	11.1	9.3	11.3
D ₅₀ SG	1.47	1.41	1.48	1.42	1.48	1.45	1.51	1.44	1.95	1.44	1.95
AV (%)	19.63	13.42	20.82	14.45	20.40	17.56	22.10	9.68	62.61	16.52	50.32
CV (MJ/kg)	28.33	30.78	27.86	30.37	28.02	29.14	27.35	32.26	11.35	29.56	16.20
Yield (%)	-	16.08	83.92	13.08	86.92	54.40	45.6	81.20	18.80	90.80	9.2
EPM	-	0.05	-	0.05	-	0.05	-	0.05	-	0.06	-
MP (%)	-	7.25	78.92	6.98	82.11	8.11	63.92	14.09	18.42	15.76	30.00
Analysis on an air-dried basis	MOAT +6.7-13.2 mm										
		30 Hz		35 Hz		40 Hz		45 Hz		50 Hz	
	Feed	P	D	P	D	P	D	P	D	P	D
D ₅₀ PSD (mm)	7.3	8.1	7.5	7.3	7.5	7.3	7.5	7.5	7.9	7.5	8.0
D ₅₀ SG	1.44	1.41	1.45	1.42	1.46	1.40	1.63	1.42	1.95	1.43	1.51
AV (%)	16.52	13.50	17.91	15.78	18.46	11.99	36.61	13.32	54.26	15.49	24.37
CV (MJ/kg)	29.56	30.75	29.01	29.85	28.79	31.35	21.62	30.82	14.65	29.56	26.45
Yield (%)	-	31.6	68.4	72.4	27.6	81.6	18.4	92.4	7.6	88.4	11.6
EPM	-	0.05	-	0.04	-	0.04	-	0.05	-	0.06	-
MP (%)	-	7.25	78.92	6.58	55.24	9.46	32.86	11.22	13.33	19.31	0.00

^a P = Product

^b D = Discard

^c SG = Specific gravity
^d AV = Ash value
^e MP = Misplaced particles
^f CV = Calorific value
^g the entire feed reported to the product, hence there is no discard portion

6.1.6 Analysis of variance (ANOVA)

The two-factor ANOVA provides insight into the interaction of the coal feed quality with process efficiency (i.e., EPM, yield, and misplaced particles) and product and discard quality (i.e., ash value, calorific value, cut-point density, and cut-point particle size) for all suction fan settings tested. The results of the ANOVA test are provided in Table 6.5.

Table 6.5: Two-factor ANOVA with replication for the interaction of coal feed quality and suction fan setting with process efficiency and quality of product and discard streams.

	Indicator of statistical significance			
	p-value	Alpha value	f-value	f-critical value
Process efficiency	1.5E-04	0.05	4.45	2.03
Product quality	1.2E-09	0.05	15.17	2.29
Discard quality	0.51	0.05	0.90	2.29

The findings presented in Table 6.5 reveal statistically significant impacts of coal feed quality and suction fan setting on process efficiency and product quality meeting the requisite criteria in terms of p-values and f-values. Notably, the computed p-values are smaller than the established alpha value, while the derived f-values exceed the critical f-values. This signifies that variations in coal feed quality and suction fan setting are prone to engender differences in EPM, yield and particle misplacement of the process as well as ash value, calorific value, cut-point density and particle size of the product. On the other hand, the ANOVA results show that discard quality is not affected by coal quality or suction fan setting.

A focused examination of the discrete influences of airspeed and coal feed quality on both process efficiency and product quality offers a heightened understanding of the separation unit's capabilities. To explore this, single-factor ANOVA tests were performed to discern the interplay among the chosen variables. These examinations are elaborated upon in the subsequent sections.

6.1.7 Suction velocity

Augmenting the suction force of the centrifugal fan induces a proportional rise in airflow magnitude, as evidenced in Table 6.3. Consequently, discernible disparities in product yield emerge across WB1, WB2, and MOAT coal samples. Specifically, an increase in suction force corresponds to an elevation in product yield. The ash number of the product initially demonstrates an improvement, as evidenced by a reduction in ash number. However, as the suction fan force intensifies, there is a subsequent rise in ash value. This trend persists across all three samples.

Nevertheless, it is important to highlight that the WB1 sample consistently exhibits a continuous increase in ash number as the suction force escalates, unlike the WB2 and MOAT samples, where a notable decline is observed upon reaching the best operational levels before an eventual increase. The EPM and D_{50} density values follow a similar pattern, with an initial improvement observed that subsequently deteriorates as the fan setting increases for all three coal specimens. Notably, differences are observed in the ash value and D_{50} density of the discard as the suction force increases for all three coal samples. Increasing the air speed increases the cut-point density and ash value of the discard indicating that a destoning operation prevails at higher air speeds. This may also provide a reason for the increase in particle misplacement to the product as airspeed increases. Table 6.6 provides a summary of the ANOVA results describing the influence of suction fan setting on variables concerning process efficiency and quality of product and discard.

Table 6.6: Single factor ANOVA for the interaction of suction fan setting with process efficiency and quality of product and discard streams.

	Indicator of statistical significance			
	p-value	Alpha value	f-value	f-critical value
Product yield	1.6E-03	0.05	9.96	3.47
EPM	0.92	0.05	0.22	3.48
Misplaced to product	0.88	0.05	0.29	3.48
Misplaced to discard	0.21	0.05	1.74	3.48
Product ash value	0.81	0.05	0.39	3.06
Product CV	0.42	0.05	1.02	3.06
Product D_{50} density	1.00	0.05	0.97	3.48
Product D_{50} PSD	0.99	0.05	0.09	3.06
Discard ash value	0.04	0.05	3.36	3.11
Discard CV	0.79	0.05	0.43	3.11
Discard D_{50} density	0.90	0.05	0.26	3.11
Discard D_{50} PSD	0.96	0.05	0.15	3.11

In the context of adjusting the suction fan settings, the ANOVA statistical analysis reveals a significant impact on the product yield, supported by a notably low p-value of 1.6E-03, accompanied by an f-value of 9.96, surpassing the critical f-value of 3.47. Manipulating fan settings may not affect separation efficiency (EPM), particles misplaced and qualities of the product (w.r.t. ash value, calorific value, D_{50} PSD and D_{50} density). Interestingly, the ANOVA results show the significance of changing the suction fan setting on the ash value of the discard but not with the corresponding calorific value, D_{50} size or D_{50} density.

Furthermore, the statistical analysis indicates a lack of significance in the influence of varying coal feed qualities on product yield. This is proven by the p-value of 0.63, accompanied by an f-value of 0.49, falling short of the critical f-value of 3.89. This outcome underscores the dominance of airspeed as the determinant of yield, irrespective of particle properties as determined by coal feed quality.

6.1.8 Feed quality

Variations in the quality of feed coal result in discernible differences in variables related to separation efficiency and subsequent product quality. Specifically, regarding EPM, the WB2 and MOAT samples demonstrate analogous values within the range of 0.04–0.06. In contrast, the WB1 specimen exhibits significantly larger EPMs spanning from 0.11 to 0.25. The congruence between WB2 and MOAT can be attributed to their akin feed density profiles, while the lower EPM values are ascribed to their higher content of near-dense materials relative to the WB1 sample. This trend is paralleled in the percentage of misplaced particles within the product. Notably, WB2 and MOAT evince similar behaviour across all five fan settings, whereas WB1 yields comparably higher percentages. Conversely, WB1 displays the lowest percentages of misplaced particles in the discard across all fan settings, followed by MOAT and WB2.

These findings underscore the variability of separation efficiency contingent upon coal feed quality, signifying that particle attributes encompassing size, shape, and density, as well as their interactions with air and unit walls, govern the stratification mechanism. This assertion is reinforced by the outcomes of the ANOVA single-factor test. Table 6.7 provides the ANOVA results describing the influence of coal quality on process efficiency and quality of the product and discard.

Table 6.7: Single factor ANOVA for the interaction of coal feed quality with process efficiency and quality of product and discard streams.

	Indicator of statistical significance			
	p-value	Alpha value	f-value	f-critical value
Product yield	0.63	0.05	0.49	3.89
EPM	1.6E-04	0.05	19.70	3.89
Misplaced to product	9.1E-06	0.05	35.50	3.89
Misplaced to discard	0.51	0.05	0.72	3.89
Product ash value	1.1E-03	0.05	12.76	3.89
Product CV	0.40	0.05	0.98	3.89
Product D ₅₀ density	1.3E-03	0.05	12.24	3.89
Product D ₅₀ PSD	0.11	0.05	2.54	3.89
Discard ash value	0.21	0.05	1.82	3.98
Discard CV	0.55	0.05	0.64	3.98
Discard D ₅₀ density	0.47	0.05	0.82	3.98
Discard D ₅₀ PSD	1.02E-05	0.05	38.94	3.98

Statistically significant correlations between feed coal quality and EPM are established with a p-value of 1.60E-04, an f-value of 19.70, and a critical f-value of 3.89. Similarly, for misplaced particles within the product, coal quality's impact is evident on the product (p-value: 9.1E-06, f-value: 35.49, critical f-value: 3.88), while the particles misplaced to the discard are influenced by airspeed (as outlined in Section 6.1.7).

Furthermore, it is imperative to acknowledge the influence of coal feed quality on product quality with respect to ash value, calorific value, cut-point density and cut-point particle size. Pertaining to the D_{50} density of the product, both WB2 and MOAT exhibit uniformity across all fan settings, ranging from 1410–1450 kg/m³. Conversely, WB1 yields higher densities varying from 1460–1630 kg/m³. This divergence can be attributed to the concordance in density profiles of WB2 and MOAT feed coal. The ANOVA single-factor analysis establishes statistical significance through a p-value of 1.3E-03, an f-value of 12.24, and a critical f-value of 3.89, underscoring the link between coal feed quality and the D_{50} density of the product. Conversely, the D_{50} density of the discard is not affected by coal feed quality with a p-value of 0.47, an f-value of 0.82 and an f-critical value of 3.98.

Regarding the ash number of the product, it is noteworthy that the WB2 and MOAT samples consistently exhibit similar product ash number values across various suction fan settings, while the WB1 sample consistently reports higher product ash values. A significant reduction in ash number is observed for all three samples at a product yield of approximately 80% corresponding to 40 Hz for WB1 and MOAT and 45 Hz for WB2. Subsequently, both the ash number of the product and the discard increase as the suction force is elevated beyond this threshold, with the discard ash number demonstrating a more pronounced increase. Interestingly, the ANOVA single-factor test reveals that only product ash value was affected by coal feed quality with a p-value, f-value, and critical f-value of 1.1E-03, 12.79 and 3.89, respectively.

WB1, WB2 and MOAT exhibit comparable D_{50} particle sizes in the product stream, whereas MOAT features a larger proportion of substantially smaller particles in the discard stream as opposed to the similar D_{50} particle sizes in the discard for WB1 and WB2. The ANOVA single-factor tests validate the interplay between coal feed quality and PSD in the discard (p-value: 1.02E-05, f-value: 38.94, critical f-value: 3.98), but not for PSD in the product (p-value: 0.11, f-value: 2.54, critical f-value: 3.89).

In summary, coal feed quality influences separation efficiency, product quality, and misplacement of the product. This underscores the dominance of particle properties (such as size, shape, and density) in the determination of separation efficiency and subsequent product quality.

6.1.9 Particle size

Clear particle size stratification is discernible through the observed distinctions in the PSD of both the product and discard, in comparison to the feed. While the WB1 and WB2 samples yield akin D_{50} particle sizes for the product and discard, the MOAT sample diverges from this trend with both product and discard PSDs relating closely to the feed. This may be on account of the MOAT

sample feed containing a larger number of smaller particles (80% reporting to the +6.7-8.0 mm fraction).

A recurring pattern is evident, wherein the product's PSD is primarily characterized by a D_{50} size aligned with that of the feed, whereas the discard displays a PSD predominantly composed of a larger D_{50} size compared to the feed. This consistent trend underscores a tendency for smaller particles to be included in the product and larger particles to be directed to the discard, irrespective of their density attributes. This provides an indication that the machine is separating on weight and not density, where finer discard materials report to the product given the particle misplacement data. This is further corroborated by the tendency of higher particle misplacement in the product than in the discard.

6.1.10 Efficiency tests at best operating conditions

The best operating conditions for +6.7-13.2 mm coal entail a suction force setting of 40 Hz relating to an average inlet velocity on the fan side of 17.09 m/s, accompanied by an inlet velocity on the other side of 16.16 m/s. Consequently, an average velocity of 60.42 m/s is achieved in the connecting pipe, coinciding with an average suction pressure of -2236 Pa. Notably, the best operating conditions for WB2 differ from those for WB1 and MOAT described above. For WB2 a suction fan setting of 45 Hz relating to fan-side inlet, other-side inlet and connecting pipe velocities of 18.83 m/s, 18.24 m/s and 67.95 m/s, respectively, was used with a suction force pressure relating to -2726 Pa. Furthermore, an optimal feed mass for these conditions is identified as 250 g, and to ensure effective fluidization, residence time was timed a maximum duration of 2 minutes. The outcomes of the efficiency tests conducted under favourable operational parameters for the WB1, WB2 and MOAT coal samples with particle size range +6.7-13.2 mm are provided in Table 6.8.

Table 6.8: Results of the WB1, WB2 and MOAT coal efficiency tests at best operating conditions.

Analysis on an air-dried basis	WB1 +6.7-13.2 mm		
	Feed	Product	Discard
D_{50} PSD (mm)	9.3	7.6	10.6
D_{50} Density (kg/m ³)	1630	1530	1950
Ash value (%)	36.20	26.03	69.32
Calorific value (MJ/kg)	21.78	25.80	8.70
Yield (%)	-	80.84	19.14
EPM	-	0.25	-
Misplaced particles (%)	-	47.40	0.00
Analysis on an air-dried basis	WB2 +6.7-13.2 mm		
	Feed	Product	Discard
D_{50} PSD (mm)	9.7	9.5	11.1
D_{50} Density (kg/m ³)	1470	1440	1950
Ash value (%)	19.63	9.68	62.61
Calorific value (MJ/kg)	28.33	32.26	11.35

Yield (%)	-	81.20	18.80
EPM	-	0.05	-
Misplaced particles (%)	-	14.09	18.42
Analysis on an air-dried basis	MOAT +6.7-13.2 mm		
	Feed	Product	Discard
D ₅₀ PSD (mm)	7.3	7.3	7.5
D ₅₀ Density (kg/m ³)	1440	1400	1630
Ash value (%)	16.52	11.99	36.61
Calorific value (MJ/kg)	29.56	31.35	21.62
Yield (%)	-	81.6	18.4
EPM	-	0.04	-
Misplaced particles (%)	-	32.86	11.22

For the WB1 sample, an EPM value of 0.25 was achieved, indicating a separation efficiency that falls below the threshold considered satisfactory when compared to EPM values reported in alternative dry processing methodologies (Weinstein and Snoby, 2007; He *et al.*, 2015; Sahu *et al.*, 2011; Jambal *et al.*, 2017; De Korte, 2013). The WB2 and MOAT samples obtained an EPM of 0.05 and 0.04, respectively, lower than the EPM values reported in alternative dry processing methodologies. The product yields of 80.84%, 81.20% and 81.6% for the WB1, WB2 and MOAT coal, respectively, are reasonably high at Marginal improvement of the D50 density observed from the feed to the product for all three samples. Enhanced ash and calorific values are observed in the product—WB1 obtained 26.03% in the product compared to 36.20% in the feed, WB2 attained 9.68% in the product from 19.63% in the feed, and MOAT yielded 11.99% ash in the product from 16.52% in the feed. The calorific values for WB1, WB2 and MOAT increased by 4.02 MJ/kg, 3.93 MJ/kg and 1.79 MJ/kg, respectively.

Particle misplacement to the product and discard, respectively, accounted for 47.40% and 0.00% in the WB1 sample, 14.09% and 18.42% in the WB2 sample and 32.86% and 11.22% in the MOAT sample. A particle size separation is evident with the product and discard fractions reporting, respectively, smaller and larger sizes than the feed. WB1's feed, product and discard D₅₀ particle sizes are 9.3 mm, 7.6 mm and 10.6 mm, respectively. Similarly, 9.7 mm, 9.5 mm and 11.1 mm are observed for the feed, product and discard of the WB2 sample. Interestingly the MOAT sample shows marginal differences in the D₅₀ PSDs of the feed, product and discard. This is attributed to the homogenous particle size range of the MOAT feed with 80% of the particles reporting to the +6.7-8.0 mm fraction. The partition curves and particle size distributions across the feed, product, and discard for the WB1, WB2 and MOAT efficiency tests at best operating conditions are illustrated in Figures 6.7 and 6.8, respectively.

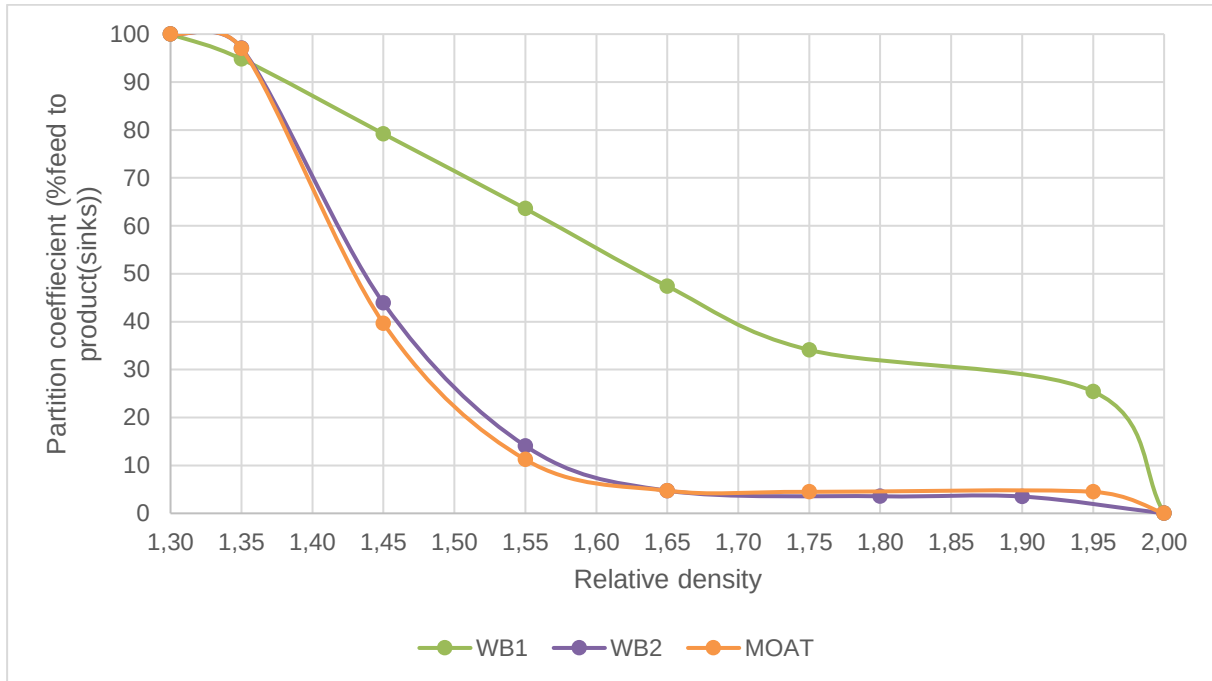


Figure 6.7: Partition curves of the product for the WB1, WB2 and MOAT +6.7-13.2 mm efficiency tests at best operating conditions.

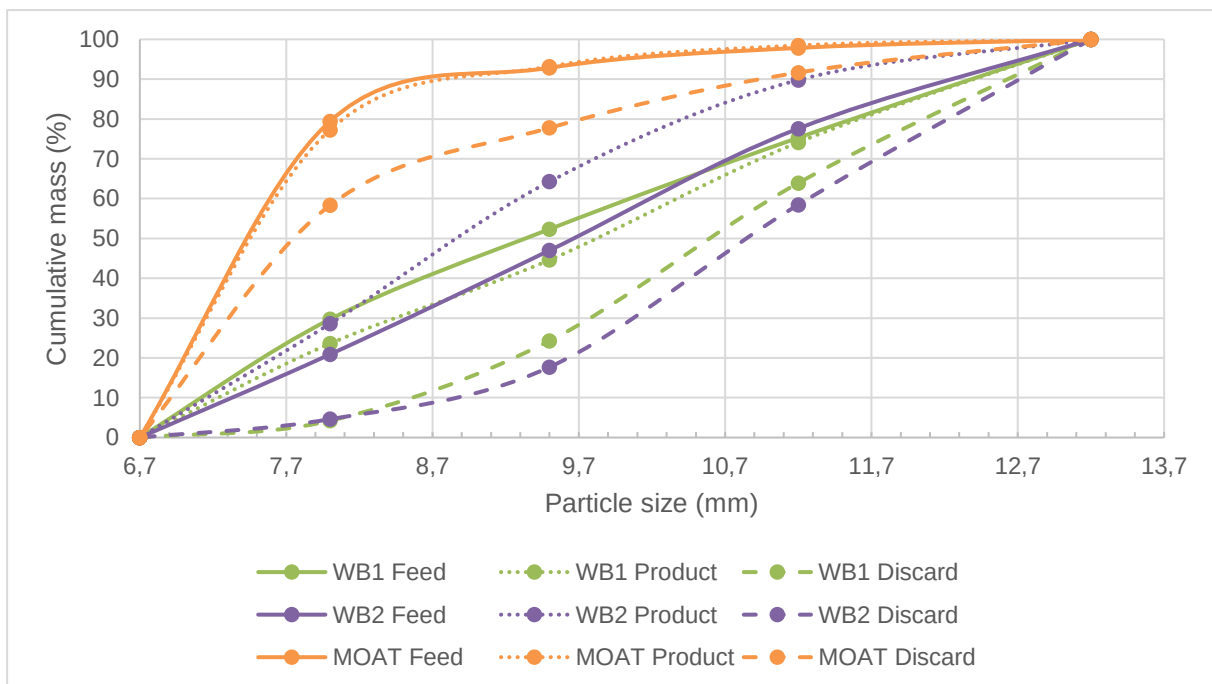


Figure 6.8: PSD of the feed, product and discard for the WB1, WB2 and MOAT +6.7-13.2 mm efficiency tests at best operating conditions.

6.1.11 Beneficiation results in context to the South African coal market

Under optimal operational conditions, the beneficiation process applied to WB2, and MOAT coal samples yields improved ash numbers (9.68% and 11.99%, respectively) and calorific values (32.26 MJ/kg and 31.35 MJ/kg, respectively), while maintaining comparably high product yields (81.20% and 81.60%, respectively). In contrast, the WB1 sample achieves a similarly high yield

(80.84%), albeit with only marginal enhancements in ash number and calorific value (26.03% and 25.80 MJ/kg, respectively). Noteworthy is the marginal advancement in D_{50} density of the product observed across all three samples.

Furthermore, efficiency evaluations conducted on WB2, and MOAT coal samples reveal notably lower EPM values of 0.05 and 0.04, respectively, contrasting with the EPM value of 0.25 obtained for the WB2 coal sample. The evident distinct separation observed in the efficiency tests for WB2 and MOAT, underscored by markedly low EPM values, strongly indicates a predominant utilization of destoning procedures. This assertion is further substantiated by the marginal alteration in the D_{50} density of the feed, accompanied by a substantial alteration in the discard stream. The WB1 efficiency test results in a product that contains a higher percentage of misplaced particles, accounting for 47.40%, compared to the lower percentages of 14.09% and 32.86% observed in the WB2 and MOAT efficiency tests, respectively. Conversely, WB2 and MOAT coal samples exhibit more misallocated particles in the discard stream, constituting 18.42% and 11.22%, respectively, as opposed to the negligible 0% for WB1.

The findings on EPM and yield are consistent with parallel investigations conducted on a pilot-scale SEP-AIR unit using South African coal of +6-13 mm (De Korte, 2021). As discussed in Section 6.1.3, these studies yielded an EPM of 0.10 and a product yield of 87.30%. The cut-point density derived from these investigations, measuring 1924 kg/m³, is notably higher than the range of 1440–1630 kg/m³ obtained in the laboratory-scale tests. Furthermore, misplaced particle percentages in both the product (1.83%) and discard (6.22%) are lower in the pilot-scale study. Additionally, product ash values of 7.7% were observed in the pilot-scale study, relatively comparable to the WB2 and MOAT ash values of 9.68% and 11.99%, respectively. The differences observed between the two studies (with respect to cut-point density and particle misplacement) could be attributed to differences in the particle properties of the feed, particularly relating to the density profile and moisture contents.

The investigation portrayed in this article suggests that the beneficiation of coal in the size range of +6.7-13.2 mm can be effectively achieved through processes like SEP-AIR, resulting in enhanced ash and calorific values in the final product. These improved product qualities are deemed suitable for various sectors of the South African market, including the domestic market, thermal coal for electricity, synthesis of fuels and export thermal coal markets (Steyn and Minnitt, 2010). Detailed product specifications in terms of size, moisture, ash value, and calorific value for different coal categories are outlined in Table 6.9 (Steyn and Minnitt, 2010).

Table 6.9: Product specifications of coal for several South African coal markets (Steyn and Minnit, 2010).

	Size (mm)	Moisture (%)	CV (MJ/kg)	AV (%)
Thermal coal	0-40	<12	>21.0	<34
Synthesis of fuels	-	<10	>22.6	<30
Domestic	0-40	<12	>24.5	<21
Export	0-50	<12	>27.5	<15

The particle size range of +6.7-13.2 mm corresponds to the pea size category, exhibiting moisture values ranging from 1.5% to 1.8%. This size range and moisture content are suitable for all four segments of the South African coal market. Furthermore, the ash and calorific values of the products derived from the WB2, and MOAT samples meet the criteria for utilization in all four market sectors. In contrast, the product derived from the WB1 sample would not meet the standards for export coal.

Moreover, the separation efficiencies achieved through applying SEP-AIR align with those prevalent in the broader range of dry methodologies employed for processing coal within the pea size category. However, the attained cut-point densities are slightly lower, ranging from 1440 to 1630 kg/m³, in contrast to the values of 1660–2000 kg/m³ reported in other dry processes. Notably, the product yield of approximately 81% achieved surpasses the yields of 57–87% observed in alternative dry processes (Weinstein and Snoby, 2007; He *et al.*, 2015; Sahu *et al.*, 2011; Jambal *et al.*, 2017; De Korte, 2013).

The separation efficiencies observed for WB2, and MOAT samples exhibit a lesser degree than water-based dense medium plants utilizing baum jigs and processing coal of analogous dimensions (SAPCS, 2015). In this context, the latter attains an EPM of 0.15 and a cut-point density of 1.61 kg/m³. Conversely, the WB1 sample aligns with the cut-point density achieved by a Baum jig but displays a higher EPM value. However, EPM values as low as 0.023 have been obtained in dense medium plants for the +6 mm particle size range (De Korte, 2013).

6.1.12 Conclusion

The SEP-AIR process effectively tailors +6.7-13.2 mm coal to meet specifications demanded by various sectors of the South African market, including domestic, export, thermal, and fuel synthesis. This is evident through the enhanced ash and calorific values achieved in the SEP-AIR product. Comparable separation efficiencies, as observed in most dry methods applied to processing pea-size coal, are achieved through SEP-AIR. However, these efficiencies fall short of those realized by water-based dense medium plants operating on coal of equivalent size.

It is important to recognize that modifications to fan settings and the ensuing alterations in air velocity wield constrained influence over separation efficiency and, consequently, product quality.

Nonetheless, these adjustments significantly affect overall yield and the quality of the discard stream. Moreover, it is essential to underscore the evident divergences in both separation efficiency and product quality arising from varying initial coal feed attributes.

The observed relationships between coal feed attributes (i.e., particle properties like size, shape, and density) and airflow characteristics (i.e., air speed) vis-à-vis the separation unit's performance in terms of efficiency and product quality, suggest that the prevailing conditions within the system are influenced by particle properties and the interaction of these particles with one another, the air and the unit walls, rather than being solely contingent upon airspeed. Consequently, alterations in particle density, size, and shape might exert a more pronounced influence on separation efficiency compared to changes in airspeed, which in turn impacts product yield. Moreover, indications that the SEP-AIR separates on weight and not density are noted from the trends in the PSDs and particle misplacement.

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CHAPTER 7: DRY BENEFICIATION OF +3.2-6.7 MM COAL (PAPER 4)

Within this chapter, the included paper, "Evaluation of pneumatic suction fluidization for the beneficiation of +3.2-6.7 mm Southern Africa coal," furnishes insights into the capacity of the laboratory-scale separation unit resembling SEP-AIR to effectively beneficiate small coal particles ranging from 3.2 mm to 6.7 mm in size, also referred to as 'duff-size'. The paper illuminates the underlying process characteristics that dictate the mechanics of this separation mechanism.

7.1 Evaluation of pneumatic suction fluidization for the beneficiation of +3.2-6.7 mm Southern African coal (Paper 4)

Contributions from authors

In her capacity as a postgraduate student, Miss N. Hughes embarked on this research initiative under the tutelage of Prof. M. le Roux and Prof. Q.P. Campbell. Professors le Roux and Campbell formulated the study's parameters and rationale. The experimental configuration was meticulously aligned with manufacturer specifications and a collaborative effort between Miss Hughes and technical support personnel from North-West University. Miss Hughes assumed responsibility for the execution of experimental protocols, encompassing data acquisition and subsequent analysis. The conclusions and ensuing discussions emanated from comprehensive consultations involving Miss Hughes, Prof. le Roux, and Prof. Campbell. Post these deliberations, the work underwent scrupulous revision, preparing it for potential publication in a peer-reviewed journal. Miss Hughes took the lead in composing the manuscript, enriched by the editorial insights contributed by Prof. le Roux.

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Evaluation of pneumatic suction fluidization for the beneficiation of +3.2-6.7 mm Southern African coal

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7.1.1 Abstract

In this study, laboratory-scale beneficiation of +3.2-6.7 mm coal was carried out using a SEP-AIR unit incorporating suction fluidization and vortex capturing. Coal samples from the Waterberg coalfield in Limpopo, South Africa, and Moatize coalfield in Tete, Mozambique, were investigated, resulting in separation efficiencies (EPMS) of 0.15 and 0.05, respectively. The product ash value showed improvement, reducing from 34.12% in the feed to 27.91% for Waterberg and from 16.52% in the feed to 13.12% for Moatize. Similarly, calorific values improved from 22.60 MJ/kg in the feed to 25.06 MJ/kg for the Waterberg and from 29.56 MJ/kg in the feed to 30.75 MJ/kg for the Moatize. The yield was reported at 75% and 95% for the Waterberg and Moatize, respectively. Furthermore, slight enhancements were observed in the cut-point densities, with values changing from 1.61 SG in the feed to 1.55 SG in the product for Waterberg and from 1.44 SG in the feed to 1.43 SG in the product for Moatize. The ANOVA analysis indicates that coal feed quality exerts the most influence on product quality. Conversely, air speed notably affects the product yield, with increasing air speed leading to higher yields. Notably, changes in fan settings had limited impact on the product quality. Differences in the product's PSDs and discard compared to the feed show that particle size separation occurs. Moreover, this particle size separation links to particle misplacement, indicating that the machine separates on weight and not density.

Keywords: Air-gravity separation, suction fluidization, fine coal beneficiation

7.1.2 Introduction

Modern coal mining techniques yield substantial quantities of valuable small and fine coal fractions (Modiga *et al.*, 2020). As the demand for high-quality coal increases, processing the finer, minus 6 mm particle sizes at larger capacities has become imperative (Honaker *et al.*, 2008). Methods such as spirals, dense medium cyclones, and froth flotation cells are commercially employed for processing these coal fractions. However, due to the specific behaviour of smaller coal particles (Majumder *et al.*, 2003; Sivamohan, 1990; Amariei *et al.*, 2014; Das and Sakar, 2018), significant water usage and associated challenges related to water licensing and pollution

(Ray and Dey, 2020; Kramer, 2022), beneficiation of small and fine coal proves to be a complex and costly undertaking (Bada *et al.*, 2010). Consequently, developing an efficient and cost-effective process for beneficiating small and fine coal remains an ongoing objective. This aspect is of paramount significance, particularly in arid regions where dry processing methods appear to be the promising path for the future.

In this context, dry beneficiation techniques have garnered attention, particularly for addressing the challenges posed by small and fine coal fractions (Bada *et al.*, 2010). Dry processing techniques offer modularity and obviate the need for water, thereby eliminating the extensive and costly post-processing of coal and mitigating concerns related to water pollution. Several research studies have investigated various techniques for beneficiation in the small and fine coal fractions, including air jigs (Boylu *et al.*, 2014), air table variants (Chavaldi *et al.*, 2016; Davaasuren *et al.*, 2016; Wotruba *et al.*, 2010), air-dense medium fluidized bed (ADMFB) (Fan *et al.*, 2001; Luo *et al.*, 2008; Sahu *et al.*, 2009; Chickerema and Moys, 2012; Langner *et al.*, 2018; Hughes *et al.*, 2017; Fu *et al.*, 2019; Peters *et al.*, 2021; Diedericks *et al.*, 2022), reflux classification (Macpherson and Galvin, 2010), and winnowing (Morgan *et al.*, 2019, 2020, 2021). However, despite the research efforts, these methods have limited commercial applicability primarily due to their relatively lower separation efficiencies than water-based alternatives.

The consensus among these studies highlights that as particle size decreases, the separation efficiency deteriorates (Fu *et al.*, 2019; Chickerema and Moys, 2012; Mohanta *et al.*, 2011; He *et al.*, 2016; Azimi *et al.*, 2017). A decreased particle size leads to lower particle momentum and higher viscosity due to the smaller mass and higher surface area of finer particles (Sivamohan, 1990; Amariei *et al.*, 2014). Furthermore, the reduced difference in settling velocities between dense and light particles hinders stratification and separation as particle size decreases (Das and Sakar, 2018). In cases where settling kinetics are slow, even with favourable density conditions, impractically long residence times are required (Das and Sakar, 2018). Slower particle kinetics are also associated with bubbling behaviour and back mixing of the fluid medium (Fan *et al.*, 2001; Mohanta *et al.*, 2011). The coal industry faces additional challenges in optimal fines processing, including issues related to dust handling (SACPS, 2015; De Korte, 2013), moisture content (SACPS, 2015; Weinstein and Snoby, 2010), and processing capacity (King, 2015).

The SEP-AIR process has emerged as a promising dry beneficiation method, offering potential solutions to the challenges of dry coal beneficiation. This technique utilizes air-gravity separation through suction fluidization and vortex capturing, and it has been designed to address issues such as dust handling, moisture sensitivity, and processing capacities (Stepanenko, 2016a;

Stepanenko, 2016b; De Korte, 2021). Consequently, SEP-AIR presents itself as a comprehensive solution for dry coal beneficiation.

7.1.3 Background and motivation

Previous research indicates that the SEP-AIR process effectively processes coal particles within the size range of 1 to 100 mm, achieving high processing capacities ranging from 45 to 200 tph. The process attains product yields ranging from 85% to 95% and demonstrates D_{50} densities between 1.78 and 1.90, with Ecart Probable Mooyen (EPM) efficiencies ranging from 0.10 to 0.17 (Stepanenko, 2016a; Stepanenko, 2016b).

However, there is a notable gap in understanding the separation efficiency of the SEP-AIR process, specifically for the minus 6 mm coal fraction. Existing studies have focused more on ash value improvement (De Korte, 2021), and limited information is available regarding EPM efficiencies, organic efficiency, yield and misplaced particles. Therefore, this study aims to investigate and evaluate the separation efficiency of the SEP-AIR process and provide a comprehensive idea of its capability for beneficiating coal particles in the size range of +3.2-6.7 mm. Moreover, the tests conducted on the SEP-AIR have focussed on Northern Hemisphere coal types, which do not contain much near-dense material. Conducting studies on Southern Hemisphere coals, which do contain a large portion of near-dense material, can help ascertain the SEP-AIR's applicability thereto. This is accomplished through a series of efficiency tests and subsequent analyses conducted on a laboratory-scale unit.

7.1.4 Experimental

A series of efficiency tests were conducted using a laboratory-scale unit to assess the viability of employing a suction fluidization process, like the SEP-AIR method, for the beneficiation of small coal. Specifically, the tests focused on coal particles within the size range of +3.2-6.7 mm. These sizes were chosen based on the definition of fine coal for South Africa's coal-to-liquid operations, coupled with manufacturer specifications stipulating a particle size range of 2:1 between the top size and smallest particle size.

7.1.4.1 Equipment and operating parameters

The laboratory-scale separation apparatus, meticulously designed and constructed to adhere to the manufacturer's specifications, is composed of three prominent sections, as visually depicted in Figure 7.1:

- The feed section incorporates an adjustable manual conveyor system that facilitates the smooth entry of particles and determines the height of the inlet air gap. The inlet on the

left of the first image in Figure 7.1 is the other-side inlet and the fan-side inlet.

- The Trojan BC60 2920 RPM centrifugal fan generates the required suction force, which is indispensable to the apparatus's overall functioning.
- The separation unit, where the crucial fluidisation processes and subsequent particle separation occur. This unit is divided into four distinct compartments: the i) fluidizing box, ii) vortex chamber, iii) connecting pipe and iv) collection bin.

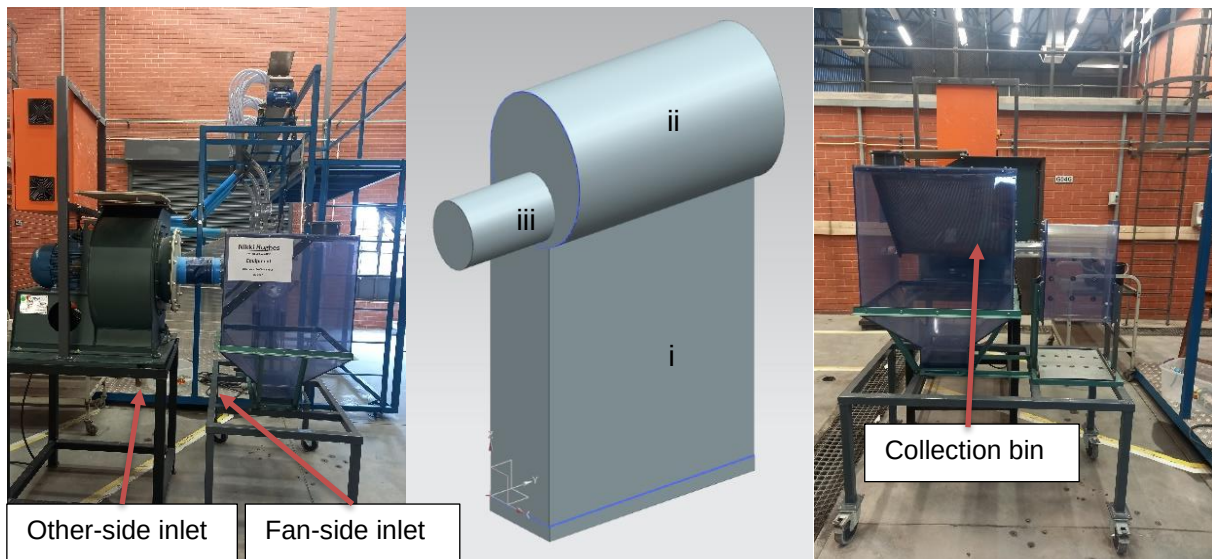


Figure 7.1: The laboratory-scale separating unit from different angles shows the feeding system and suction fan (left), suction nozzle with fluidizing box, vortex chamber and connecting pipe (centre) and collection bin (right).

The particles are introduced onto the manual conveyor positioned below the separation unit. Upon encountering the upward suction force, they undergo fluidization and stratification based on their specific properties, including size, shape, and density. Particles possessing properties that enable them to fluidize within the height of the fluidizing chamber sufficiently are captured by the vortex formation in the vortex chamber. Subsequently, these captured particles are accelerated within the connecting pipe and directed towards the collection point as the desired product. Conversely, particles that cannot be captured by the vortex formation within the vortex chamber remain within the fluidizing chamber and are subsequently discharged as discard material.

The fluidizing properties within the suction nozzle, comprising the fluidizing chamber, vortex chamber, and connecting pipe, are primarily influenced by the airflow dynamics within the unit. This airflow is sustained by the suction fan in conjunction with the height of the fluidizing chamber situated above the conveyor system. To ensure optimal performance, the height of the fluidizing box inlet above the conveyor plate is determined based on the particle size range, specifically requiring it to be no less than 1.5 times greater than the largest particle within the designated size

range (A.I. Stepanenko, CEO Gormash Export, personal communication, September 2019). For the investigated particle size range of +3.2-6.7 mm, the inlet height was determined to be 10 mm.

A comprehensive set of optimization tests, utilizing tracers and coal samples at varying suction fan settings, has been conducted to identify the best operating conditions for the particle size range of +3.2-6.7 mm. These tests showed that the suction fan setting should range to 25 Hz. Moreover, the optimal feed mass for these conditions was determined to be 150 g, ensuring efficient performance. To prevent excessive fluidization residence time, a maximum duration of 2 minutes was established to achieve desirable outcomes. These carefully selected operating conditions have been employed to ensure accurate and reliable efficiency testing within the scope of this study.

7.1.4.2 Materials

In the present study, two distinct coal qualities were employed, originating from the Waterberg coalfield in Limpopo, South Africa, and the Moatize coalfield in Tete, Mozambique. Essential sample preparation procedures, including air drying for coal to reach inherent moisture content, crushing, sieving, and sampling, were diligently carried out. Crushing and sieving techniques were employed to achieve the desired particle size range of +3.2-6.7 mm. Proximate and calorific value analyses were performed on the initial coal feed to ascertain the moisture content, ash value, and heating value. Moreover, the particle size distribution (PSD) of the feed coal, along with the density distribution determined via a standard float and sink test, were examined. A summary of the feed coal quality is shown in Table 7.1.

Table 7.1: Feed quality of the Waterberg and Moatize coal samples under consideration.

Analysis on an air-dried basis	Waterberg +3.2-6.7 mm	Moatize +3.2-6.7 mm
Moisture content(%)	1.53	1.57
Ash value (%)	34.12	16.52
Calorific value (MJ/kg)	26.60	29.56
D ₅₀ cut point PSD (mm)	4.85	4.40
D ₅₀ cut point density (kg/m ³)	1610	1440
Near dense material (%)	30	80

Regarding the moisture content, ash value, and calorific value, both coal samples exhibit similar qualities. However, there is a notable distinction in their particle size distributions (PSD). The Waterberg sample displays a larger D₅₀ particle size, indicating that 50% of the particles in the sample are above 4.85 mm. In contrast, the Moatize sample has a D₅₀ particle size of 4.4 mm. Moreover, the Waterberg sample has a larger top size of 6.7 mm in comparison to the Moatize coal's top size of 5.6 mm. This indicates that the Moatize sample has a narrower PSD and the difference in PSD between the two coal samples is represented in Figure 7.2.

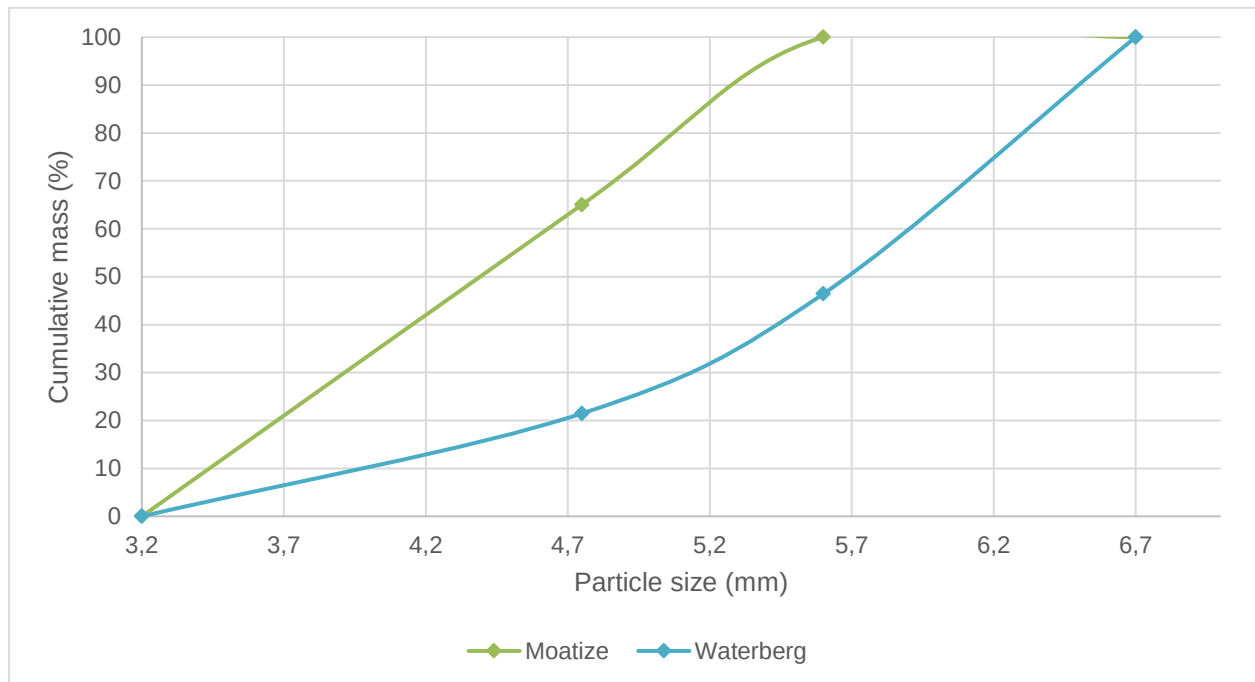


Figure 7.2: A comparison of the PSDs of the Waterberg and Moatize coal samples.

Furthermore, the Waterberg sample exhibits a higher D_{50} density of 1610 kg/m^3 , whereas the Moatize sample has a comparatively lower D_{50} density of 1440 kg/m^3 . Additionally, it is worth noting that the Moatize sample shows a larger proportion of near-dense material, with 80% compared to the 30% in the Waterberg sample. A visual comparison of the density distributions for the Waterberg and Moatize samples is presented in Figure 7.3.

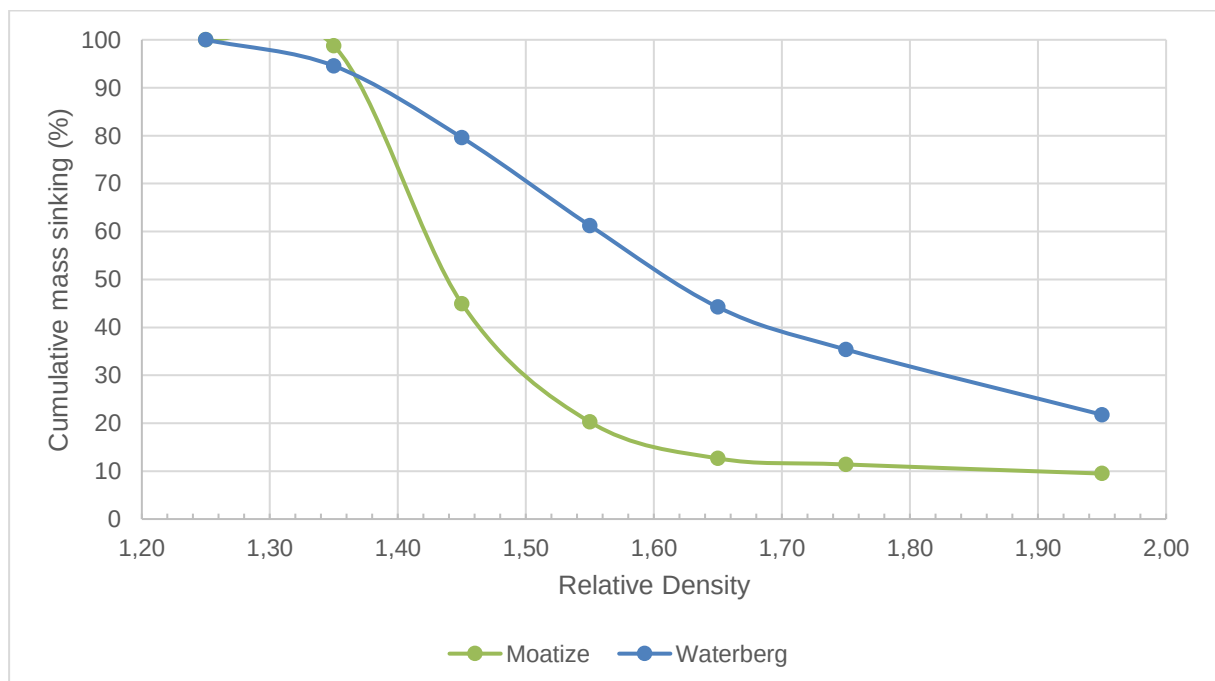


Figure 7.3: Comparison of the density distributions for the Waterberg and Moatize coal samples.

7.1.4.3 Efficiency tests, significance and repeatability

A series of efficiency tests were conducted on the Waterberg and Moatize coal samples, encompassing several suction fan settings. The effectiveness of the separation process was evaluated based on multiple parameters, including the density distribution of the product and discard, EPM, organic efficiency, and misplaced particles. In addition, analyses were performed to assess the ash value, calorific value, and particle size distribution (PSD), providing insights into the improved quality of the obtained product and discard coals.

Additionally, single-factor and two-factor Analysis of Variance (ANOVA) tests were conducted to evaluate notable disparities among means while comparing relevant variables. The ANOVA test yields two key statistics: the p-value and the f-value, indicating the statistical significance between mean values of different data groups. These metrics were utilized to determine the significance of varying factors such as coal feed quality and airspeed. Significance in statistical terms is presumed when the p-value is less than the predetermined alpha value of 0.05, and the f-value surpasses the f-critical value, which is also computed in the ANOVA process (Kenton, 2023).

To determine the repeatability of the efficiency tests, the mean, standard deviation, and 95% confidence interval (CI) were calculated for three repeated tests on the Moatize coal and the product and discard yield, and the D₅₀ density and EPMs were determined. The results in Table 7.2 and Figures 7.4 and 7.5 indicate that generally low standard deviations were observed for these parameters.

Table 7.2: Product quality and process efficiency variables demonstrating repeatability.

Analysis on an air-dried basis	Test 1	Test 2	Test 3	Mean	SD	95% CI
Product yield (%)	60	59	58	59	0.83	58.1–59.9
Discard yield (%)	40	41	42	41	0.83	41.1–41.9
Product D ₅₀ density (kg/m ³)	1435	1428	1430	1431	0.003	1431–1431
Discard D ₅₀ density (kg/m ³)	1490	1470	1470	1477	0.009	1477–1477
Product D ₅₀ size (mm)	4.3	4.3	4.4	4.3	0.05	4.2–4.4
Discard D ₅₀ size (mm)	4.8	4.8	4.9	4.8	0.05	4.7–4.9
EPM	0.05	0.05	0.05	0.05	0.00	0.05–0.05
Misplaced to product (%)	10.34	8.15	9.52	9.34	0.91	8.3–10.4
Misplaced to discard (%)	35.71	41.59	42.86	40.1	3.11	36.6–43.6

The data in Table 7.2 suggests that the separation unit consistently produces product and discard qualities (in terms of ash value, cut-point size and cut-point density) and process efficiencies, yields and percentage of misplaced particles that exhibit repeatability across multiple experiments conducted under the same conditions. Notably, only the percentage of particles misplaced to the discard portrays a higher standard deviation and 95% CI.

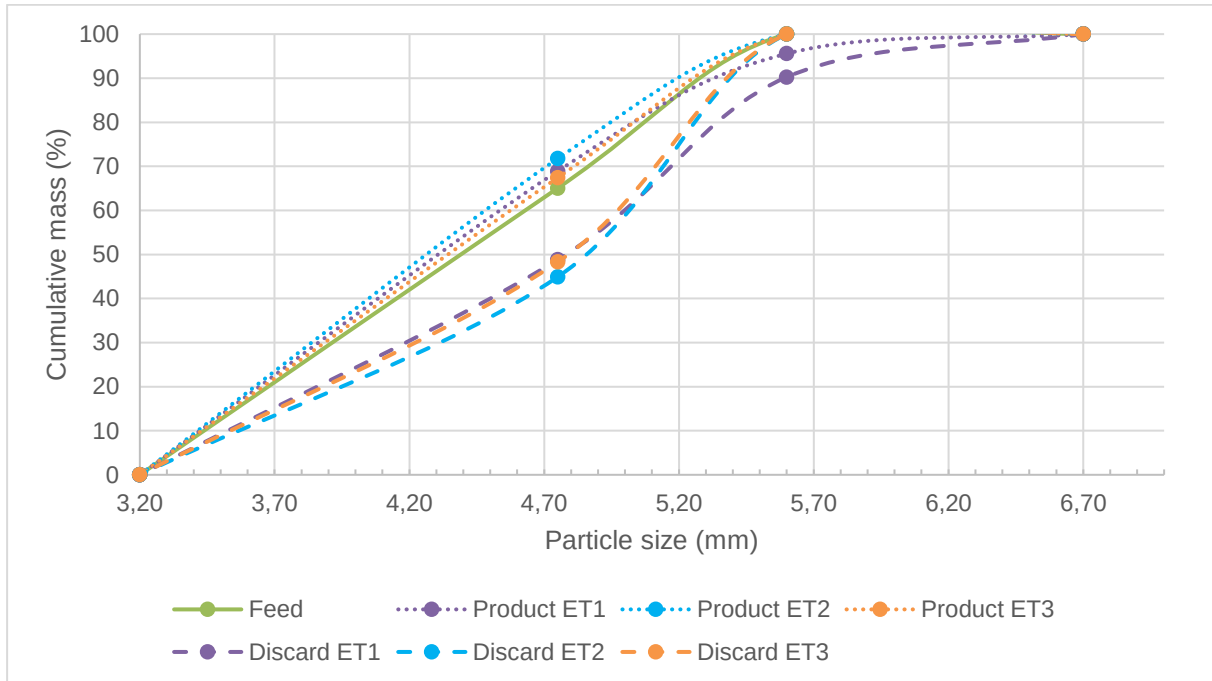


Figure 7.4: Comparison of PSD for the feed, product and discard of repeated efficiency tests (ETs) with MOAT.

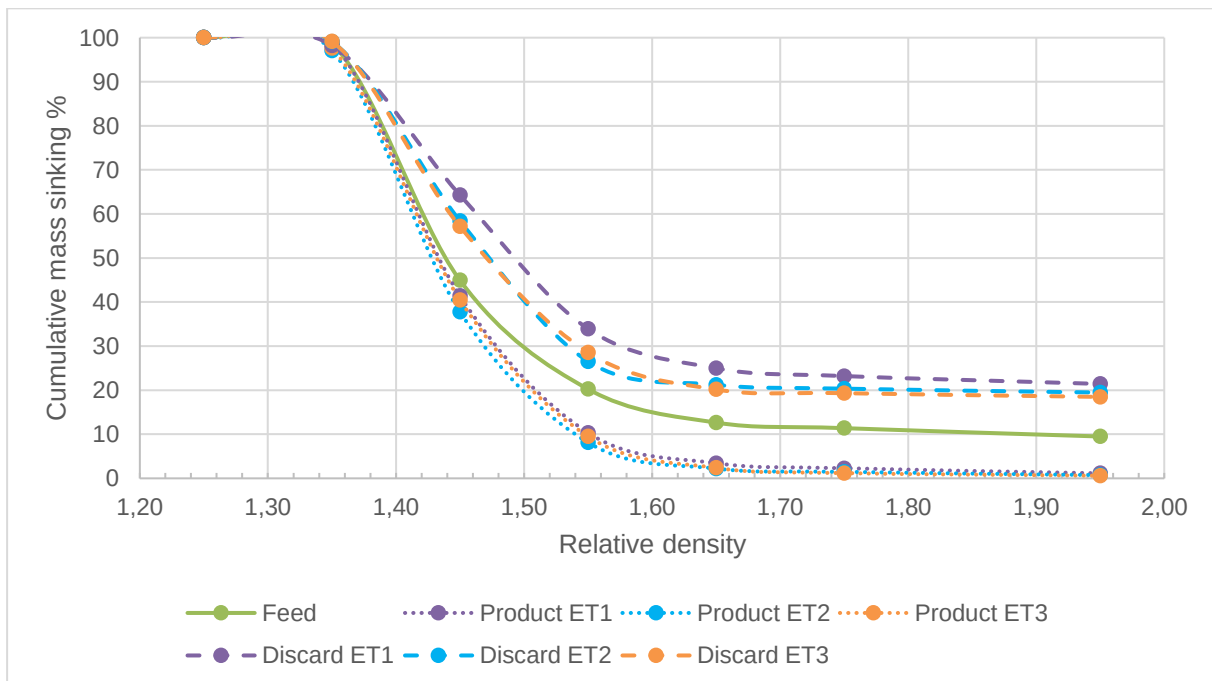


Figure 7.5: Comparison of density profiles for the feed, product and discard of repeated efficiency tests (ETs) with MOAT.

7.1.5 Results and discussion

Aside from those related to the particles, properties of the airflow can also affect the pseudo fluid characteristics of the semi-fluidized particulate bed. To investigate this relationship, three different suction fan settings were examined to assess the potential improvement in separation efficiency, as indicated by the development of a distinct velocity profile. The fan setting and associated average fan-side inlet, other-side inlet and connecting pipe velocities are provided in Table 7.3.

Table 7.3: Suction fan setting and corresponding fan-side, other-side and connecting pipe velocities.

Fan setting		Fan-side inlet velocity (m/s)	Other-side inlet velocity (m/s)	Connecting pipe velocity (m/s)
1	22.5 Hz	9.61	9.11	33.99
2	25.0 Hz	10.68	10.12	37.76
3	27.5 Hz	11.75	11.13	41.54

The outcomes of said investigation are systematically presented in Table 7.4, elucidating the quality of the feed, product, and discard, as well as the process efficiency, across the three suction fan settings for both the Waterberg and Moatize coal samples.

Table 7.4: Efficiency test results obtained at different suction fan settings for Waterberg and Moatize coal.

Analysis on an air-dried basis	Waterberg +3.2-6.7 mm						
	Fan setting 1			Fan setting 2		Fan setting 3	
	Feed	Product	Discard	Product	Discard	Product	Discard
D ₅₀ PSD (mm)	4.85	4.35	5.15	4.65	5.55	5.00	5.50
D ₅₀ Density (kg/m ³)	1610	1530	1633	1550	1950	1590	1950
Ash value (%) AD	34.12	25.84	36.59	27.91	52.75	32.05	49.30
Calorific value (MJ/kg) AD	22.60	25.87	21.98	25.06	15.24	23.42	16.60
Yield (%)	-	23	77	75	25	88	12
EPM	-	0.16	-	0.15	-	0.20	-
Misplaced particles (%)	-	30.77	30.23	38.78	14.63	7.14	41.58
Analysis on an air-dried basis	Moatize +3.2-6.7 mm						
	Fan setting 1			Fan setting 2		Fan setting 3	
	Feed	Product	Discard	Product	Discard	Product	Discard
D ₅₀ PSD (mm)	4.4	4.3	4.8	4.8	5.3	4.5	4.5
D ₅₀ Density (kg/m ³)	1440	1430	1490	1430	1950	1430	1950
Ash value (%)	16.52	13.04	21.74	13.20	25.97	13.51	48.20
Calorific value (MJ/kg)	29.56	30.93	27.49	30.87	25.82	30.75	17.04
Yield (%)	-	40	60	74	26	95	5
EPM	-	0.05	-	0.05	-	0.05	-
Misplaced particles (%)	-	35.71	10.34	11.22	33.33	9.09	9.58

Increasing the suction force leads to an increase in the magnitude of the velocity within the suction nozzle and results in significant differences in the yield to the product for both Waterberg and Moatize coal. Specifically, as the suction force increases, the yield to the product also increases. The ash value of the product demonstrates initial improvement and as the suction force increases; however, it then begins to deteriorate. This trend holds true for the Waterberg sample, whereas

the Moatize sample consistently maintains the same ash value in the product regardless of the fan setting.

The EPM and D_{50} density values follow a similar pattern, with an initial improvement observed that subsequently deteriorates as the suction force increases for Waterberg coal. In contrast, there is no discernible change from the feed for the Moatize coal in terms of the EPM and D_{50} density. Notably, differences are observed in the ash value and D_{50} density of the discard as the suction force increases for both coal samples. Moreover, a clear particle size separation is evident from the observed differences in the particle size distributions (PSD) of the product and discard in comparison to the feed.

To determine the extent of interactions between the air and particle properties (suction fan setting and coal feed quality, respectively) and the process efficiency (EPM, yield and misplaced particles) and product quality (ash value, calorific value, cut-point density and cut-point size) an ANOVA two factor with replication test was conducted. The results are portrayed in Table 7.5.

Table 7.5: Two factor ANOVA with replication for the interaction of coal feed quality and suction fan setting with process efficiency and quality of product and discard streams.

	Indicator of statistical significance			
	p-value	Alpha value	f-value	f-critical value
Process efficiency	2.6E-03	0.05	4.73	2.51
Product quality	1.63E-37	0.05	6770	2.51
Discard quality	2.02E-15	0.05	93.08	2.51

In terms of process efficiency, which relates to EPM, yield and misplaced particles, the ANOVA two factor with replication test results in a p-value of 2.6E-03 which is lower than the selected alpha value of 0.05 and an f-value of 4.73 which is above the threshold f-value of 2.51. This indicates that there is an interaction between suction fan setting and/or coal feed quality with process efficiency. Similarly, the product and discard qualities are influenced by suction fan setting and coal quality, as indicated by p-values below 0.05 and f-values that supersede the f-critical value. Noteworthy is the significantly low and high p-value and f-value, respectively, for the product quality indicating that the interaction of particle and air properties is more significant in determining product quality as when compared to discard quality and process efficiency.

7.1.5.1 Efficiency test: Waterberg +3.2-6.7 mm

The results of the efficiency test conducted under the optimal operating conditions for the Waterberg +3.2-6.7 mm coal sample are presented in Table 7.6. The variables, as discussed in Section 7.1.4.3, have been compared for the feed, product, and discard obtained in the study and correspond to a suction fan setting of 25 Hz with fan-side and other-side inlet velocities of 10.68

m/s and 10.12 m/s, respectively and a connecting pipe velocity of 37.76 m/s with related suction pressure of -873 Pa.

Table 7.6: Results of the Waterberg coal efficiency test for +3.2-6.7 mm particle size range.

Analysis on an air-dried basis	Waterberg +3.2-6.7 mm		
	Feed	Product	Discard
D ₅₀ PSD (mm)	4.85	4.65	5.55
D ₅₀ Density (kg/m ³)	1610	1550	1950
Ash value (%)	34.12	27.91	52.75
Calorific value (MJ/kg)	22.60	25.06	15.24
Yield (%)	-	75	25
EPM	-	0.15	-
Organic efficiency (%)	-	85.50	-
Misplaced particles (%)	-	38.78	14.63

An EPM value of 0.15 was achieved, indicating a similar separation efficiency observed in other dry processing methods feeding small coal (Davaasuren *et al.*, 2016; Wotruba *et al.*, 2010; Fu *et al.*, 2019; Macpherson and Galvin, 2010; Morgan *et al.*, 2019, 2020, 2021). The corresponding organic efficiency was measured at 85.50%, and the yield to the product was 75%. The density distribution of the feed and partition curves for the product and discard is illustrated in Figure 7.6.

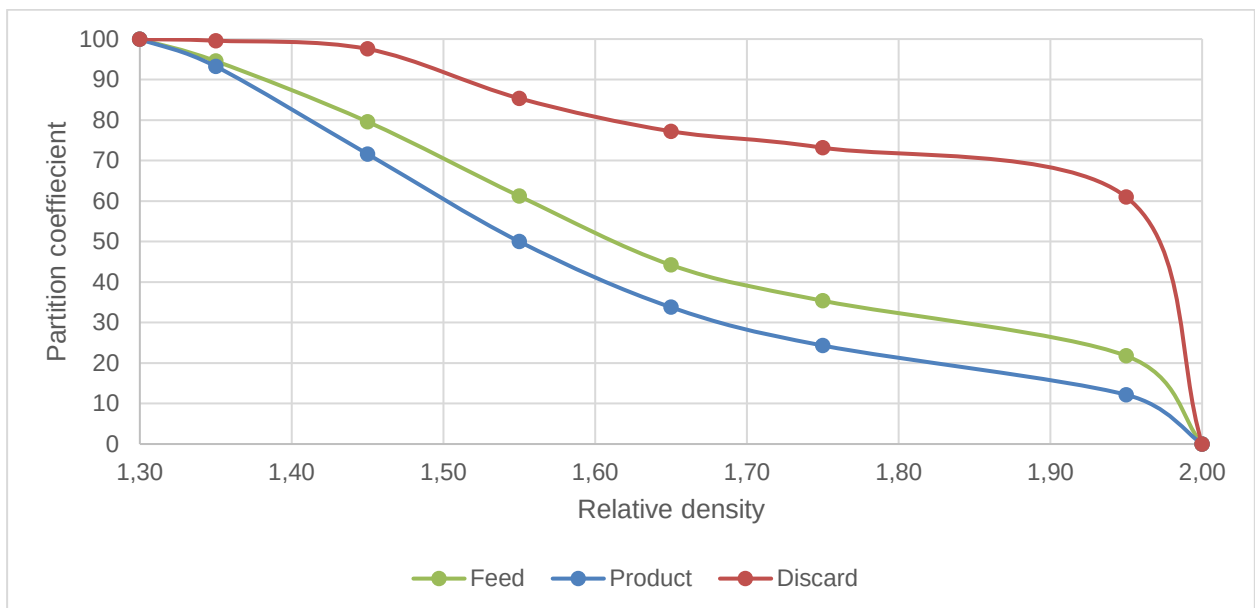


Figure 7.6: The density distributions of the feed and partition curves for the product and discard for the Waterberg +3.2-6.7 mm efficiency test at best operating conditions.

A slight improvement in the D₅₀ density is observed from the feed (1610 kg/m³) to the product (1550 kg/m³). Notably, there is an improvement of 6.21 percentage points in ash value observed from the feed to the product. Additionally, an improvement of 2.46 MJ/kg in the calorific value (CV) is observed for the product compared to the feed. However, it is worth mentioning that a notable number of particles (38.78%) are misplaced to the product, indicating the tendency of the machine to separate on weight rather than density with finer discard material erroneously

reporting to the product. These findings suggest that particle size distribution may also affect the misplacement phenomenon, along with the nature of the density distribution (as described above).

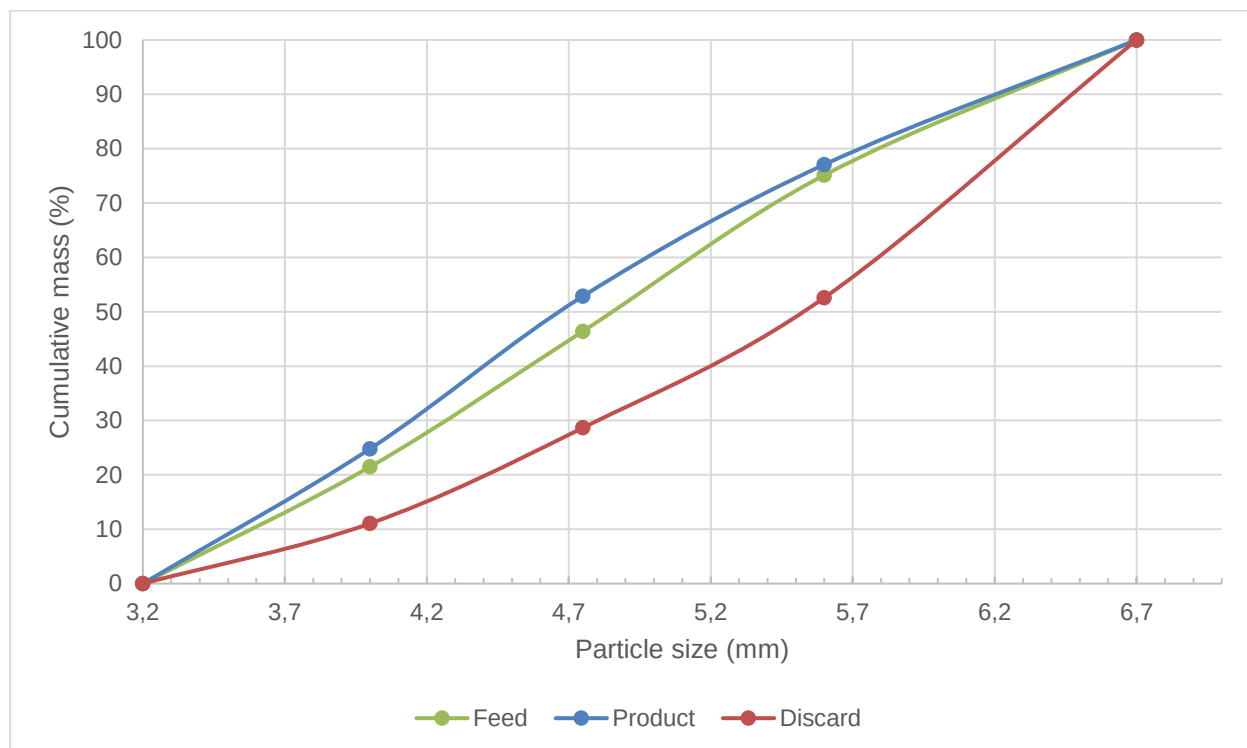


Figure 7.7: The density distributions of the feed, product and discard for the Waterberg +3.2-6.7 mm efficiency test at best operating conditions.

Differences are observed in the PSD of the product and discard and corresponding D_{50} particle size. Smaller particles report to the feed and larger particles to the discard. However, for the Waterberg sample, the feed and product PSDs are relatively close (as visible in Figure 7.7). This could be indicative of the of liberation of more vitrinite rich coal at the size range in question (Potgieter, 2017).

7.1.5.2 Efficiency test: Moatize +3.2-6.7 mm

The results of the efficiency test for the Moatize +3.2-6.7 mm coal sample at best operating conditions are presented in Table 7.7. This test corresponds to a suction fan setting of 27.5 Hz with fan-side inlet, other-side inlet and connecting pipe velocities of 11.75 m/s, 11.13 m/s and 41.54 m/s, respectively. The suction pressure relates to -1057 Pa.

Table 7.7: Results of the Moatize coal efficiency test for +3.2-6.7 mm particle size range.

Analysis on an air-dried basis	Moatize +3.2-6.7 mm		
	Feed	Product	Discard
D_{50} PSD (mm)	4.4	4.5	4.5
D_{50} Density (kg/m ³)	1440	1430	1950

Ash value (%)	16.52	13.51	48.20
Calorific value (MJ/kg)	29.56	30.75	17.04
Yield (%)	-	95	5
EPM	-	0.05	-
Organic efficiency (%)	-	75.33	-
Misplaced particles (%)	-	9.09	9.58

The achieved EPM value of 0.05 indicates a satisfactory separation efficiency, close to that obtained from wet dense medium processes for the same particle size (SACPS, 2015). The organic efficiency reached 75.33%, while the product yield stood at 95%. Notably, there was no enhancement in the D_{50} density from the feed (1440 kg/m^3) to the product (1430 kg/m^3) while significant improvement in the D_{50} density was observed for the discard (1950 kg/m^3). The density distribution of the feed and partition curves for the product and discard is visually depicted in Figure 7.8.

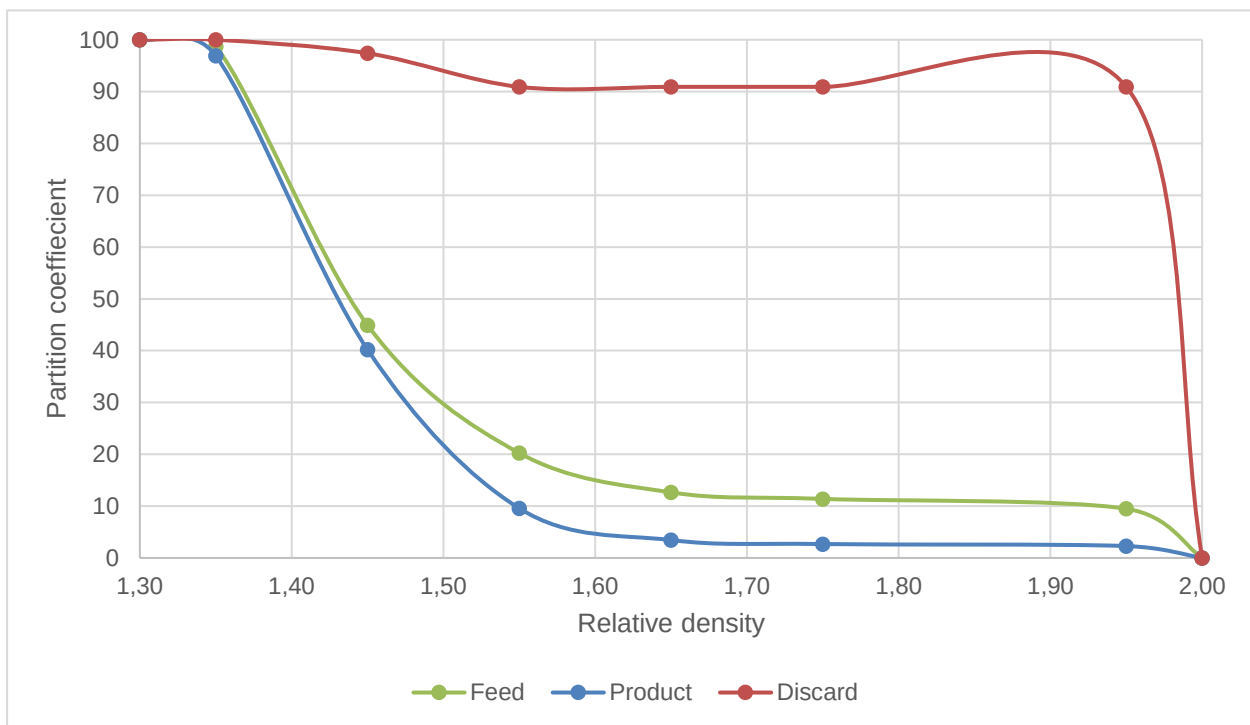


Figure 7.8: The density distributions of the feed, product and discard for the Moatize +3.2-6.7 mm efficiency test.

There was a slight improvement in the ash value, characterized by a decrease of 3.01 percentage points observed from the feed to the product. Moreover, the product exhibited an improvement of 1.16 MJ/kg in the calorific value (CV) compared to the feed. The number of particles that are misplaced to the product relate to 9.09% and those misplaced to the discard are 9.58%. The quality of the Moatize sample consists of low ash, calorific and density values which is considered product-level coal. This along with the large portion (80%) of near dense material present in the feed, enacted a destoning operation which removed high density material while the product and feed qualities remained similar. Interestingly, no particle size separation is observed in the

Moatize coal sample with feed, product and discard D_{50} particle sizes remaining similar. This could be attributed to the Moatize sample containing more than 65% of particles in the +3.2-4.8 mm fraction and containing 80% near dense material which is indicative of a more homogenous feed in terms of particle size and density, once again lending credence to the destoning operation phenomenon.

To determine the specific variables relating to air and particle properties that influence the process efficiency and quality of the product and discard, single factor ANOVA tests are conducted. The results of these are discussed in the sections that follow.

7.1.5.3 Suction velocity

The results pertaining to the single factor ANOVA test indicating the effect of suction fan setting on each variable assessed for process efficiency and quality of the product and discard are summarised in Table 7.8.

Table 7.8: Single factor ANOVA for the interaction of suction fan setting with process efficiency and quality of product and discard streams.

	Indicator of statistical significance			
	p-value	Alpha value	f-value	f-critical value
Product yield	8.7E-03	0.05	33.85	9.55
EPM	0.95	0.05	0.05	9.55
Misplaced to product	0.23	0.05	2.50	9.55
Misplaced to discard	0.95	0.05	0.05	9.55
Product ash value	0.95	0.05	0.05	9.55
Product CV	0.95	0.05	0.05	9.55
Product D_{50} density	0.42	0.05	1.17	9.55
Product D_{50} PSD	0.23	0.05	0.11	9.55
Discard ash value	0.41	0.05	1.23	9.55
Discard CV	0.39	0.05	1.32	9.55
Discard D_{50} density	0.01	0.05	29.52	9.55
Discard D_{50} PSD	0.58	0.05	0.65	9.55

Regarding the suction fan setting, the single factor ANOVA statistical analysis reveals that only product yield and discard cut-point density are significantly influenced by increased suction force and subsequent elevation of air velocity, as indicated by the p-values of 8.7E-03 and 0.01, respectively. This finding suggests that while certain improvements were observed in product quality and process efficiency, the sole variable demonstrating statistical significance upon changing the air velocity properties is product yield. Consequently, modifying the fan settings may not necessarily enhance the efficiency of the separation process or result in an improved product quality.

7.1.5.4 Coal feed quality

Both the Waterberg and Moatize coal samples demonstrated improvements in ash and calorific value for the product, with yields of 75% and 95%, respectively. However, the Waterberg coal sample displayed a more substantial enhancement in these aspects. Additionally, the D_{50} density of the product from the Waterberg coal showed notable improvement compared to the Moatize coal, where only marginal improvement was observed. This may be related to the Moatize feed coal quality representing low ash values and densities with a large portion of near dense material.

However, it is important to note that the efficiency tests conducted on the Moatize coal sample yielded a lower EPM value of 0.05, in contrast to the EPM value of 0.15 obtained for the Waterberg coal sample. This difference can be attributed to the significantly larger amount of near dense material, accounting for 80% of the Moatize coal feed. The sharp separation efficiency suggests that the primary operation involved mostly destoning, as supported by the fact that the improvement in D_{50} density from the feed to the product was not significant for the Moatize coal. Given that the EPM is determined from difference between the D_{25} and D_{75} densities, a smaller value can be obtained from a sample with largely near dense material. Destoning has the effect of pulling the cumulative sinks curve more upright resulting in D_{25} and D_{75} values that are closer to one another and consequently provide a smaller EPM.

Table 7.9 provides a summary of the results from the single-factor ANOVA test, revealing the impact of different suction fan settings on specific variables evaluated for both process efficiency (EPM, yield and misplaced particles) and product and discard quality (ash value, calorific value, cut-point density, cut-point size).

Table 7.9: Single factor ANOVA for the interaction of coal feed quality with process efficiency and quality of product and discard streams.

	Indicator of statistical significance			
	p-value	Alpha value	f-value	f-critical value
Product yield	0.78	0.05	0.09	7.71
EPM	1.4E-04	0.05	61.71	7.71
Misplaced to product	0.62	0.05	0.29	7.71
Misplaced to discard	0.37	0.05	1.01	7.71
Product ash value	1.12E-03	0.05	70.30	7.71
Product CV	1.1E-03	0.05	70.48	7.71
Product D_{50} density	0.50	0.05	0.56	7.71
Product D_{50} PSD	0.61	0.05	0.32	7.71
Discard ash value	0.21	0.05	2.22	7.71
Discard CV	0.22	0.05	2.06	7.71
Discard D_{50} density	0.81	0.05	0.07	7.71
Discard D_{50} PSD	0.11	0.05	4.05	7.71

The ANOVA single-factor statistical analysis was used to compare the product quality and process efficiency of the two coal samples under investigation. The obtained p-value, f-value and

f-critical value of 1.4E-04, 61.71 and 7.71, respectively for EPM, highlight the statistical significance of coal feed quality on process efficiency. Additionally, the f-value and f-value obtained for the influence of coal feed quality on product ash and calorific values meet the criteria for statistical significance. These results indicate that separation efficiency and product quality are determined by coal feed quality or more specifically the particle properties of the feed such as size, shape and density.

7.1.5.5 Particle size

The Waterberg coal yields a smaller PSD in the product, while the PSD of the feed and discard remain relatively similar. In contrast, the Moatize coal exhibits similar PSDs between the feed and product, with a slightly larger PSD observed in the discard. As mentioned, this indicates a liberation effect of more vitrinite rich coals at size of +3.2-6.7 mm.

Interestingly, the Waterberg sample reports 38.78% of particle misplaced to the product whereas the Moatize sample reports 9.09%. The misplacement of the particles to the discard are similar for both samples at 14.63% and 9.58%. These findings suggest that particle size distribution may also affect the misplacement phenomenon, along with the nature of the density distribution. Moreover, it provides an indication that the machine is separating on weight and not density, where finer discard materials report to the product. This misplacement of particles to the product is less for the Moatize sample on account of the more homogenous size and density properties of the feed.

7.1.6 Conclusion

Observations indicate that beneficiation of +3.2-6.7 mm coal is feasible by employing processes like SEP-AIR, resulting in improved ash and calorific values in the final product. These improved product qualities are considered suitable for thermal coal used for electricity generation, synthesis of fuels and export thermal coals as the ash, calorific and moisture values fall within the respective required ranges (Steyn and Minnitt, 2010). Detailed product specifications in terms of size, moisture, ash value, and calorific value for different coal categories are outlined in Table 7.10 (Steyn and Minnitt, 2010).

Table 7.10: Product specifications of coal for various South African coal markets (Steyn and Minnitt, 2010).

	Size (mm)	Moisture (%)	CV (MJ/kg)	AV (%)
Thermal coal	0-40	<12	>21.0	<34
Synthesis of fuels	-	<10	>22.6	<30
Domestic	0-40	<12	>24.5	<21
Export	0-50	<12	>27.5	<15

The particle size range of +3.2-6.7 mm corresponds to the duff size category, exhibiting moisture values ranging from 1.5% to 1.8%. This size range and moisture content is suitable for all four segments of the South African coal market. Furthermore, the ash and calorific values of the products derived from the Waterberg sample is suitable for thermal, synthesis of fuels and domestic markets. The Moatize sample is suitable for all four markets.

Additionally, the separation efficiencies achieved through SEP-AIR and ranging from 0.05-0.20, align with those attained by most other dry methods employed for processing small coal (Davaasuren *et al.*, 2016; Wotruba *et al.*, 2010; Fu *et al.*, 2019; Macpherson and Galvin, 2010; Morgan *et al.*, 2019, 2020, 2021). Separation efficiencies are, however, poorer than those obtained from water-based dense medium plants, processing the same size and yielding EPM of 0.025 and cut-point density of 1.35 kg/m³ (SAPCS, 2015).

It is worth noting that altering fan settings and, consequently, air velocity, has limited impact on the separation efficiency of the process. However, it significantly affects the overall yield. It is important to emphasize that a discernible difference in product quality was observed based on variations in the initial coal feed qualities. The empirical, analytical, and statistical observations presented above indicate that the fluidization properties, crucially determining particle movement, are susceptible to substantial influences from the inherent characteristics of the particles within the unit. The configuration of the SEP-AIR unit induces a semi-fluidized bed of particles, endowed with pseudo fluid attributes. Notably, variations in particle properties, encompassing size, shape, and density, exert discernible effects on the pseudo fluid, thereby altering its performance characteristics. Consequently, the separation efficiency witnessed in the SEP-AIR apparatus may be significantly influenced by notable distinctions in the particle properties introduced to it.

The observed relationships between particle and airflow properties and the unit's performance suggests that the prevailing conditions within the system are influenced by the particle properties, rather than being solely dependent on airflow. Thus, changes in density, size, and shape of the particles may have a more pronounced influence on the unit's separation efficiency than alterations in air speed which in turn affects the product yield. This underscores the significance of knowing and controlling the feed quality to regulate the resulting product quality (De Korte, 2013). However, changes in the air flow profile (and not just speed) may have an impact on the separation efficiency and subsequent product quality—requiring more investigation.

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CHAPTER 8: CONCLUSION AND RECOMMENDATIONS

This chapter encapsulates the summarized conclusions and recommendations from the extensive research in this thesis. The conclusions align with the research objectives in Chapter 1, Section 1.2. Complementary to these conclusions, recommendations pertaining to the SEP-AIR technology are furnished within this chapter, serving as a compass for prospective investigations and deeper explorations of the subject matter.

8.1 Conclusions

The ensuing conclusions have been arrived at throughout this research endeavour and are succinctly outlined in direct response to the stipulated objectives expounded in Chapter 1, Section 1.2:

- Chapters 1 and 2 of this study address the first research objective, emphasizing coal's global significance due to its abundance, cost-effectiveness, and reliability. South Africa heavily relies on coal, particularly in the energy, export, metallurgy, and petrochemical sectors, with this dependence expected to persist. Coal beneficiation predominantly employs water-based methods, presenting challenges in regions with limited water resources like South Africa. Despite a growing demand for small coal fractions, these valuable resources are often overlooked. However, the distinctive characteristics of these smaller particles complicate the beneficiation process. Furthermore, in remote and underdeveloped areas of South Africa with limited infrastructure, the mining and beneficiation of coal become logistically challenging. The industry is actively exploring dry coal beneficiation as a potential solution in response to these challenges.
- Chapter 3 addresses the second research objective, highlighting the transition towards waterless coal processing driven by economic and environmental considerations. However, this shift must consider various limitations, including coal type, particle size, moisture content, and operating parameters. Several dry processing methods are available, but they face efficiency challenges, capital and operating cost concerns, and the need for suitable feed preparation. Among the commercially established dry processing methods, gravity-based separators such as the air-jig, air-table variants (including FGX, standard, AKAFLOW, and KAT), air-dense medium fluidized bed (ADMFB), and suction fluidization methods like SEP-AIR, AMSEP, and NPPS are the most relevant. However, the air-jig and FGX, despite

their high capacities, exhibit subpar separation efficiencies. The standard, KAT, and AKAFLOW air tables are suitable only for intermediate and small coal fractions; however, offering reduced capacity. Notably, the ADMFB stands out with superior separation efficiency and precise cut-point density, but it involves complex post-processing requirements for coal and dense medium recovery, which may not be efficient in dry processing scenarios. Moreover, the fine-sized dense medium used in the ADMFB is moisture-sensitive, making it less suitable in wetter conditions. In contrast, the SEP-AIR offers slightly reduced separation efficiency compared to the ADMFB but does not require a dense medium, mitigating related operational challenges. This method excels in high throughput, accommodates a wide range of particle sizes, and is particularly effective in handling large and small particles.

- In Chapter 4, Section 4.1, the third research objective is discussed, focusing on the SEP-AIR process as a prominent research area within South African coal processing. However, a noticeable gap exists in the published studies regarding its separation efficiency, particularly concerning smaller coal fractions.
- Chapter 4, Sections 4.2 and 4.3, encompass a portion of research objective 4, where the feasibility of employing the SEP-AIR for coal fraction beneficiation below 13 mm is explored using an in-house designed laboratory-scale separation unit, adhering strictly to the manufacturer's specifications. The investigation evaluates the impacts of various design and operational parameters on the process.
- In Chapter 4, Section 4.4, an analysis of airflow attributes is provided as stipulated in Objective 4. This investigation aims to establish an accurate and stable air velocity profile across the separating unit concerning speed and direction at different suction fan settings. The findings reveal that air velocities fall within the transitional and turbulent regimes. The airflow enters horizontally through both inlets and ascends vertically in a curved trajectory, forming a vortex within the vortex chamber. This vortex accelerates through the connecting pipe, decelerates within the collecting bin, and exits through the suction fan. Experimental measurements using an s-type pitot probe unveil variable flow directions near the wall, suggesting the presence of eddying currents, a phenomenon that can influence airspeed. Additionally, smoke tests validate the observed airflow directions. Uniform air velocities are noted in the inlets and connecting pipes, with minor variances. However, a substantial variance is observed within the fluidizing box, particularly with higher airspeeds in its lower section and near the connecting pipe. Furthermore, the impact of varying inlet gap heights is explored, showing minimal effects on airspeed within the inlets and connecting pipes. Nonetheless, substantial disparities become evident in the fluidizing box. Varying inlet gap

heights significantly influence the velocity profile, affecting the formation of semi-fluidized particulate bed and influencing separation efficiency.

- Chapter 4, Sections 4.5 and 4.6 address the last portion of objective 4, relating to particle interactions, where firstly, individual tracers exhibit distinct trajectories and velocities once they achieve sufficient fluidization for capture, reinforcing the formation of a vortex within the vortex chamber, increased airspeed in the connecting pipe and decreased airspeed in the collecting bin. Secondly, the design of the air inlet, featuring two inlets drawing air inward, results in the suction of tracers from the fan-side inlet, but the inflow of air from the other-side inlet augments tracer fluidization. Third, the fluidization of individual tracer particles is characterized by turbulence throughout the fluidizing box, without a discernible trajectory pattern. Tracers respond to local air stream conditions, fluidizing and accelerating in high-velocity regions, decelerating and descending in low-velocity areas, and exhibiting swirling and tumbling motions within eddying currents. These movements continue until a tracer is captured as a product or descends as a discard. Fourth, the interaction between tracers and the conveyor surface influences the time required for tracers to become energized by airflow and initiate fluidization. This suggests that initial particle movement induced by vibration, or a rougher surface plays a vital role in efficient particle fluidization. However, it is essential to acknowledge that particle interactions can also have adverse effects, altering a particle's trajectory. The multiple particle investigations show that particle interactions might indeed enhance separation efficiency by reducing the fan setting that captures a similar density individual particle. This elucidates the formation of a semi-fluidized bed, aiding the separation. Further experiments show that overloading and underloading the system negatively affects the fluidization and subsequent product yields. Increasing experiment residence times improved product yield but had no discernible influence on product particle size.
- Chapter 5, Sections 5.1, 5.2 and 5.3, revolve around the fifth study objective, encompassing airflow simulations and particle tracks within the separation unit. This investigation concentrated on three distinct airflow intensities: low, medium, and high. The comparison between the modelled and experimental velocities indicates a substantial level of agreement, as reflected in the coefficient of determination (R^2). Nonetheless, certain deviations were noted in the predicted velocities within the fluidizing chamber, signified by the root mean square error (RMSE) and mean absolute error (MAE) values. For the low-flow system, the R^2 , RMSE, and MAE values were calculated at 0.95, 1.13, and 0.81, respectively. Similarly, in the medium flow system, the R^2 , RMSE, and MAE values were determined to be 0.93, 4.09, and 3.09, respectively. Lastly, the R^2 , RMSE, and MAE values were obtained within the high flow system as 0.94, 6.78, and 5.14, respectively. In Chapter

5, Section 5.3, the analysis of simulated particle tracks is provided, which validate the observations made during the tracer tests. The seemingly random movements of particles can be classified into three categories with the assistance of these tracks, i) particles that immediately fluidize and are subsequently captured, ii) particles that continue to circulate in the lower section of the fluidizing box, with the possibility of being captured or remaining in the fluidized state, and iii) particles that remain on the conveyor plate. Notably, these different simulated behaviours are observable among particles sharing identical properties, highlighting the significant role played by the air velocity profile within the fluidizing box in shaping particle trajectories, regardless of their individual characteristics. Additionally, regardless of their position, particles within the system exhibit continuous motion, emphasizing the dynamic nature of particle movement and interactions.

- Chapter 6 addresses study objectives 6 and 7 in part, relating to beneficiation of +6.7-13.2 mm particles. Three coal samples, namely WB1, WB2 (from the Waterberg coalfield in Limpopo, South Africa), and MOAT (from the Moatize coalfield in Tete, Mozambique), were investigated, resulting in separation efficiencies (EPMs) of 0.25, 0.05, and 0.04, and product yields of 81%, 81%, and 82%, respectively. Improvements were observed in product ash values, with WB1 decreasing from 36% in the feed to 26% in the product, WB2 decreasing from 20% to 10%, and MOAT decreasing from 17% to 12%. Calorific values also increased, with WB1, WB2, and MOAT reaching 26 MJ/kg, 32 MJ/kg, and 32 MJ/kg, respectively. Minor enhancements in cut-point densities were noted as well. Analysis of Variance (ANOVA) results highlighted the significant influence of coal feed quality on separation efficiency and product quality. Additionally, airspeed was found to impact product yield and discard quality, with higher air speeds leading to increased yields and higher ash values in the discard, while adjustments to fan settings minimally affected product quality.
- Chapter 7 addresses study objectives 6 and 7 concerning +3.2-6.7 mm particles with coal samples originating from the Waterberg and Moatize coalfields and yielding separation efficiencies (EPMs) of 0.15 and 0.05, respectively. Improvements were observed in product quality, with the product ash value decreasing from 34.12% in the feed to 27.91% for Waterberg and from 16.52% in the feed to 13.12% for Moatize. Similarly, calorific values improved from 22.60 MJ/kg in the feed to 25.06 MJ/kg for the Waterberg and from 29.56 MJ/kg in the feed to 30.75 MJ/kg for the Moatize. The yield was reported at 75% and 95% for the Waterberg and Moatize, respectively. Furthermore, slight enhancements were observed in the cut-point densities, with values changing from 1.61 SG in the feed to 1.55 SG in the product for Waterberg and from 1.44 SG in the feed to 1.43 SG in the product for Moatize. The ANOVA test revealed that coal feed quality had the most significant influence on product quality, while airspeed notably impacted product yield, with higher air speeds

resulting in increased yields. Fan setting adjustments minimally affected product quality. Differences in the product's PSDs and discard compared to the feed show that particle size separation occurs. Moreover, this particle size separation links into particle misplacement, indicating that the machine separates on weight, not density.

- In summary, the efficiency tests demonstrate that the SEP-AIR effectively beneficiates several coal types, resulting in high product yields and improved product quality, notably reduced ash values, while achieving separation efficiencies comparable to similar dry processes. However, observations of particle misplacement suggest suboptimal operating conditions for proper particle fluidization, stratification, and capture. Changes in air velocity impact yields and discard quality but have minimal effects on product quality. Alterations in particle properties influence both product quality and separation efficiency. This highlights the interconnected influence of particle and airflow properties on the overall performance of the SEP-AIR, along with certain design parameters, as evident in simulations, individual particle experiments, multiple particle experiments and efficiency tests.

8.2 Recommendations

Based on the findings, the following recommendations are proposed for future research to gain deeper insights into the operation and capabilities of the SEP-AIR for dry coal beneficiation.

- Conduct comprehensive tests to investigate the impact of varying inlet gap heights on the velocity profile within the fluidizing box, encompassing a wider range of gap heights than those considered in this study. Furthermore, perform efficiency tests to elucidate the influence of different velocity profiles resulting from adjustments in the inlet gap height on separation efficiency, product quality, and particle misplacement. Since airflow has been demonstrated to affect product yield, gaining a more profound understanding of the effects of different velocity profiles induced by altering the inlet gap height and varying the suction fan setting for increased velocity could provide valuable insights.
- Conduct tests to investigate the effect of different moisture contents ranging from 0 to 12% (the threshold described by the South African market for several small coal products) on separation efficiency. While most studies show that the SEP-AIR can operate with coal moisture contents of 3–7% for larger coal fractions, the impact of increasing moisture on the separation efficiency of small coal fractions is not widely reported. This study uses air-dried coal with moisture content below 2%. However, even slight differences in moisture could potentially affect the separation efficiency of small coal in the SEP-AIR, given that particle properties govern the separation mechanism, and higher moisture content leads to increased particle mass. Understanding the potential trend of separation efficiency from

completely dry to the market threshold is important, as processing at "as-received" moisture contents would save on drying costs and prevent handling issues associated with dry coal.

- Conduct tests to examine the effects of different feed particle size ranges on separation efficiency, product quality, and particle misplacement. Notably, in the present study it is observed that a particle size separation phenomenon occurred with the product yielding smaller D_{50} particle size cut-points than the discard. Since particle properties have been shown to impact product quality and separation efficiency, an investigation into the effects of particle size can offer valuable insights into particle misplacement and its implications.
- Enhance the accuracy of CFD simulations of airflow and particle tracks by focusing on the fluidizing chamber, where significant discrepancies were observed. This can be achieved by exploring more advanced transition and turbulence models within STAR-CCM+ to capture better the interaction between the upward airflow and the vortex. The refinement of meshing models in this specific region can also improve predictions. Additionally, considering the use of different transition or turbulence models for various flow profiles observed in different sections of the suction nozzle may lead to more accurate velocity predictions and, in turn, particle tracking.
- The laboratory-scale separating unit commissioned at the North-West University could benefit from re-designing the conveyor plate feeding system. Introducing an automated, porous and continuous conveyor system would allow for testing the effects of particle feed in terms of mass, speed, and orientation. This adjustment is particularly valuable given the limitations of most belt-driven processing techniques and the observations made by employing a frictional surface and initial vibration to the particles during this study.
- To investigate potential improvements in flow patterns observed, adjustments to the design of the separation nozzle are warranted. The current configuration of the inlet and vortex chamber leads to the development of a pronounced s-shaped airflow profile, resulting in dead spots and eddying currents within the fluidizing chamber. To address this, a potential enhancement involves a slight outward taper of the bottom of the fluidizing box at a 45-degree angle, facilitating a more uniform velocity profile across the entire width of the fluidizing chamber while mitigating low-flow regions near the walls. Modifying the gap height on the other-side (OS) to be slightly smaller than that of the fan-side (FS) inlet may enhance the formation of the fluidized bed in the lower sections of the fluidizing box, thereby ensuring adequate particle fluidization. Additionally, incorporating a lip in the suction nozzle section where the vortex interacts with the upward-flowing air may help reduce the negative influence of the vortex on the velocity profile within the fluidizing chamber.

- A comprehensive economic evaluation of the SEP-AIR process is highly recommended. This evaluation should cover all stages, from mining run-of-mine (ROM) coal to converting energy to electricity. It should also consider waste management and associated costs for a thorough economic assessment.
- Additionally, a proposed approach can involve a combination of continuous drying and separation operations. The airflow through the suction nozzle capitalizes on the porous characteristics of the coal, making it feasible to rapidly reduce significant moisture content in the coal. Furthermore, using adsorbent-assisted drying techniques necessitates a subsequent separation process to segregate the adsorbent from the coal. This separation can be effectively achieved using the SEP-AIR, leveraging the notable distinctions in density, size, or shape between the adsorbents and coal.
- Broaden the investigation into the practical approaches for pre-and post-processing small coal for beneficiation in the SEP-AIR, particularly concerning screening for the different size ranges below 6mm and handling, storage, and transport of said feed and the obtained products.