



Development and evaluation of a pneumatic grain separation system using CFD and DEM

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

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DECLARATION OF AUTHORSHIP

I, Paul Greyvensteyn, declare that this dissertation presents my original work. Whenever contributions of others are involved, every effort was made to indicate this clearly, with due reference to the literature.

No part of this work has been submitted in the past or is being submitted for a degree or examination at any other university or course.

Signed at Potchefstroom on 01/02/2024.

Paul Greyvensteyn

PREFACE

The format of this dissertation is in accordance with Academic Rule 4.10.5, which states: "Where a candidate is allowed to submit the research product in the form of a research article or articles, such research product must be presented for examination purposes as an integrated unit, supplemented with a problem statement, an introduction and a synoptic conclusion as prescribed by faculty rules and the manuscript submission guidelines, or the URL link to the manuscript guidelines, of the journal or journals concerned."

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Styles of numbering and referencing

It should be noted that the formatting, style of referencing, figure and table numbering and general outline of the one co-authored and three original articles, as required by the editors of the publications, have been modified for the sake of uniformity in the thesis. No modifications to the original texts (apart from minor spelling or typographical errors) of the papers were made because these articles had already been peer-reviewed and/or were accepted/submitted for publication. Some articles have already appeared in print and are available online.

STATEMENTS OF CO-AUTHORS

The following co-authors are recognised for their contributions, and their statements follow:

Prof LJ Grobler

Dr. OC Koekemoer

Mr. DB Vorster

Statement of consent: Prof LJ Grobler

To whom it may concern, I, LJ Grobler, give my consent to Paul Greyvensteyn, candidate for the degree Master in Mechanical Engineering at the North-West University, to include in his dissertation entitled: **Development and evaluation of a pneumatic grain separation system using CFD and DEM**, the following publications, of which I am a co-author:

P. Greyvensteyn, O. Koekemoer, L. Grobler, and D. Vorster, “Design and Testing of a Pneumatic Grain Aspirator for Efficient Separation of Impurities,” in *Proceedings of the 12th International Conference on Mechanics and Industrial Engineering*, London: Avestia, Aug. 2023. doi: 10.11159/icmie23.141.

P. Greyvensteyn, O. Koekemoer, L. Grobler, ‘Grain Aspirator: Validation and Performance Analysis Optimisation using a coupled CFD-DEM simulation approach’, Complete and ready for publication.

The relative contributions to the paper by the different authors are given in each respective article. This statement serves to comply with academic rules 4.10.8 and 4.10.9 of the North-West University.

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To whom it may concern, I, Ockert Koekemoer, give my consent to Paul Greyvensteyn, candidate for the degree Master's in Mechanical Engineering at the North-West University, to include in his dissertation entitled: **Development and evaluation of a pneumatic grain separation system using CFD and DEM**, the following publications, of which I am a co-author:

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To whom it may concern, I, Danie Vorster, give my consent to Paul Greyvensteyn, candidate for the degree Master in Mechanical Engineering at the North-West University, to include in his dissertation entitled: **Development and evaluation of a pneumatic grain separation system using CFD and DEM**, the following publications, of which I am a co-author:

P. Greyvensteyn, O. Koekemoer, L. Grobler, and D. Vorster, “Design and Testing of a Pneumatic Grain Aspirator for Efficient Separation of Impurities,” in *Proceedings of the 12th International Conference on Mechanics and Industrial Engineering*, London: Avestia, Aug. 2023. doi: 10.11159/icmie23.141.

The relative contributions to the paper by the different authors are given in each respective article. This statement serves to comply with academic rules 4.10.8 and 4.10.9 of the North-West University.

Signed at Potchefstroom on 01/02/2024.

Mr. Danie Vorster

LIST OF PUBLICATIONS

The publications presented in this dissertation in accordance with rule 4.10.8 are:

Article 1

Manuscript guidelines - <https://icmie.net/author-guidelines/>

P. Greyvensteyn, O. Koekemoer, L. Grobler, and D. Vorster, “Design and Testing of a Pneumatic Grain Aspirator for Efficient Separation of Impurities,” in *Proceedings of the 12th International Conference on Mechanics and Industrial Engineering*, London: Avestia, Aug. 2023. doi: 10.11159/icmie23.141. (Best Paper Award)

Article 2

P. Greyvensteyn, O. Koekemoer, L. Grobler, ‘Grain Aspirator: Validation and Performance Analysis Optimisation using a coupled CFD-DEM simulation approach’, Complete and ready for publication.

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ABSTRACT

As the global demand for food continues to increase, grain and seed cleaning equipment has to evolve along with it. The demand for efficient grain and seed cleaning equipment is rising, underscoring its crucial role in maintaining the quality and efficiency of agricultural processes. This equipment is essential for enhancing grain and seed quality by removing impurities like chaff, toxic seeds, and dust, thereby reducing spoilage and increasing market value. Pneumatic grain separators are particularly effective in removing these lightweight impurities, operating on principles of airflow and density to separate contaminants from grain. Despite the industry's reliance on trial-and-error methods, this study aims to examine the hydrodynamics of grain particles in pneumatic separators to contribute and assist in the development of more efficient cleaning equipment, ultimately benefiting the agricultural and food processing sectors. This study seeks to leverage the precision of numerical modelling techniques like Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM), as well as coupled CFD-DEM simulations, despite the inherent complexity and challenges in their implementation to aid in both the development and increased performance of pneumatic separators. This study is stratified into two approaches: (a) concept development using CFD simulations to simulate the airflow, pressure drop, and recirculating phenomena within the aspirator and (b) aspirator analysis and optimisation using coupled CFD-DEM simulations.

This research employs numerical modelling techniques to design and optimise pneumatic grain separators for agricultural and industrial applications. Utilising ANSYS Fluent® for fluid flow and Rocky® DEM for particle dynamics, the study offers a multiphase two-way coupling approach to investigate particle hydrodynamics. This study addresses a gap in the existing literature and presents an integrated methodology with the potential to transform the agricultural and food processing industry. This study investigated the development and testing of a grain aspirator and the validation of CFD, DEM and coupled CFD-DEM simulations.

In the first approach, a horizontal pneumatic grain aspirator was simulated, designed, manufactured, and evaluated for cleaning maize and soya. Utilising ANSYS Fluent® simulations and real-world prototype testing, the aspirator's design was optimised for efficient impurity separation. The final model achieved a 95.9% efficiency rate, offering a reliable method to enhance grain cleaning in agriculture and the food processing industry.

The second approach employed a two-way coupled CFD-DEM simulation in the ANSYS-Rocky[®] framework to optimise a grain aspirator system. A two-tiered validation approach was used, comparing the simulation's outputs to empirical data and experimental results. The simulation results are in good comparison to the experimental results, with a cleaning efficiency error of only 4.69% and a cleaning loss error of 6.18%. This validated coupled CFD-DEM methodology optimised the grain aspirator and provided key insights for a more time and cost-efficient design process. Therefore, this approach can form the basis for designing and optimising complex hydrodynamic systems.

Keywords: Aspiration, CFD, DEM, Grain, Impurities, Separation

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CHAPTER 1 - INTRODUCTION

This chapter consists of the introduction, where a detailed background and rationale, problem statement and purpose, aim and objectives, research methodology and experimental methods for the dissertation are provided.

1. Introduction

1.1 Background and rationale

The global grain and seed cleaning equipment market is expanding due to rising food product demand, intelligent farming technology acceptance, and agricultural mechanisation adoption [1]. Studies [2] suggest that the global grain and seed cleaning market size is anticipated to increase by 6.6% each year between 2023 and 2028, where the rising demand for customised grain and seed cleaning equipment is one of the major factors driving growth in the global market for grain and seed cleaning.

According to Rosentrater and Evers [3], cleaning equipment can aid in reducing grain loss during processing and storage, leading to a more sustainable value-added cycle. Grain quality starts to deteriorate as soon as it is harvested; therefore, it is essential to remove dust, chaff, and other contaminants to halt deterioration [3]. As part of food processing equipment, grain-cleaning equipment enhances grain quality, reduces spoilage, and increases market value [4]. Thus, better yields can be anticipated when using an air-classifying grain cleaner, as cleaner grain has a higher value than grain contaminated with straws, chaff, dirt, and other non-grain elements.

In the case where grain is stored in silos, impurities can build up in the middle of silos [3], potentially lowering the grain's quality rating when sold; additionally, these impurities occupy storage space within the silos. The use of pneumatic grain separators can reduce mould development, bug invasions, and other factors that affect the safety and quality of the grain by eliminating debris and other contaminants, therefore leading to less grain spoilage and contamination during the storage period and transportation [3]. Clean seeds and grains significantly reduce the operating costs of conveying, as the unwanted impurities are not transported. All grains and seeds undergo operations like pre-cleaning, fine cleaning, and grading before and during processing [5]. This ensures that the grain meets industry standards for both equipment safety and human consumption.

Pneumatic grain cleaning and grading operations are typically performed by gravitational, fluidised bed, inertial or centrifugal air classifiers [6]. Pneumatic separators operate on the principle of using air streams that are oriented and normalised by vanes in a certain way using a fan, as illustrated by Figure 1. According to Adewumi *et al.* [7], grain and impurity particles can be separated with a blowing airstream depending on the particle's relative density and surface condition. This separation technique delivers high-quality, accurate multi-fractional separation of

various grains and seeds and offers many adjustable approaches to each particle of the separating flow [7]. A pneumatic cleaner is often far more adaptable and easier to use, as the fan speed is adjustable for various grain types, sizes, and throughput rates. Grain particles that differ from the impurities in relative density, size and shape can be separated, meaning the airflow will lift the dust and other minor pollutants from the mixture.

The working principle of the two pneumatic grain separators that will be focussed on in this dissertation can be seen in Figure 1 and Figure 2 below. Figure 1 represents a cascade (zig-zag) classifier, and Figure 2 shows a crossflow gravitational air classifier.

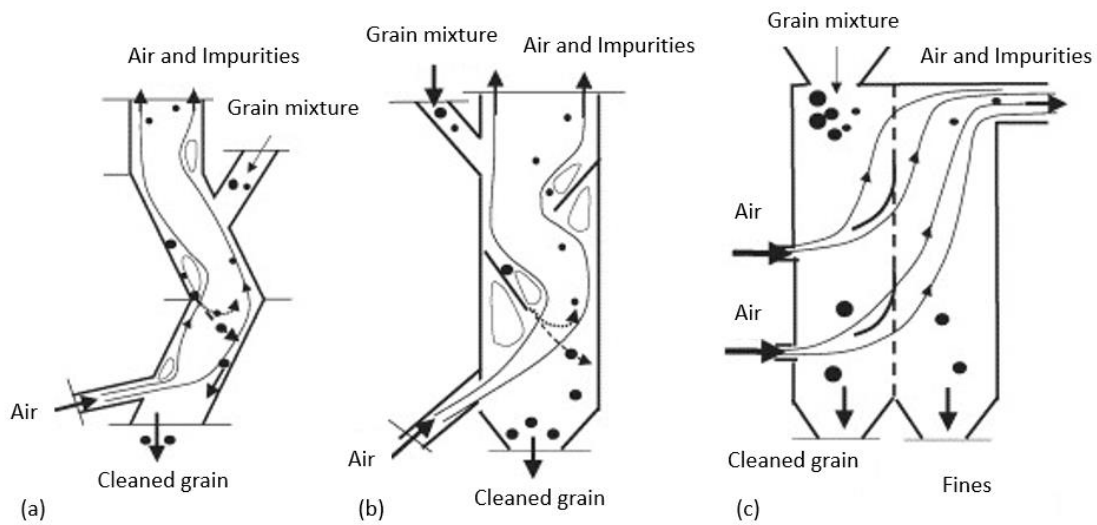


Figure 1: Cascade (zig-zag) air classifier, adapted from [6]

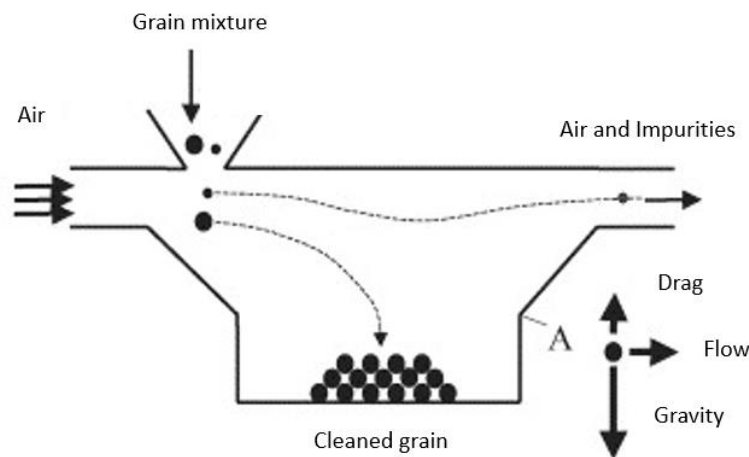


Figure 2: Crossflow gravitational air classifier, adapted from [6]

A well-known method for cleaning, separating, and classifying grains is pneumatic separation. In the industry, much of the aerodynamic data necessary to optimise impurity separation has been collected through trial-and-error approaches. However, due to the shape complexity and wide range of grain particle properties, studying the hydrodynamics of grain particles and impurities in pneumatic grain separators is challenging. Overall, the study contributed to developing more efficient grain and seed cleaning equipment, which can improve the sustainability and profitability of the agricultural sector, oil seed extraction, and milling industry.

Note: Grain classifiers and aspirators are commonly misunderstood in the industry. This study focuses on a grain aspirator, which can be defined as removing lightweight impurities from the prominent grain using an airstream. Thus, a grain aspirator is a pneumatic particle separator which classifies a grain mixture into two different streams.

1.2 Research problem and research purpose

Motivated by the various advantages of pneumatic grain separators, a compact, energy-efficient and low-maintenance pneumatic grain separator should be developed and tested. The design process generally relies heavily on trial-and-error methods, which, while functional, lack the precision offered by numerical modelling techniques like Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM). Numerical modelling techniques such as CFD and DEM offer several advantages when developing pneumatic grain separation systems; however, properly implementing these techniques can present a significant challenge.

1.3 Aim and objectives

This study aims to develop a pneumatic grain separation system that separates lightweight impurities from the prominent grain, using numerical modelling during the design process.

The objectives are the following:

Article 1

- Develop a cascade (zig-zag) type air aspirator concept that meets the requirements.
- Perform CFD simulations to aid with the design of the aspirator.
- Verify the CFD simulations.
- Develop the aspirator.
- Construct an experimental setup.
- Validate the CFD simulations.

Article 2

- Construct an experimental setup.
- Perform coupled CFD-DEM simulations on the cascade-type grain aspirator.
- Qualitatively validate the coupled simulation approach with experiments.
- Quantitatively validate the coupled simulation approach with experiments.

1.4 Research Method

This dissertation intended to develop a grain air classifier for agriculture, oil seed extraction and the milling industry. The literature survey covered the pneumatic characteristics and engineering properties of grain particles. This analysis was followed by investigating various pneumatic particle separators' operational principles and respective advantages. The survey addressed the fundamentals of the coupled CFD-DEM simulation approach and an overview of the available software packages. The first article employed CFD to design and develop a fully functional grain aspirator that met the user requirements. The second paper elaborated on coupled CFD-DEM simulations for the pneumatic grain aspirator. The aim was to optimise the efficiency of pneumatic grain separators by leveraging simulations to accurately predict the separator's performance. A method to combine ANSYS Fluent® (CFD) and Rocky® (DEM) software in a multiphase two-way coupling for simulations was investigated. Rocky solved each unique particle's movement individually, accounting for particle interactions and collisions, whereas ANSYS Fluent® solved the continuum airflow. This way, the hydrodynamics of the particles in the airstream was investigated. This paper filled a gap in the literature by exploring the use of coupled CFD-DEM models for pneumatic grain separators. Overall, this study provided an integrated approach to designing and developing pneumatic grain separators with the potential to revolutionise the grain and seed cleaning industry.

CFAM Technologies (Pty) Ltd. supplied manufacturing equipment, instrumentation, and funding.

Mesh Dependence Test

In accordance with established guidelines in the literature [8]–[10], the mesh size during the coupled CFD-DEM simulations was specifically chosen to be at least three times the diameter of the largest particle in areas where particles and airflow are expected to interact. This ensured that each computational cell in these regions had adequate fluid volume for accurate fluid-particle interactions, which was solved by the volume-averaged Navier-Stokes equations [9]. A smaller

mesh size was employed in other areas where such interactions are less critical. The mesh cells were optimised to allow for mesh independence by ensuring that further mesh refinement will not significantly alter the simulation results while abiding by the guidelines for coupled CFD-DEM mesh cell formulation.

1.5 Experimental methods

The plan was to conduct a comprehensive study on the performance of pneumatic grain separators, supported by a thorough experimental validation process.

The pneumatic grain separator was calibrated to standard operating parameters (airflow and grain throughput) to ensure consistency throughout the various experiments. The impurity composition in the mixture was defined prior to the testing phase and used as a reference point for the cleaned samples.

The method included collecting grain samples from the different outlets and analysing the contents in the grain samples after cleaning. The measurements were taken with adequate precision digital scales, allowing for an exact determination of the mass of impurities and, thus, assessing the effectiveness of the grain separator. The average values of the samples were used in the analysis to guarantee a balanced and reliable evaluation.

This approach to the experimental validation provided a trustworthy foundation for assessing the effectiveness of the pneumatic grain separator.

Note: Refer to Chapter 3, Chapter 4, and Appendix A for exact specifics on the experimental methods and instrumentation used during both qualitative and quantitative validation techniques.

1.6 Dissertation chapter outline

Figure 3 below clearly represents a "House of Quality" matrix layout, showing each article's role in the study.

Importance level 1 ○		Article 1	Article 2
Importance level 2 ○			
Importance level 3 ○			
		Solution characteristics (How)	
Development of a pneumatic grain separation system	Requirements (What)	○	
CFD simulations		○	○
DEM simulations			○
Coupled CFD-DEM simulations			○
Verification of CFD simulations		○	
Validation of coupled CFD-DEM simulations			○

Figure 3: House of Quality matrix planning for the articles in the study

Chapter 1

This section consists of the introduction, where a detailed background and rationale, problem statement and purpose, aim and objectives, research methodology and experimental methods are discussed. The dissertation layout will conclude this chapter.

Following the introduction of the dissertation, respective chapters were allocated for each research article.

Chapter 2

In this segment, a literature survey delves into the established understanding of pneumatic grain cleaning. It examines the operational principles and distinctive features of pneumatic grain cleaners, encompassing the pneumatic attributes, terminology, and engineering characteristics specific to grain particles. The different types of available CFD-DEM software packages for simulating the complex airflow-granular system were reviewed.

Chapter 3

This section presents the first article, which is entitled: *Design and Testing of a Pneumatic Grain Aspirator for Efficient Separation of Impurities*. The article elaborates on the simulation, development, and evaluation of a novel pneumatic grain aspirator. This peer-reviewed article was presented at the 12th International Conference on Mechanics and Industrial Engineering (ICMIE'23) and published in the Proceedings of the 9th World Congress on Mechanical, Chemical, and Material Engineering (MCM'23). After completion of the conference, the paper had another peer-review process with the session chairs and received the **best paper award**.

Chapter 4

This section contains the second article, which is entitled: *Grain Aspirator: Validation and Performance Analysis Optimisation using a coupled CFD-DEM simulation approach*. The article uses coupled CFD-DEM simulations to analyse and optimise the grain aspirator. This article is complete and ready for publication.

Chapter 5

This section refers to the conclusion and recommendations, which summarise the conclusions made in the research articles. The research purpose and objectives are evaluated, and justifications are presented to demonstrate that the objectives are met. Recommendations for additional research are made, and explanations are given to demonstrate how the study broadens the area of knowledge.

Annexures

This section contains all the data the research articles could not have presented. The instrumentation that was used for taking measurements is listed and described. The experimental setup's machinery and components are shown and elaborated on. The manufacturing techniques used during the development phase are shown. The experimental setup details, prototype, industry testing, and soybean mixture testing are all part of the first article. The data used to validate the CFD simulations are presented. It is shown that the maize mixture was first calibrated before performing the coupled CFD-DEM simulations.

CHAPTER 2 – LITERATURE SURVEY

This chapter comprises a literature survey on pneumatic particle separation and the available software packages for performing coupled CFD-DEM simulations on the system. The survey delves into the theoretical foundations and principles for comprehending pneumatic grain separator development.

Note: Each article has a literature study on detailed and specific topics related to the work in the article; the purpose of the survey is to cover broader literature that cannot specifically be addressed within the individual articles.

2. Literature survey

2.1 Pneumatic characteristics and engineering properties of grain particles

The pneumatic separation and classification of grain particles is widely adopted but also a complex process in the agricultural and food processing industries. A thorough understanding of the pneumatic properties of grain particles in airflow is required to develop pneumatic grain cleaning systems. This section of the literature survey aims to understand better the factors that influence the behaviour of grain particles in airflow.

The dominant grain particle properties that influence the behaviour of particles in airflow are the particle shape, weight, and surface conditions [11], [12]. Figure 4 below shows how particle moisture affects the rest of the properties of the grain mixture.

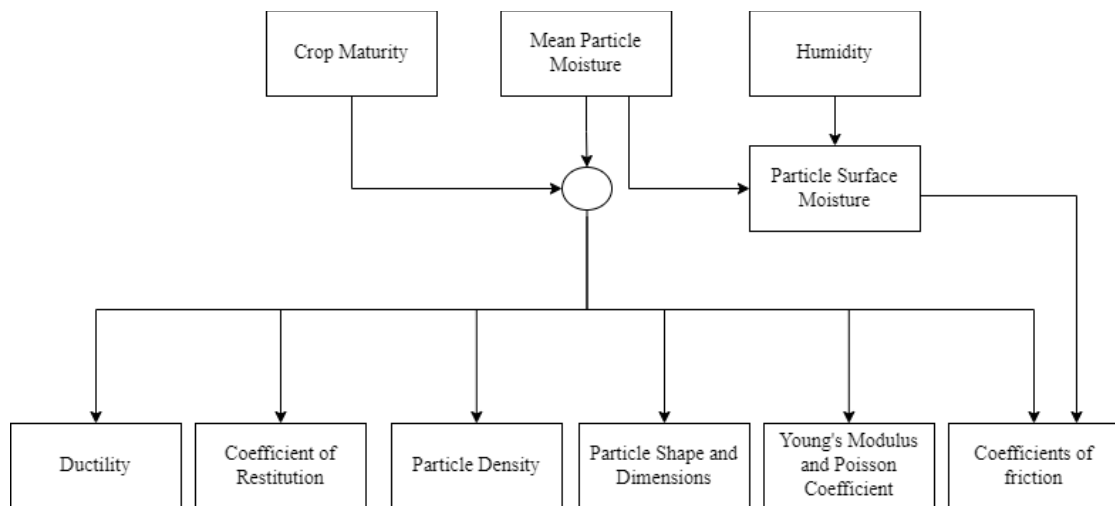


Figure 4: Particle moisture effect on the properties of the grain, adapted from [13]

Figure 5 below shows the complete flow diagram of all the present parameters, which should be accounted for in pneumatic separators.

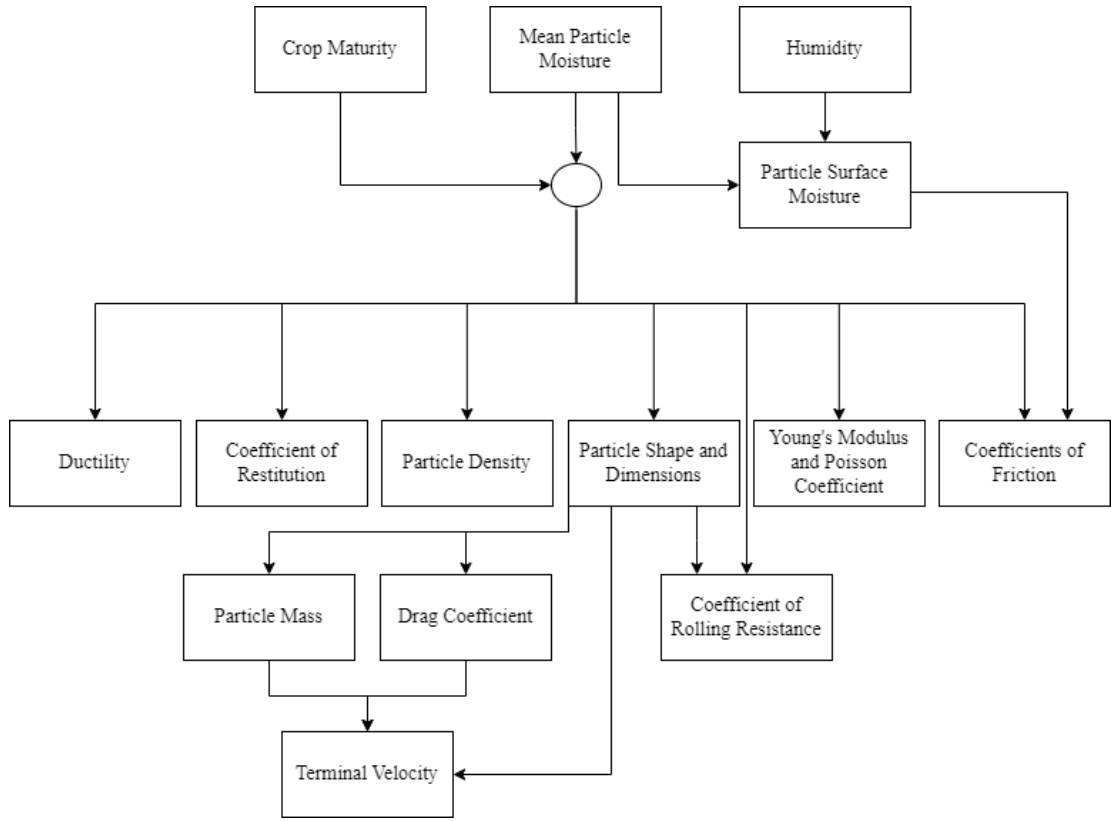


Figure 5: The particle properties influencing the terminal velocity, adapted from [13]

Figure 4 and Figure 5 show that pneumatic grain cleaning systems should be designed to quickly adapt for not only various grain types but also for the same grain mixture being cleaned at different throughput rates and having varying properties that influence the terminal air velocity. Figure 5 shows that the main influential factor is the terminal air velocity. Thus, the difference in terminal air velocity of the particulate matter in the mixture will influence the separation efficiency.

The terminal velocity of a particle can generally be described as the maximum free-falling velocity of a particle or the velocity which will cause drag and gravity forces to be in equilibrium. Theoretically, a general expression for a particle's terminal velocity can be obtained by setting the airflow resistance drag force, F_D , equal to the particle's weight, W , and assuming that the air velocity, V_a , is equal to the particle's terminal velocity V_t .

$$V_a = V_t \quad (1)$$

$$F_D = 0.5C_D\rho_fA_pV_t^2 = m_pg = W \quad (2)$$

$$V_t = \sqrt{\frac{2m_p g}{C_D \rho_f A_p}} \quad (3)$$

Where C_D represents the drag coefficient, ρ_f the fluid density, A_p the frontal area and m_p the mass of the particle. The terminal velocity of the grain is determined by the particle's frontal area, density, mass, and drag coefficient. An increase in the total mass flow of the grain mixture will require the airflow to increase above the terminal air velocity [11].

Figure 6 below shows the critical air velocity of various crops, which is the minimum airflow velocity needed to lift the seed [11].

Crop	Velocity of air (m/s)
Poppy	4.67
Phacelia	4.90
Winter rape	7.65
Oat	8.03
Sunflower	8.38
Naked oat	8.70
White mustard	9.02
Winter barley	9.06
Spring barley	9.44
Winter rye	9.53
Spring wheat	9.54
Winter triticale	9.55
Sugar beet	10.24
Sorghum	10.43
Winter wheat	10.54
Field pea	12.41
White lupine	12.87
Maize	13.29
Soya	13.84
Pea	14.85

Figure 6: Critical air velocity needed for various crops, adapted from [11]

In a vertical classifying system, the lighter impurities will only be conveyed upwards if the airflow velocity is higher than the terminal velocity of that specific particle. This condition occurs when the drag force acting on that particle overcomes the downward gravitational force. In a horizontal

separator, the impurities will still move to the side whether the airflow velocity meets the terminal velocity or not. This is due to the phenomenon that the crossflow airstream imparts a force on the particle in the horizontal direction due to the drag of the particle. The horizontal drag force will immediately cause the particle to move sideways because it is the only force acting on the particle in the horizontal direction.

2.2 Pneumatic particle separators

The classification of particulate matter occurs through a specialised air classifier or aspirator, wherein the particles undergo distinct interactions influenced by the dynamics of a directed airstream. In principle, there are four different separation zones, each with advantages and characteristics, namely the gravitational-counterflow, gravitational-crossflow, centrifugal-counterflow and centrifugal-crossflow zone [6], [14].

Gravitational counterflow pneumatic particle separation

Figure 7 below shows a gravitational counterflow-type pneumatic particle separator. This type of separator operates on the principle that an air stream rises constantly from the bottom upward through the particles. Particles in this stream are subjected to various forces, but mainly two forces pulling in opposite directions: gravity and drag. Larger and heavier particles migrate downward against the airflow if their terminal velocity exceeds the speed. Smaller and lighter particles with a terminal velocity lower than the airstream, on the other hand, rise upwards with the airstream. When gravity and drag forces balance out, the separation threshold, also known as the cut size, is established, with the condition that the terminal settling velocity matches the airflow velocity [6].

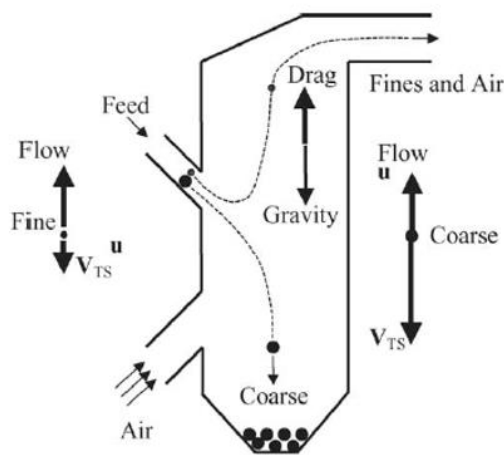


Figure 7: Gravitational counterflow pneumatic separator, adapted from [6]

Kharchenko et al. [15] experimented with a vertical gravitational counterflow separator and found that separation efficiency increases when the layer of grain is preliminary stratified.

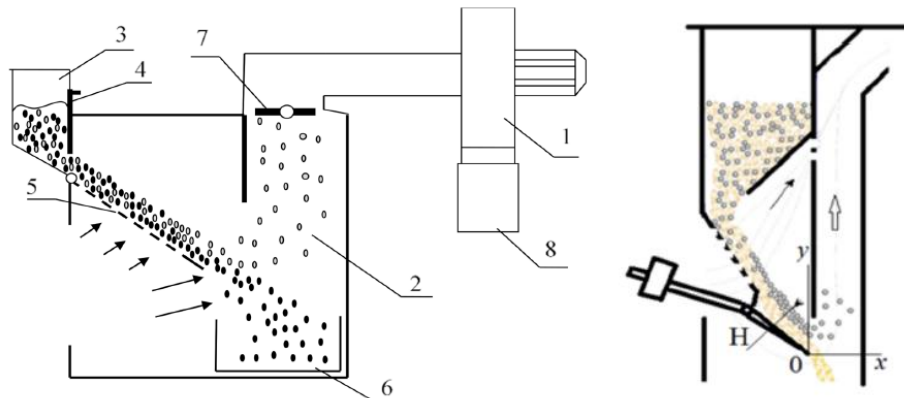


Figure 8: Preliminary stratification in a gravitational counterflow separator, adapted from [15]

The approach in Figure 8 above allows the lighter particles to float on top of the grain layer before aspiration takes place, which prevents the coarse grain particles from retaining the lighter particles. The particles enter the separator from the loading hopper (3) and then slide over the scaled surface (5), where the preliminary stratification occurs. The particles split into the pneumo-separation duct (2) and the cleaned particle hopper (6). This method of pneumatic particle separation is simple in principle and effective with low energy consumption.

Gravitational crossflow pneumatic particle separation

Figure 9 below shows a gravitational crossflow type pneumatic particle separator, which functions on the winnowing principle. A horizontal air stream enters the chamber while being orientated in a particular direction toward the outlet in the horizontal crossflow type separator. The particles enter the chamber at nearly zero velocity and promptly fall into the airstream. Because of the shape of each particle, the drag force accelerates them horizontally, while gravity causes them to fall. By the end of this acceleration phase, the particles' horizontal velocity nearly equalled the airflow speed, resulting in no separation in the horizontal direction [6]. The particle separation occurs due to the particles' vertical movement [6]. Each particle descends with its terminal velocity, settling in different parts of the chamber—coarse particles at the intake, finer particles closer to the outlet, while the lightest particles are blown out with the airstream. Shapiro and Galperin [6] state that particle separation is a two-dimensional process within the crossflow type separator. Unlike in the vertical counterflow zone, the cut size here is influenced not only by the

terminal velocity of the particles but also by the dimensions of the chamber, which defines where the different fraction sizes of the mixture end up.

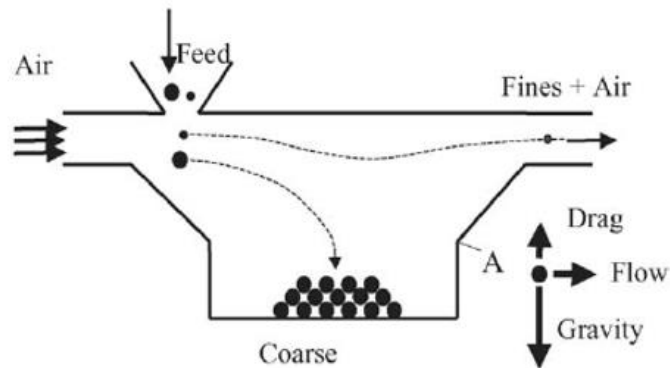


Figure 9: Gravitational crossflow pneumatic separator, adapted from [6]

Research papers [7], [16]–[20] elaborate on the gravitational crossflow type pneumatic particle separator with the following main findings:

- The initial particle mixture can easily be classified into various sections.
- This concept has a low energy consumption.
- The optimal blower angle for each particle mixture will differ, ranging from 0° to 45° .
- An increase in particle moisture reduces the separation efficiency.
- An increase in airflow velocity increases the separation efficiency and the number of valuable particles being carried away.

Panasiewicz et al. [21] show an exciting concept of gravitational crossflow pneumatic grain cleaning in Figure 10, where the crossflow airflow flows in a vertical direction and the grain in a horizontal direction.

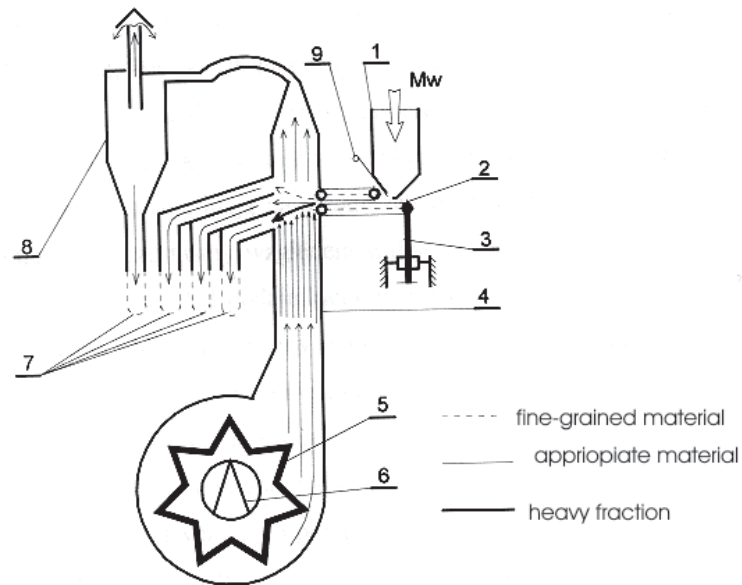


Figure 10: Vertical crossflow gravitational separator, adapted from [21]

This concept proved to give suitable purification and separation of the grain mixture if the airstream was well regulated [21]. The particles enter through the hopper (1) and conveyor (2), into the cylindrical separation channel (4) with a fan (6), causing the mixture to fractionate in the throughs section (7). The airstream intensity, feed rate and the feeding method are the most influential factors to account for [21]. This concept of gravitational grain cleaning will not produce a significant pressure drop for the fan to overcome and can classify the grain.

Figure 11 below shows a concept with multilayer feeding in the gravitational crossflow pneumatic separator. The particles enter through the batcher (1), leading to the gates (2) and multilayer feeder device, causing the particles to enter the pneumatic separation channel (4) in multiple layers. The heavier particles pass through the louvres (10), and the lighter particles collect at the impurity outlet (11).

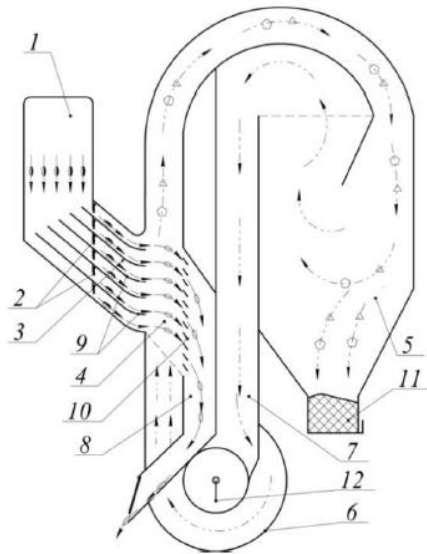


Figure 11: Layered grain feeding for gravitational crossflow pneumatic separator, adapted from [22]

Nesterenko [22] states that multilayered feeding increases the separation efficiency by up to 30%, but this method significantly decreases the particle's separation rate.

Figure 12 below shows a leg (cascade) aspirator, a mixture between a counter and a crossflow-type gravity separator.

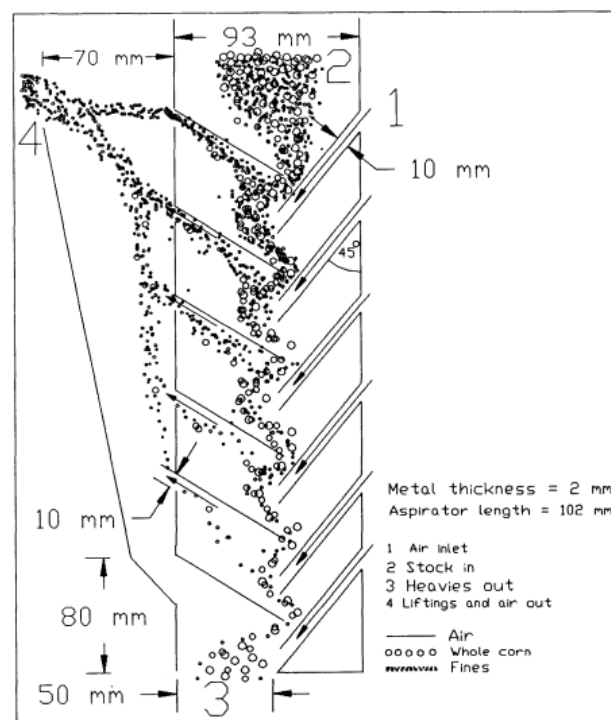


Figure 12: Kice Leg Aspirator, adapted from [23]

Al-Yahya et al. [23] state that the aspirator can achieve high efficiencies without appreciable removal of whole pieces, and the aspirator can also be adjusted to remove the fines from the mixture.

Figure 13 below shows a gravitational pneumatic separator, where the grain is fed onto a cone from the top, and airflow is supplied from (1) where the grains collide with the cone, (2) in the area of separation, and (3) at the output of the grain fractions. The airflow causes the lighter particles to spread to the sides more than the heavier particles. The grain fractions of the highest density will accumulate at (I), medium density fractions at (II), and the lowest density fraction at (III).

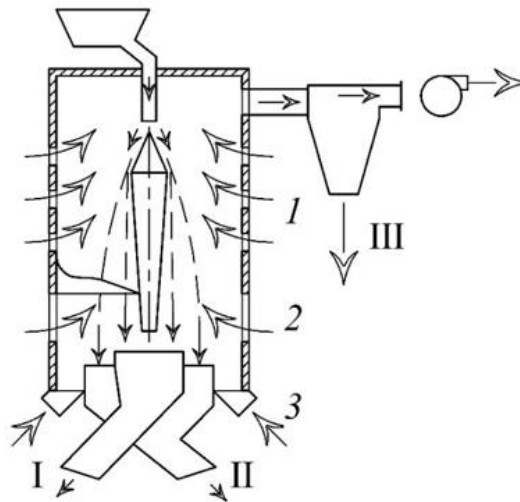


Figure 13: Gravitational type pneumatic separator, adapted from [24]

Stepanenko et al. [24] state that an uneven annular cross-section causes an unevenly directed airflow field, allowing for better mixture fractionation and reduced energy consumption. The trajectory splitting and efficiency coefficients were increased by 15–25% and 7–21%, respectively [24].

Centrifugal counterflow pneumatic particle separation

Figure 14 below shows a centrifugal counterflow type pneumatic separator. An air vortex within the centrifugal counterflow separator chamber (cyclone), which has a strategically placed tangential input and a central exit at the top and bottom, induces particle separation. The spiralling (vortex) airstream causes centrifugal and aerodynamic drag forces on the particles. Coarser particles, more significantly impacted by centrifugal force, remain closer to the cyclone's

periphery, ultimately making their gravitational descent through the bottom outlet. Finer particles, prone to the radial drag force, escape through the upper outlet with the airflow.

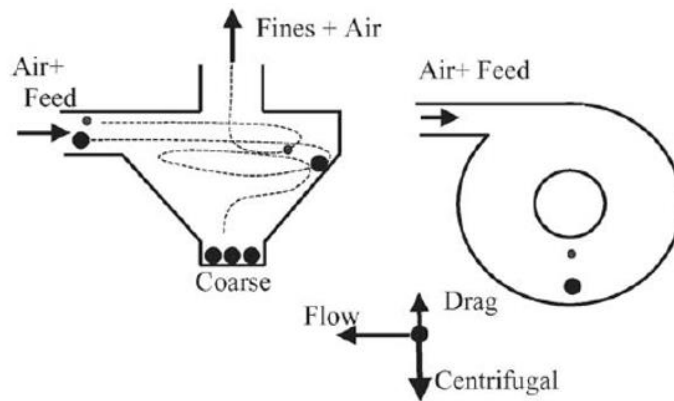


Figure 14: The centrifugal-counterflow pneumatic separator, adapted from [6]

Figure 15 below shows a centrifugal pneumatic particle separator, where the particles enter tangent to the separation chamber.

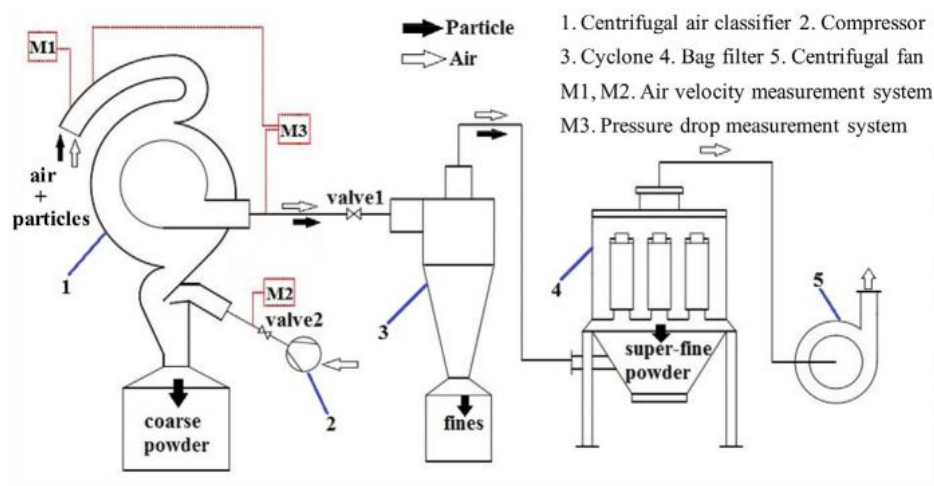


Figure 15: Centrifugal type pneumatic particle separator, adapted from [25]

This method of pneumatic separation is effective as it allows for the recirculation of the fine particles within the chamber by controlling the secondary air stream [25].

Centrifugal crossflow pneumatic particle separation

Figure 16 below shows the particle separation in a centrifugal crossflow pneumatic separator. The separation process is initiated by an aerodynamic vortex within a cylindrical chamber, with the inlet and outlet located at diametrically opposite ends of the chamber's central axis. Particulate

matter and airflow enter the through vanes that orient the flow, creating a spiral motion within the chamber. The design of the blade profiles must eliminate the radial airflow component throughout the chamber [6]. Particles swirl around as they gradually drift radially toward the chamber's walls, moving at velocities dependent on their size. Concurrently, as they navigate axially through the chamber, they make contact with the wall at various points. Larger and heavier particles reach the wall faster than smaller and lighter particles.

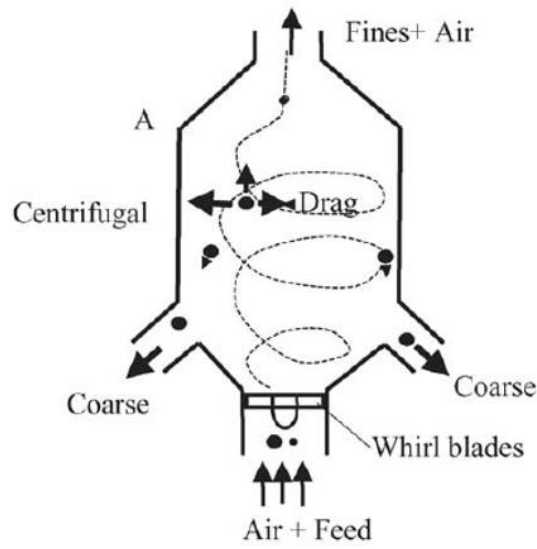


Figure 16: The centrifugal crossflow pneumatic separator, adapted from [6]

Figure 17 below shows a unique vortex flow concept from Adamchuk et al. [26], where particles enter through a dosing device (2) onto a spreader (3), the air can enter the chamber from the louvred cone (6) and wall (7), causing the lighter fractions to leave through the suction pipe (8).

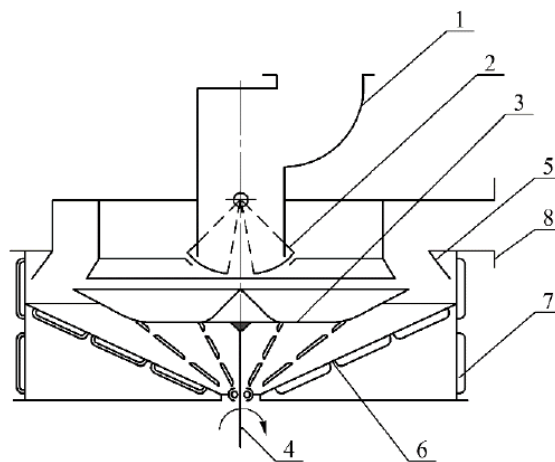


Figure 17: Centrifugal crossflow type pneumatic separator, adapted from [26]

The study from Adamchuk et al. [26] shows that the vortex chamber can achieve separation efficiencies up to 20% higher than other methods; they also proved that this concept is appropriate for high throughput rates of up to 200 [TPH].

2.3 Coupled CFD-DEM Approach

Analysing and improving the design and performance of pneumatic grain cleaning systems is crucial and has become a significant industry need. Integrating CFD and the DEM has revolutionised how we simulate complex interactions between fluids and particulate systems. The coupled CFD-DEM approach integrates the fluid flow analysis capabilities of CFD with the particle dynamics modelling capabilities of DEM. Coupled CFD-DEM applications extend to processes involving cohesive and non-cohesive particles, including gas fluidisation, pneumatic conveying, drying, granulation, segregation, agglomeration, and particle dispersion in solid-fluid mixtures [9].

The discretisation of computational domains in Computational Fluid Dynamics (CFD) involves finite volume, finite difference, or finite element approximations [27]. These methods are applied iteratively to solve the nonlinear Navier-Stokes equations governing the conservation of mass and momentum. Distinct from CFD, the Discrete Element Method solves granular flows, accommodating various particle types, shapes, and characteristics. It solves Newton's equation of motion for each particle, considering particle-to-particle and particle-to-boundary interactions and collisions [28]–[31]. Norouzi et al.[9], states that CFD multiphase models face limitations in estimating particulate matter phases, mainly when dense flows are applied. To address this disparity, the coupled CFD-DEM numerical approach has been introduced, addressing inaccuracies between discrete and fluid phases highlighted in earlier investigations [32], [33].

Figure 18 below shows how the forces present in the CFD and DEM simulations are integrated into the coupled CFD-DEM simulation.

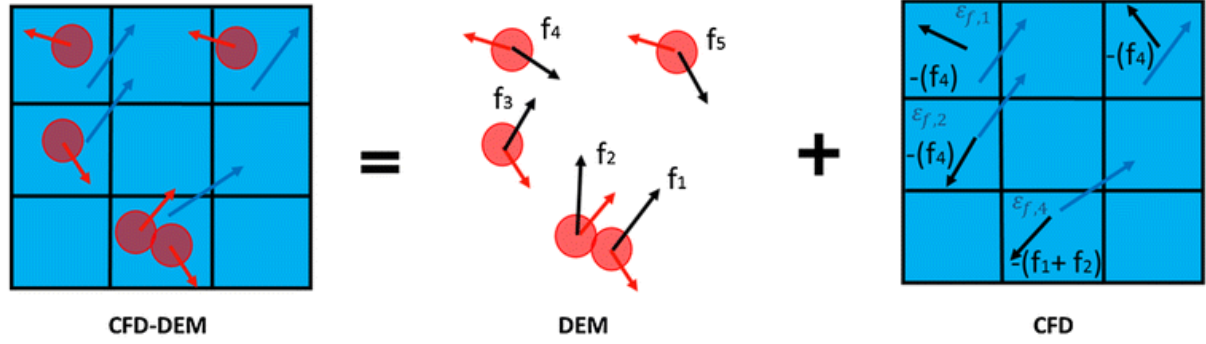


Figure 18: Resultant forces in coupled CFD-DEM: Integration of fluid and particle components, adapted from [34]

Several available commercial and open-source CFD-DEM software programs can be easily accessed; Table 1 shows the various currently available packages.

Table 1: Commercial and open-source CFD-DEM simulation packages

CFD-DEM Software	Description
ANSYS-ROCKY®	Rocky® solves the DEM and ANSYS Fluent® the CFD
PFC™	PFC™ solves the DEM and CFD
CFDEM®	LIGGGHTS solves the DEM and OpenFoam® the CFD
SAMADII®	SAMADII® solves the DEM and CFD
MFIX-DEM	MFIX-DEM solves the DEM and CFD
YADE	YADE solves the DEM and CFD
LIGGGHTS®	LIGGGHTS® solves the DEM and CFD
EDEM®	EDEM® solves the DEM, and ANSYS Fluent® the CFD

2.4 Literature survey conclusion

The literature extensively explores diverse pneumatic grain cleaner types, dissecting their strengths and weaknesses. Its critical analysis pinpoints practical concepts and emphasises crucial design considerations—such as preliminary stratification, multilayer feeding, airflow management, and grain distribution—to enhance cut precision and separation efficiency. Additionally, the research underscores the viability of horizontal grain particle separation as a promising method for purging impurities from an airstream. Unlike vertical separation systems reliant on airflow surpassing grain terminal velocities for separation, horizontal systems achieve classification at lower velocities,

offering a notable advantage. Thus, the study will focus on developing a horizontal pneumatic separation system.

The survey covers the working principles of coupled CFD-DEM simulations and thoroughly examines the spectrum of available software packages. These insights form a solid groundwork for practical implementation across diverse research and industrial applications.

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CHAPTER 3 – ARTICLE 1

This chapter represents the first article that is completed in this dissertation. There is a need for a novel pneumatic grain aspiration system, as there are still numerous gaps in the literature and the industry regarding pneumatic grain separation systems. The concept of a horizontal crossflow airstream aspiration system, rather than a typical vertical aspiration system, will be investigated. There are various gaps in the literature regarding pneumatic grain separation, specifically coupled CFD-DEM simulations. Thus, this chapter will focus on using CFD simulations to aid during the development process and verify and validate the CFD simulations, which can potentially be used in further investigations of coupled CFD-DEM simulations.

3. Article 1- Design and testing of a pneumatic grain aspirator for efficient separation of impurities

Paul Greyvensteyn*, Ockert Koekemoer, LJ Grobler, Danie Vorster

Abstract - In agriculture, pneumatic grain aspirators are commonly used to clean harvested grains such as maize, wheat, chickpeas, and soybeans from impurities. An aspirator can separate contaminants from the grains, including chaff, straw, tiny seeds, dust, and fines that can lower the quality and value of the grains or cause damage to processing equipment downstream. For this purpose, grain separators are often used, which use an air stream to separate impurities from the main grain types. The design and development of an efficient horizontal pneumatic grain aspirator that can meet specific requirements are challenging due to the system's inherent complexity. This study presents the design and evaluation of a pneumatic grain aspirator capable of efficiently separating impurities from harvested grains. The design process involved using Ansys Fluent simulations and experimental testing on a prototype aspirator. The fluid flow simulations optimised the aspirator's design, ensuring uniform airflow across the grain mixture and specifying a suitable fan with a sufficient volume flow rate to efficiently separate impurities from the grain mixture. The experimental prototype was tested in real-world conditions to identify any design shortcomings, evaluate different configurations, and make necessary adjustments for the manufacturing process. The final manufactured pneumatic aspirator was highly efficient in separating impurities from a grain mixture, achieving an efficiency of 95.9% at maximum aspiration. The combination of simulation and experimental testing led to successfully designing a horizontal pneumatic grain aspirator that meets the specific requirements. This approach can help create efficient grain aspirators that improve the value and quality of harvested grains in agriculture and seeds in the food processing industry.

Keywords: Grain aspirator, CFD, Design, Development, Pneumatic separator

3.1 Introduction

3.1.1 Background

Grain aspirators are used in agriculture to clean harvested grains from impurities. Grain aspirators can provide several advantages to grain producers and suppliers. Removing contaminants can impact the harvested grain's appearance, flavour, and nutritional content [1]. Growing yields and enhancing crop quality are the main goals of contemporary agriculture [2]. According to Kolankowska et al., [3] the storage and processing of grain heavily rely on cleaning seeds. The use of grain aspirators can reduce the chance of mould development, bug invasions, and other issues that affect the safety and quality of the grain by eliminating debris and other contaminants, thus leading to less grain spoilage and contamination during the storage period and transportation [4]. Air aspirators blow air at a set speed, to the direction of the grain movement. It is possible to control the crossflow of air's velocity so that particles with high terminal velocities fall through and those with low terminal velocities rise [5]. Applying this theory makes it possible to sort the grain from the chaff, straw, tiny seeds, dust, and fines in an aspirator if their terminal velocities are lower than those of the grain [4]. Studies conducted by Eissa [6] and Panasiewicz [7] indicate that a vertical aspiration duct is highly effective in removing impurities from a grain mixture. Kharchenko [8] and Bulgakov [9] verified that vertical separation ducts could be successfully modelled using numerical modelling techniques, allowing accurate separation performance predictions and selecting appropriate design parameters. Research papers in the literature [10]-[12], use grain separation machines with various sieves, screen dividers, and rotating blades that can damage the grain. According to Adewumi et al. [6], horizontal crossflow separators can increase the rate of production, save space, and reduce production costs. However, no literature is available on designing and verifying compact horizontal crossflow grain aspirators that can remove impurities from a mixture without having interchangeable sieves, screens or rotating blades in contact with the grain. In addition, no research is available that elaborates on the design process that uses numerical modelling to optimise the design of the grain aspirators. This paper aims to address the gap in literature and industry.

3.1.2 Product requirements & specifications

The aspiration system must comply according to the requirements by adhering to the set specifications listed in Table 1:

Table 1: Design specifications

Parameter	Description
System design	Compact, energy-efficient, inline design
Throughput rate	7 tonnes/hour with various grain types
Material	Stainless steel (3CR12) is used to comply with the food industry standards
System regulation	A butterfly valve is implemented on the fan outlet to adjust the operating conditions
Vanes	The inlet vanes sub-assembly design should prevent clogging
Flow regulation	A false air inlet for airflow regulation to improve grain separation
Optimal airflow	Inlet vanes for uniform and normalised airflow
Particle flow	Internal deflector plates to guide particle movement
Fan type	Centrifugal fan to overcome the pressure drop of the cyclone
Maintenance	The inlet vanes sub-assembly will be bolted onto the aspirator to simplify cleaning
Production	Manufacturing jigs regulate product quality

3.2 Design and development

This section will elaborate on the methods of approaching the conceptual, preliminary, and detailed design to meet the set requirements.

3.2.1 Conceptual design

Figure 1(a) below illustrates the concept for the grain aspirator; this concept will be continually improved and used as a reference during the design phase.

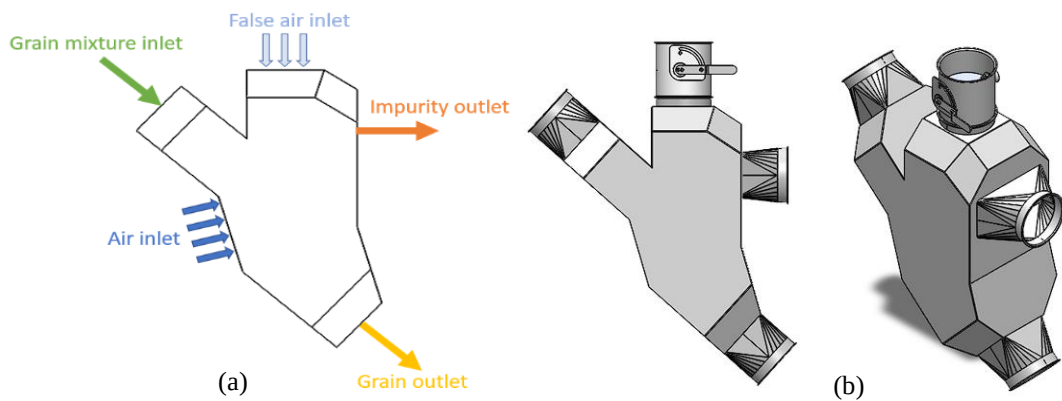


Figure 1: (a) Grain aspirator concept; (b) Preliminary design of the grain aspirator

The aspirator concept has a compact, flexible design that can be easily adapted to comply with the product requirements and specifications listed in Table 1. Grain particles enter the aspirator at such an angle that ensures the grain particles are evenly distributed along the width of the aspirator, causing a smooth layer of particles to pass through the horizontal crossflow of air. A crossflow airstream draws through the grain mixture curtain, removing the lighter impurities, and gravity enables the grain to descend to the bottom of the aspirator. The surface of the inlet vanes is not parallel with the grain inlet chute, and this design feature prevents grain particles from clogging the air inlet. The air stream carries dust and light impurities through the blower and into a conduit to the intended disposal location. The false air inlet enables airflow regulation for different grain varieties and throughput rates by allowing the user to increase or reduce the airflow. This grain aspirator concept has no moving parts, thus making it a low-maintenance component. The aspirator concept can be used in applications ranging from stationary to mobile grain cleaning. The grain inlet angle should be between 42° and 45° degrees to ensure no particles become stagnant in the spouting. The outlet duct is opposite the air inlet allowing a horizontal aspiration effect. This grain aspirator concept can clean the grain before it enters and exits storage.

3.2.2 Preliminary design

Figure 1(b) presents the preliminary design of the grain aspirator. The grain aspirator has a butterfly valve acting as the false air inlet on the top. The grain inlet and outlet consist of square to round duct fittings with standard spigot pipe sizes at the ends. The impurity outlet comprises a rectangular to round duct fitting with a standard-size spigot pipe at the end. The ends of the spigot pipes are flared to ensure the system is easily coupled with pipe clamps into existing systems. The sheet metal body and duct fittings are joined with welding while the inlet vane sub-assembly is bolted to the body. The inlet vane sub-assembly was designed to be bolted in place rather than welded, making the maintenance much easier and quicker.

3.2.3 Ansys Fluent simulations

Ansys Fluent flow simulations were conducted before manufacturing the preliminary design as a prototype to ensure adequate airflow within the aspirator. As seen in Figure 2(a) below, the air crossflow from the vane inlet into the impurity outlet was not uniform, meaning that the airflow had to follow a curved path, which could cause impurities to drop out of the crossflow stream. The simulations in Figure 2(a) also prove that the incoming air from the grain inlet and outlet dampens

the crossflow of air. Due to the fluid flow simulation findings, the impurity outlet was shifted downwards, and internal deflector plates were added to the design. The false air inlet was closed entirely for the simulations in Figure 2(a) and (b), and all the conditions remained constant for the different sets of simulations.

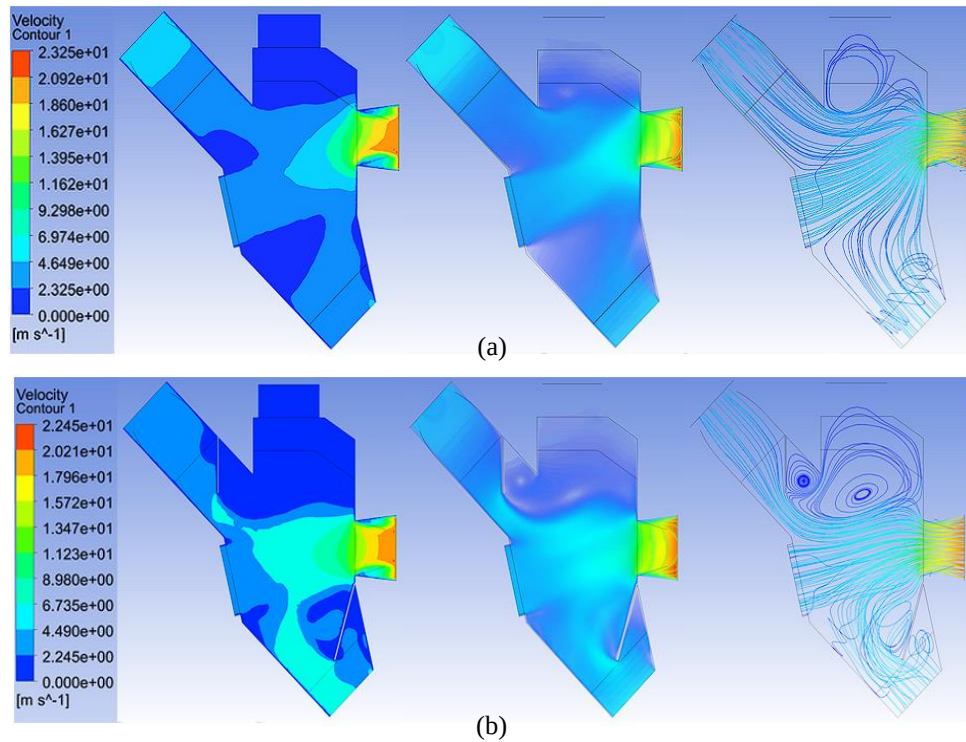


Figure 2: Ansys Fluent simulations on the preliminary design (a) Iteration 1; (b) Iteration 2

Figure 2(b) illustrates the improved design's simulations, as the inner deflector plates increase the airflow from the inlet vanes while decreasing the airflow from the grain entrance and exit areas, allowing the absolute translational velocity to be more significant in the crossflow region. The curvature in the crossflow of air transformed into a uniform and straight airflow. Internal deflector plates in the aspirator also aid in guiding and preventing particles from bouncing into the impurity outlet. The fluid flow simulations assisted in optimising the airflow within the aspirator by reducing recirculation, ensuring a uniform airflow across the grain mixture, and specifying a suitable fan with a sufficient volume flow rate to separate impurities from the grain mixture efficiently.

3.2.4 Prototype

Figure 3 below illustrates the improved preliminary design based on the findings in the fluid flow simulations. The improved preliminary design will be used as the prototype for testing.

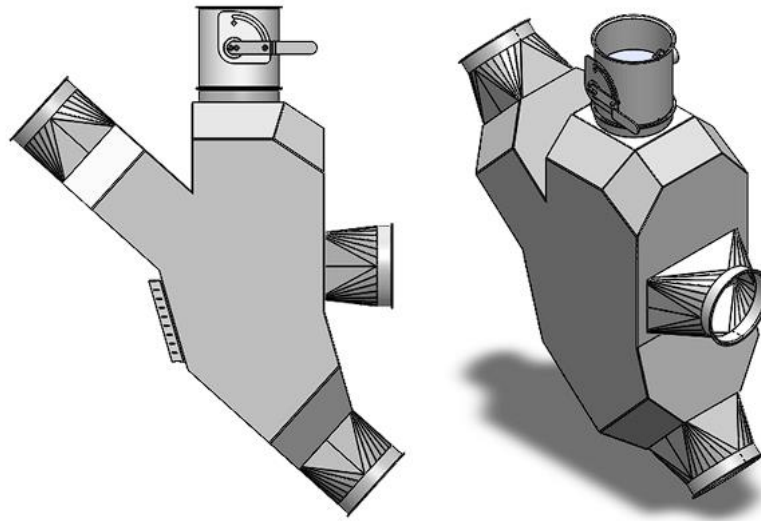


Figure 3: Improved preliminary design

The tests on the grain aspirator prototype can help determine whether the fan size and type, as specified in the simulations, are sufficient. The tests will aid as validation to determine whether the aspirator concept functions as required and expected. The tests will also assist in gaining valuable insight into what components to improve for the detailed design.

3.2.5 Fan specification with Ansys Fluent simulations

The system into which the grain aspirator will be coupled will determine the system resistance that the fan must overcome, making it challenging to select the appropriate fan size. A significant, influential factor would be whether a cyclone will be coupled to the aspirator to remove the impurities from the air. The "CFAM 3 [kW] 2Pole Backward Inclined Centrifugal Fan" produces a maximum pressure of 3580 [Pa] at a minimum volume flow rate of 880 [m³/h] and a minimum pressure of 640 [Pa] at a maximum volume flow rate of 2940 [m³/h]. This fan's wide operating range meets our requirements, making it an ideal option for the aspirator. Ansys Fluent simulations were used to get an estimate of what the air crossflow velocity will be when the fan operates at minimum and maximum airflow. For this set of simulations, the aspirator boundary conditions

were adjusted as if the grain is fed with an auger feeder and exits into a chute, which will restrict the incoming airflow from the grain inlet port. Figure 4(a) below shows that when simulating a maximum airflow of 2940 [m³/h], the velocity at the impurity outlet is 46 [m/s], and the air crossflow velocity is 14 [m/s] on average. Figure 4(b) shows that when simulating a minimum airflow of 640 [m³/h], the velocity at the impurity outlet is 10 [m/s], and the air crossflow velocity is 2.5 [m/s] on average. This fan will provide sufficient cross-airflow to aspirate light impurities with low terminal velocities.

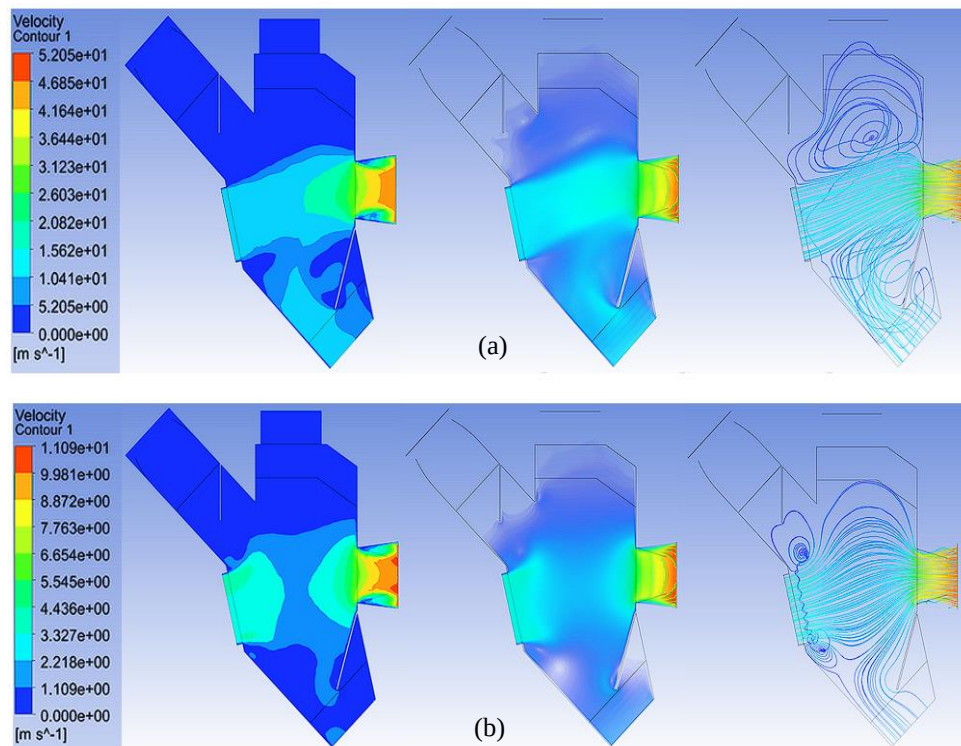


Figure 4: (a) Maximum airflow, (b) minimum airflow

3.2.6 Manufacturing and production of improved design

The manufacturing and testing procedure of the preliminary design led to several recommendations for improvement. The grain aspirator is manufactured from 3CR12 stainless steel. Figure 5(a) shows the final detailed design with all the sub-assembly parts.

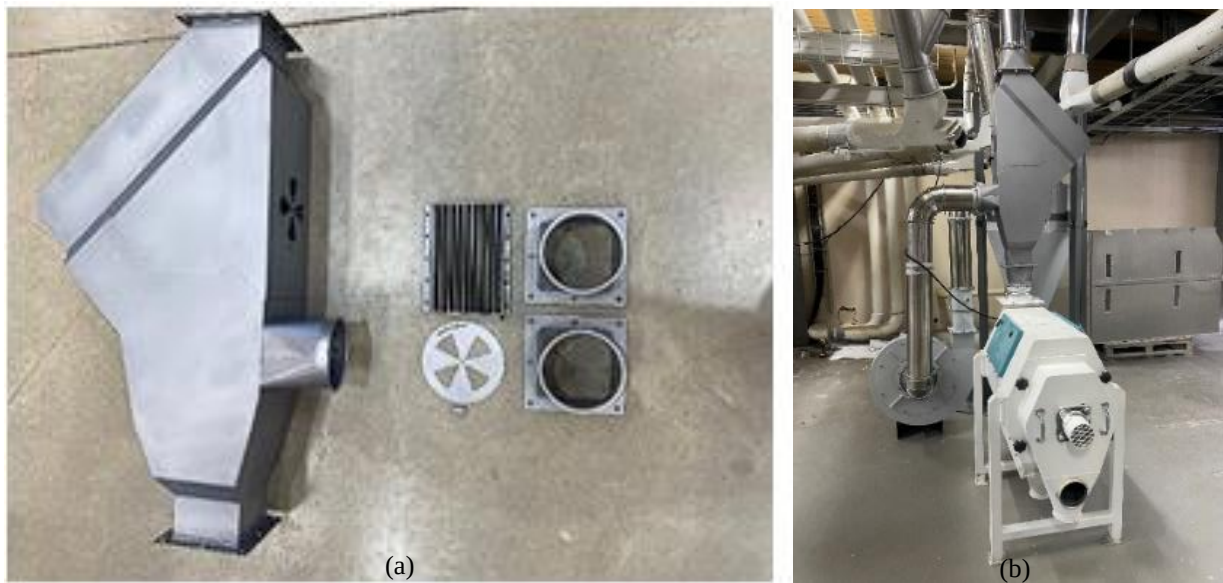


Figure 5: (a) Manufactured final design; (b) Final design experimental setup

3.2.7 Experimental setup

The experimental setup for the prototype and the final design was different. The prototype's experimental setup was used to determine how the design could be improved and how the prototype operated when being integrated into different configurations. The final design's experimental setup was realistic and, in the industry, where all the variables and parameters were controlled to determine the efficiency of the aspirator efficiently.

Prototype experimental setup

The tests were conducted with 120 [kg] samples of the maize mixture, translating to a throughput rate of 7 tonnes per hour. The test mixture consists of corn kernels, broken corn kernels, corn husks, and fines (small pieces of broken corn), as shown on the left of Figure 6. The prototype testing setup included a feeding auger, grain separator, fan, and cyclone. Tests were conducted with the fan before, after, and without the cyclone to determine whether the aspirator could adapt to different configurations. Tests were undertaken with grain mixtures with varying densities and moisture contents, as the aspirator can easily be adjusted to consider these unknowable factors. *Experimental setup 1* consisted of the auger feeder feeding the grain aspirator, where the fan was directly coupled to the aspirator and blew into the cyclone. In this setup, the impurities travelled through the fan, which has the disadvantage of increasing wear on the impeller. *Experimental setup 2* consisted of the auger feeder feeding the grain aspirator, where there is a direct coupling between the cyclone and the aspirator, causing the fan to suck out of the cyclone. In this setup, the impurities

leave through the cyclone, and only air exits through the fan, with the advantage that contaminants won't wear the fan impeller but the disadvantage of the extra cost of a vortex breaker and rotary airlock on the cyclone. *Experimental setup 3* consisted of the auger feeder feeding the aspirator, where the fan was directly coupled to the aspirator and blew the impurities into the air. This setup is the cheapest option; however, it is only for external use.

Final design experimental setup

The final design was tested in the industry at a milling company; the setup consisted of degermed white maize from the degerminator falling into the aspirator, where the aspirator should separate the bran (husks) from the mixture. The aspirator's outlet was connected to a turbo sifter to separate the cleaned corn from the fines. The aspirator was connected to the suction side of the fan while the fan blew into a cyclone. Figure 5(b) shows the experimental setup. Two tests were conducted: one with the fan on maximum flow while the false air inlet was closed entirely and another where the fan and aspirator were adjusted only to remove impurities from the mixture. The degerminator throughput rate was set to 7 tons per hour, where the throughput rate for the impurities, fines, and maize kernels was measured separately by weighing a bag that was getting filled for a specific time at each outlet. The maize mixture entering the aspiration system was analysed prior to experimental testing, the mixture contained 6.45% husks, and the remaining mass fraction percentage was endosperm fragments. Samples were taken from the two tests, where each section's throughput rate and bulk density were calculated. Three measurements were taken for each outlet's sample, and the average was used in the calculations to minimise human error.

3.3 Results and discussion

3.3.1 Prototype

The prototype test results can be seen below, where Figure 5(a) shows the maize mixture before aspiration and Figure 6(b) and (c) shows the cleaned samples after aspiration.



Figure 6: Prototype test results

After necessary adjustments on the aspirator, the results obtained for the three experimental setups proved very similar. The aspirator proved versatile as it could easily be adjusted to adapt to different configurations.

3.3.2 Final design

Figure 7 and Figure 8 below illustrates the test results when the system operated on maximum and adjusted aspiration, respectively. Figure 7 below shows the test results for when the aspirator system was adjusted to aspirate only corn husks, leaving behind endosperm pieces that still have nutritional value. In Figure 7 and Figure 8, part (a) shows the maize mixture before aspiration, while part (b) and (c) shows the cleaned samples after aspiration.



Figure 7: Adjusted aspiration sample results



Figure 8: Maximum aspiration sample results

Adjusted aspiration

The efficiency of the aspiration system, when it was set to only remove impurities which are the husks and not endosperm pieces from the mixture, was calculated below using Eq (1).

$$n_{adjusted} = \frac{X_{Percentage\ husks\ removed}}{X_{husks}} \times 100 \quad (1)$$

Where $n_{adjusted}$ is the aspiration efficiency, $X_{Percentage\ husks\ removed}$ is the percentage of husks aspirated and X_{husks} is the initial percentage of husks present in the mixture.

The experimental tests determined that the aspirator removed 5.27% impurities (husks) from the mixture that initially had 6.45% husks. The efficiency was determined by the ratio between the percentage of husks removed from the mixture and the percentage of husks in the initial mixture. The calculations showed that 81.71% of the husks could be removed from the mixture with the aspirator without removing other material with nutritional value (endosperm fractions). The aspirator's efficiency can be improved, but there will be a trade-off, as the aspirator will start to remove endosperm pieces that still have nutritional value. Before this test, the macro (butterfly valve) and micro (false air inlet) adjustments were adjusted on the aspirator to only aspirate husks and not endosperm fractions.

Maximum aspiration

This procedure tested what percentage of husks could be removed from the grain mixture. The efficiency during maximum aspiration was calculated by using a different method than in the previous tests. There will be small endosperm fractions present in the aspirated husks mixture, thus the throughput mass percentage for the aspirated impurities cannot be used. The efficiency for maximum aspiration was calculated using Eq (2) below.

$$n_{max} = \left(1 - \frac{X_{husks \text{ remaining}}}{X_{husks}}\right) \times 100 \quad (2)$$

Where n_{max} is the maximum efficiency, $X_{husks \text{ remaining}}$ is the percentage of husks remaining in the cleaned mixture and X_{husks} is the initial percentage of husks present in the mixture.

The mass fraction percentage of the husks still present in the cleaned mixture was 0.26% of the total 6.45%, thus during maximum aspiration, 95.9% of the husks were removed from the grain mixture. During this test some broken corn pieces (endosperm) were also aspirated, as seen in Figure 8 (aspirated impurities).

The efficiency will vary for each product and impurity type, where the particles' density and shape play the most significant role. During testing it was noted that smaller broken corn particles have a lower terminal velocity due to its shape and size, causing the smaller particles to be aspirated before the bigger particles. This aerodynamic phenomenon can be beneficial as it allows for classification of not only husks and the corn fractions, but classification between broken and whole corn pieces. The ability to classify between these wide range of particles and impurities allows this aspirator design to be used in the agriculture, oil seed extraction, and milling industry. Table 2 below shows the measured throughput rates the calculated bulk densities for the adjusted and maximum aspiration experiments.

Table 2: Maximum and adjusted aspiration test data

	Maximum aspiration test		Adjusted aspiration test	
	Throughput percentage	Bulk density (kg/m ³)	Throughput percentage	Bulk density (kg/m ³)
Maize mixture	100%	566.3	100%	566.3
Aspirated impurities	33.92%	433.8	5.27%	211
Cleaned maize	66.08%	612	94.73%	645.2

3.4 Conclusion

The aspirator concept was verified using Ansys Fluent simulations and various testing on a prototype aspirator during the design process. The final developed pneumatic aspirator was highly effective in removing impurities from a grain mixture and fulfilled all the requirements. The research also fills a gap in the literature and industry by delving into the design process for

a compact horizontal crossflow grain aspirator that can remove impurities from a mixture without using interchangeable sieves and screens. The aspirator demonstrated its ability to readily adapt to diverse configurations without using sieves and dividers, relying instead on macro and micro-adjustments. The initial prediction was correct, as the horizontal aspiration grain separator could separate impurities from a grain mixture at high efficiencies.

3.5 Acknowledgements

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CHAPTER 4 – ARTICLE 2

This chapter represents the second article that is completed in this dissertation. The grain aspiration system was developed in Chapter 3, and the CFD simulations were verified and validated. It is necessary to perform coupled CFD-DEM simulations on the grain aspirator to understand better how it works. The coupled CFD-DEM simulations can be used to analyse and optimise the grain aspirator. The need is to validate the coupled simulations using experiments in qualitative and quantitative ways.

4. Article 2- Grain aspirator: Validation and performance analysis optimisation using a coupled CFD-DEM simulation approach

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Abstract

Coupled Computational Fluid Dynamics (CFD) and Discrete Element Modeling (DEM) are used in industry to simulate complex particle-fluid interactions and can be used to analyse and optimise drying, screening, conveying, and pneumatic separation systems. Current research on pneumatic separation systems using the coupled CFD-DEM approach predominantly focuses on one-way coupling and lacks detailed setup and implementation information, thus limiting the accuracy, applicability, and repeatability of solving real-world industrial problems. The grain aspirator system was modelled utilising a multiphase, two-way coupled CFD-DEM simulation approach within the ANSYS-Rocky[®] framework. A two-tiered approach was employed to validate the computational CFD-DEM model: first, by comparing the predictive outputs of cleaning efficiency and cleaning loss against results from the designed experimental setup; second, by assessing the simulation's ability to reproduce observed experimental phenomena. The simulation achieved validation by closely matching the experimental data with a cleaning efficiency error of 4.69% and a cleaning loss error of 6.18% and replicating observed experimental phenomena, thereby confirming the model's predictive capabilities. The multiphase, two-way coupled CFD-DEM simulation was invaluable for further optimising the grain aspirator system and demonstrating that CFD-DEM is highly advantageous for simulating realistic pneumatic grain separation systems. The simulation offers essential insights that streamline the design process while yielding significant time and cost savings.

Keywords: CFD-DEM, ANSYS-Rocky, Grain Aspirator, Optimisation, Two-way Coupled Analysis

4.1 Introduction

In agricultural and food industries, grain sorting and classification processes entail the concurrent movement of fluids and particles. A deep understanding of the interactions between fluids, particles and boundaries is required to develop, optimise, or analyse these systems. Agriculture crops primarily include cereal grains, seeds, and pulses, which range in physical qualities such as shape, size, and density. Zhong et al. [1] state that 70% of all raw materials, which includes agricultural grain, are non-spherical particles. There are limitations in open-source and commercially available CFD packages like STARCCM+[®], ANSYS Fluent[®], OpenFOAM[®], and MFIX regarding the particle shape and particle interactions present in multiphase flow applications. The particle shape limitation in CFD packages is that they can only solve for spherical and glued spherical particles instead of polyhedral-shaped particles, which reduces the accuracy of the simulation [2], [3]. The particle interaction limitation is to model adhesive-cohesive particle attraction forces [3]. Predicting granular systems in airflow is highly complex; therefore, a coupled simulation is essential to solve the system accurately.

ANSYS Fluent[®] is a CFD software that is used to analyse systems involving fluid flow to solve the averaged Navier-Stokes equations, which include the continuity equations (conservation of mass), momentum equations (conservation of momentum), and energy [4]. ESSS Rocky[®] DEM utilises DEM as a numerical technique to predict the behaviour of polydisperse solids [5]. DEM is a numerical approach for dealing with granular flows of various particle types, shapes, and characteristics by solving Newton's equation of motion for each individual particle, accounting for particle-to-particle and particle-to-boundary collisions and interactions. The complicated hydrodynamics of particle-fluid flow systems can be obtained using numerical approaches, particularly the coupled computational fluid dynamics and discrete element method [6]. The coupled CFD-DEM numerical approach overcomes the inaccuracy and gap between the discrete and fluid phases, as introduced by various early investigations [7], [8]. A coupled CFD-DEM simulation refers to an Euler–Lagrange approach, a combination of CFD and DEM [9]. ANSYS-Rocky[®] solves the continuous fluid phase with the finite volume method (FVM) and the discrete phase with the discrete approach. The conservation equations are integrated across the Eulerian grid, spanning the entire flow domain, where momentum exchange between the discrete and fluid phases facilitates the coupling [10]. A coupled CFD-DEM simulation with ANSYS-Rocky[®] can be either a single-phase or multiphase system with various one-way and two-way coupling options. During a single-phase coupling, the effect of the Rocky[®] DEM particles over the fluid is

produced by defining the domain in Fluent as a porous medium [3]. Rocky[®] DEM subsequently adjusts the Fluent model, treating the DEM particles as a medium with permeability, incorporating momentum source terms within the fluid phase equations to accurately represent interactions and collisions between the fluid and particles [3]. As the simulation advances, alterations occur in the domain's pore distribution due to fluctuations in the concentration of the discrete phase. In a multiphase coupling, the Eulerian multiphase model is employed in Fluent, with Rocky[®] DEM particles represented by a separate dedicated phase. The multiphase coupling method requires more processing but produces more accurate results [3]. The ANSYS-Rocky[®] CFD-DEM coupling allows for various one-way and two-way coupling methodologies. The one-way coupling has a constant, Lattice Boltzmann Method (LMB), and steady-state method. The two-way coupling can be a Fluent or Fluent semi-resolved coupling. The two-way Fluent method can accurately capture the fluid-particle and particle-fluid interactions.

Due to constraints in computing capabilities, the intricate geometries of grain structures, and material interactions, contemporary CFD-DEM simulations encounter increased complexity in addressing practical particulate systems within the industry. Presently, the methods used to couple CFD-DEM can be categorised into one-way, two-way, three-way, and four-way approaches [9]. However, the majority of studies in the agricultural field predominantly concentrate on one-way coupling, whereas alternative coupling methods are acknowledged for their enhanced precision and accuracy in mirroring real contacts [11]. Three-dimensional CFD-DEM simulations are usually limited to systems with a limited number of particles, and simulating large ranges in grain shapes and sizes in some aerodynamic systems is still a significant challenge. While combining CFD with DEM has effectively simulated the air-grain flow separation and is suggested for enhanced predictions, its limited application in agricultural grains is attributed to the notable diversity in grains' characteristics. Few CFD-DEM simulations are available on grain separation, while the current research papers are vague in illustrating the methodology to set up a coupled simulation for a specific problem.

Using CFD-DEM coupled simulations in agricultural engineering has become a focal point in recent years. Comparison of simulations with experimental outcomes revealed that employing a coupled CFD-DEM model effectively portrays particle-fluid interactions and collisions, potentially expanding its applicability to various aerodynamic processes within the agricultural sector [11]. Almeida et al. [12], [13] showed that coupled CFD-DEM simulations can give good predictions for pneumatically separating sugarcane bagasse particles. Korn et al. [14], [15]

performed a coupled CFD-DEM simulation of straw separation in a combine harvester where the simulation had some correspondence with the experiments; however, it is concluded that further improvement is required. Hu et al. [16] analysed and optimised a pneumatic safflower separation machine using coupled CFD-DEM simulations and proved the simulation consistent with the experiments. Orhan et al. [17] used coupled CFD-DEM simulations to obtain more insight and predict the performance parameters of a cyclone separator with straw particles. Li et al. [18] performed coupled CFD-DEM simulations to optimise the design parameters of a pneumatic walnut separator. Ma et al. [19] verified that coupled CFD-DEM simulations can be conducted to analyse a pneumatic rice separator, which can be used to optimise the pneumatic cleaner during the design process. El-Emam [20] conducted coupled CFD-DEM simulations to optimise a cyclone separator designed explicitly for jojoba seeds; the numerical model was validated through experimental comparisons and demonstrated a high degree of correlation. The abovementioned research proves the capabilities regarding coupled CFD-DEM simulations; however, it is also concluded that there are still many discrepancies in these complex simulations.

The abovementioned research proved that coupled CFD-DEM simulations can be advantageous for a grain aspirator. Research regarding the coupling procedure between ANSYS-Rocky[®] for a specific industry problem is still vague. Additionally, literature is absent on solving coupled CFD-DEM simulations on aerodynamic agriculture machinery like the grain aspirator, where the governing equations, parameters and general issues are provided and elaborated on in detail to allow repeatability. This research paper aims to fill the gap in literature and industry to accelerate aerodynamic agricultural mechanisation. A one-way coupling is a suitable simulation method for specifically larger particles in agricultural machinery, ultimately reducing the computational power requirements for the simulation. Two-way and four-way coupled simulations are frequently employed to characterise particle flow within fluidised beds, particularly within the realm of chemical or pharmaceutical industries [11]. However, these techniques have been scarce within the agricultural domain, resulting in a substantial void in simulation applications for various aerodynamic systems related to agriculture. Previous literature provides the basis for developing and optimising pneumatic separation systems in the agricultural and food processing machinery industry. By using CFD-DEM simulations, it is possible to investigate the particle-fluid interactions and collisions, which can help improve the efficiency and performance of pneumatic grain separators [11].

Simulation studies are essential during equipment development, analysis and optimisation, as they can provide realistic expectations without the need to perform time-consuming and costly experimental tests. The focus is to validate that the grain aspirator can be simulated while obtaining sufficient information from the simulation to optimise the aspirator further. The paper will also determine whether using CFD-DEM to simulate a realistic system is worthwhile.

4.2 Numerical model

A two-way multiphase coupled CFD-DEM coupling method using ANSYS-Rocky[®] will be applied on the grain aspirator in this investigation. This coupled simulation approach can improve pneumatic separation systems, ultimately reducing costs and labour. The validation in this study aims to establish confidence in the predictive capabilities of coupled CFD-DEM simulations by demonstrating that it can reproduce the behaviour and trends observed in the real-world aspiration system. The coupled CFD-DEM simulations will serve as a guiding framework for optimising the existing design, offering novel insights that remain inaccessible through sole reliance on conventional CFD simulations.

4.2.1 Fluid phase governing equations

This study will focus on a multiphase (Eulerian) two-way coupled CFD-DEM simulation, where the airstream is the continuous fluid phase, and the particles represent the discrete phase. The fluid phase is characterised using the classical Navier-Stokes equations averaged in volume to solve the continuum airflow in the grain aspirator. Equations (1) and (2) show the mathematical formulations for the continuity/conservation of mass and conservation of momentum equations, respectively [8].

$$\frac{\partial}{\partial t}(\alpha_f \rho_f) + \nabla(\alpha_f \rho_f \mathbf{u}) \quad (1)$$

$$\frac{\partial}{\partial t}(\alpha_f \rho_f \mathbf{u}) + \nabla(\alpha_f \rho_f \mathbf{u} \mathbf{u}) = -\alpha_f \nabla p + \nabla(\alpha_f \mathbb{T}_f) + \alpha_f \rho_f \mathbf{g} + \mathbf{F}_{p \rightarrow f} \quad (2)$$

where α_f denotes the fluid volume fraction in the CFD mesh, p the shared pressure, ρ_f the fluid density, $\mathbf{u}$ the fluid phase velocity vector, and $\mathbb{T}_f$ the fluid phase stress tensor [3], shown in Eq. (3):

$$\mathbb{F}_f = \mu_f(\nabla \mathbf{u} + \nabla \mathbf{u}^T) + \left(\lambda_f - \frac{2}{3} \mu_f \right) \nabla \cdot \mathbf{u} \mathbf{I} \quad (3)$$

In Eq. (2) the $\mathbf{F}_{p \rightarrow f}$ term reflects the momentum source term from interactions with the particulate phase, which is the forces generated by the particles on the fluid, as indicated in Eq. (4).

$$\mathbf{F}_{p \rightarrow f} = - \frac{\sum_{p=1}^N \mathbf{F}_{f \rightarrow p}}{V_c} \quad (4)$$

where N is the number of particles in the computational cell volume V_c , and $\mathbf{F}_{f \rightarrow p}$ represents the force of the fluid airstream on the particles, which will be discussed in the particle-fluid interactions section.

4.2.2 Fluid phase turbulence model

The selection of a turbulence model is crucial as it not only influences the accuracy of the complicated flow field but also underpins the precision of the CFD simulation of air inside the aspirator, which is dependent on an accurate specification of the turbulent properties of the flow. The RNG k- ε model is formulated from the Navier-Stokes equations using the "renormalisation" group theory. This turbulence model has numerous advantages over the standard k- ε model [4]:

- An additional term is introduced to the epsilon equation, which increases accuracy for rapidly strained flows.
- The effect of swirls on turbulence is considered, improving the accuracy of swirling flows.
- Unlike the standard model, which uses user-specified constants, an analytical formula for turbulent Prandtl numbers is employed.
- The model includes an analytically developed differential formula for effective viscosity, accommodating low-Reynolds number effects.

These enhancements make the RNG k- ε model more reliable across a broader range of flows and more appropriate for this study. The symbols k and ε represent the turbulence kinetic energy and dissipation rate, respectively. Equations (5) and (6) show the transport equations for the RNG k- ε model [4], [21].

$$\frac{\partial}{\partial t}(\rho_f k) + \frac{\partial}{\partial x}(\rho_f k \mathbf{u}) = \frac{\partial}{\partial x}(\alpha_k \mathbf{u}_{eff} \frac{\partial k}{\partial x}) + G_k + G_b - \rho_f \varepsilon - Y_M + S_k \quad (5)$$

$$\begin{aligned}
& \frac{\partial}{\partial t}(\rho_f \varepsilon) + \frac{\partial}{\partial x}(\rho_f \varepsilon \mathbf{u}) \\
& = \frac{\partial}{\partial x} \left(\alpha_\varepsilon \mathbf{u}_{eff} \frac{\partial \varepsilon}{\partial x} \right) + C_1 \frac{\varepsilon}{k} (G_k + C_3 G_b) - C_2 \rho_f \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon
\end{aligned} \tag{6}$$

where $\mathbf{u}_{eff}$ is the fluid effective turbulent viscosity, G_k and G_b represents the generation of turbulence kinetic energy due to the mean velocity gradients and buoyancy. Y_M is the fluctuating dilatation's contribution to the overall dissipation rate in compressible turbulence. The variables α_k and α_ε are the inverse effective Prandtl numbers for k and ε , respectively, while S_k and S_ε are user-defined source terms. R_ε is the dissipation of swirl and rotational effect on turbulence, whereas C_1, C_2 and C_3 are constant values.

4.2.3 Discrete phase governing equations

Rocky[®] DEM tracks all the individual particles inside the computing domain in a Lagrangian manner by directly solving Euler's first and second laws, which regulate translational and rotational particle motion by solving Eqs. (7) and (8) below, respectively [3].

$$m_p \frac{d\mathbf{v}_p}{dt} = \mathbf{F}_c + \mathbf{F}_{f \rightarrow p} + m_p \mathbf{g} \tag{7}$$

where m_p represent the particle mass, $\mathbf{v}_p$ is the particle velocity vector, and $\mathbf{F}_c$ is the contact force for particle-particle and particle-boundary interactions.

$$\mathbf{J}_p \frac{d\boldsymbol{\omega}_p}{dt} = \mathbf{M}_c + \mathbf{M}_{f \rightarrow p} \tag{8}$$

where $\boldsymbol{\omega}_p$ is the particle angular velocity vector, $\mathbf{J}_p$ is the moment of inertia tensor, and $\mathbf{M}_c$ denotes the net torque induced by tangential forces, which causes the particle to rotate.

Due to particle-fluid interaction, two more terms occur when compared to a DEM only simulation. $\mathbf{F}_{f \rightarrow p}$ is the additional force on particles accounted for by the interaction with the fluid phase, and $\mathbf{M}_{f \rightarrow p}$ is the fluid-generated torque caused by the fluid phase velocity gradient. The exact specifics of the fluid-generated torque $\mathbf{M}_{f \rightarrow p}$ can be found in [3].

4.2.4 Contact force model

The contact forces in Rocky[®] DEM are made up of normal and tangential forces to the contact plane. The contact plane for spherical particles is perpendicular to the line connecting the centres of the two spheres. The process for determining a contact plane for non-spherical particles is more sophisticated. In the case of physical contact, the contact plane can be determined by the closest points of two particles, the closest points of a particle and a triangle, or the two spots with the most significant overlap distance [5], [11].

4.2.4.1 Normal contact force model

The normal force model in the Rocky[®] DEM simulation must meet two essential requirements: exert a repulsive force and allow for energy dissipation, considering that a granular medium is a highly dissipative system [5]. The three normal force models in Rocky[®] DEM are the Hysteretic linear spring model, the Linear spring-dashpot model, and the Hertzian spring-dashpot model. In this investigation, the Hertzian spring-dashpot model will be utilised. The model is more computationally expensive, but accuracy is needed since the husk particles experience elastic deformation.

When the particles overlap during contact, the Hertzian model can be formulated as shown in Eqs. (9), (10), and (11).

$$F_n = \frac{4}{3} E^* \sqrt{R^* s_n^3} + n_h \sqrt{\frac{4}{3} m^* E^* \sqrt{R^* s_n}} \times \dot{s}_n \quad (9)$$

$$\frac{1}{E^*} = \frac{(1 - \nu_i^2)}{E_i} + \frac{(1 - \nu_j^2)}{E_j} \quad (10)$$

$$R^* = \frac{R_i R_j}{R_i + R_j} \quad (11)$$

where E^* is the reduced Young's modulus, R^* the radius, E_i , E_j and ν_i , ν_j are Young's moduli and Poisson's ratios of the two spheres in contact with the radii of R_i , R_j , s_n the normal overlapping and n_h the damping ratio, which is a dimensionless parameter which correlates with the restitution coefficient [5], [22], [23].

4.2.4.2 Tangential force model

The tangential force models in Rocky[®] DEM used to calculate the tangential components of the contacts are the Linear Spring Coulomb limit model, the Coulomb limit model, and the Mindlin-Deresiewicz model [5]. The Linear Spring Coulomb limit model, also known as the Linear Elastic-frictional model, was chosen for this investigation because it is simple, effective, and has the correct assumptions for granular materials. If the tangential force is considered elastic, its value at time t is expressed in Eq. (12).

$$\mathbf{F}_{T,e}^t = \mathbf{F}_T^{t-\Delta t} - r_K K_{nl} \Delta \mathbf{s}_T \quad (12)$$

where $\mathbf{F}_T^{t-\Delta t}$ is the tangential force at the previous time, K_{nl} the loading normal stiffness, r_K the user-defined tangential stiffness ratio, and $\Delta \mathbf{s}_T$ the tangential relative displacement of particles during the time-step [5]. However, in this correlation, the tangential force cannot exceed Coulomb's limit; thus, the complete expression for the tangential force is shown in Eq. (13).

$$\mathbf{F}_T^t = \min(|\mathbf{F}_{T,e}^t|, \mu \mathbf{F}_n^t) \frac{\mathbf{F}_{T,e}^t}{|\mathbf{F}_{T,e}^t|} \quad (13)$$

where $\mathbf{F}_n^t$ is the contact normal force at time t , μ the friction coefficient, which refers to the user-defined static μ_s or μ_d dynamic friction coefficient, respectively [5]. The static friction coefficient is used if no sliding occurs at the contact, and the dynamic friction coefficient is used if sliding occurs. Once the tangential force is larger than the static frictional force $\mu_s \mathbf{F}_n^t$, sliding is taking place.

4.2.5 Adhesive force model

The moisture content of the maize mixture of broken kernels and husks causes them to adhere to themselves and other surfaces they come into contact with. This "stickiness" between the mixture and the boundaries must be accounted for in the DEM simulation to comprehend the true particle interactions. To estimate the flow characteristics of this behaviour, the repulsive normal force must be supplemented with the attractive normal force [5]. The constant adhesive force model will be used in this investigation since it is not computationally expensive, while the adhesive force is regarded as constant when the particles are within a certain distance of each other. The adhesive

force applied due to this model is correlated to the particle gravity force and the user-defined force fraction; the gravity force of the smaller particle will be used, as shown in Eq. (14).

$$F_{n,adh} = \begin{cases} 0 & \text{if } -s_n \geq \delta_{adh} \\ f_{adh} g \min(m_1, m_2) & \text{if } -s_n < \delta_{adh} \end{cases} \quad (14)$$

where $F_{n,adh}$ is the normal adhesive force, s_n the contact normal overlap, m_1 and m_2 the mass of particles in contact, g the gravitational acceleration, δ_{adh} the user-defined adhesive distance, and f_{adh} the user-defined force fraction [5], [11].

4.2.6 Particle-fluid interactions

The $\mathbf{F}_{f \rightarrow p}$ fluid-particle interaction force in Eq. (15) consists of drag forces $\mathbf{F}_D$, and non-drag forces $\mathbf{F}_{ND}$ [3].

$$\mathbf{F}_{f \rightarrow p} = \mathbf{F}_D + \mathbf{F}_{ND} \quad (15)$$

$$\mathbf{F}_{ND} = \mathbf{F}_{\nabla p} + \mathbf{F}_L + \mathbf{F}_{VM} \quad (16)$$

Equation (17) below shows the drag force $\mathbf{F}_D$ that acts on the particles due to the continuum airflow.

$$\mathbf{F}_D = \frac{1}{2} C_d \rho_f A' |\mathbf{u} - \mathbf{v}_p| (\mathbf{u} - \mathbf{v}_p) \quad (17)$$

where $\mathbf{u} - \mathbf{v}_p$ represents the relative velocity between the particles and fluid in the projected particle area's flow direction A' [3]. For the coupled simulation model to accurately represent the drag force due to the grain particle shapes being non-spherical, Ganser's drag law is used. The Ganser drag correlation is more accurate as it calculates both the Navier-Stokes and Newton equations while considering the shape and alignment of the particle with the flow field to estimate the drag coefficient [24]. Equation (18) below shows the expression for the drag coefficient C_d in Ganser's drag law.

$$\frac{C_d}{K_2} = \frac{24}{Re_p K_1 K_2} \left[1 + 0.1118 (Re_p K_1 K_2)^{0.6567} \right] + \frac{0.4305}{1 + \frac{3305}{Re_p K_1 K_2}} \quad (18)$$

All the different drag correlations use the same relative particle Reynolds number Re_p as depicted in Eq. (19). For isometric and non-isometric particles K_1 and K_2 have the following expressions in Eqs. (20) and (21) respectively.

$$Re_p = \frac{\rho_f |\mathbf{v}_p - \mathbf{u}| d_p}{\mu_f} \quad (19)$$

$$K_1 = \left(\frac{1d_n}{3d_p} + \frac{2}{3} \emptyset^{-\frac{1}{2}} \right)^{-1} - 2.25 \frac{d_p}{D} \quad (20)$$

$$K_2 = 10^{1.8148(-\log_{10} \emptyset)^{0.5743}} \quad (21)$$

where d_n represents the diameter of the particle if it would have been spherical, with the corresponding projected area in the direction of flow, d_p refers to the diameter of the particle if it would have been spherical, but with the volume of the actual particle, D is the container diameter, and μ_f is the dynamic viscosity of the fluid [5].

The non-drag forces $\mathbf{F}_{ND}$ mainly consist of pressure gradient forces $\mathbf{F}_{\nabla p}$, $\mathbf{F}_L$ lift forces, and $\mathbf{F}_{VM}$ virtual mass forces, as shown in Eq. (16). The pressure gradient forces exerted on the particles occurs due to variations in air pressure along the flow direction [3]. The virtual mass force arises when a particle accelerates, dragging along a portion of the surrounding fluid mass [3]. The pressure gradient and virtual mass forces are denoted in Eqs. (22) and (23) below, respectively.

$$\mathbf{F}_{\nabla p} = -V_p \nabla p \quad (22)$$

$$\mathbf{F}_{VM} = C_{VM} \rho_f V_p \mathbf{a}_r \quad (23)$$

where V_p is the particle volume, C_{VM} is the virtual mass coefficient, $\mathbf{a}_r$ represents the relative acceleration, and [3], [9].

The lift force acts transverse to the direction of the particle's relative velocity with respect to the fluid. It arises from various factors, such as fluid velocity gradients or the rotation of the particle, which creates differing pressure values on its sides [3]. While the lift force is negligible compared to the drag force, it will be included in this study involving the pneumatic separation of impurities to ensure the simulation's accuracy. The lift force in this investigation will be based on Saffman's lift force correlation for three-dimensional flows as expressed in Eq. (24) [3].

$$\mathbf{F}_{L,Saffman} = 6.46\sqrt{\rho_f\mu_f}\frac{d_p^2}{4}\mathbf{u}_r \times (\nabla \times \mathbf{u})|\nabla \times \mathbf{u}|^{-\frac{1}{2}} \quad (24)$$

4.3 ANSYS-Rocky[®] solution algorithm

During the ANSYS-Rocky[®] two-way coupled CFD-DEM procedure for the grain aspirator, the first step is to determine the DEM time step based on particle properties and system stiffness. The fluid flow field, which includes parameters like velocity, pressure, and physical properties, is initialised in the CFD simulation, and the data is transferred to the DEM model. Subsequently, particle volume fraction and interaction terms (forces) are calculated in DEM and transferred to the CFD model. Importantly, the CFD time step is an integer multiple of the DEM time step. This CFD time step is further divided by the sub-stepping integer value for time step correction. After this adjustment, the particulate phase field in the CFD model is updated based on the information derived from the DEM model. The CFD and DEM simulations are executed in parallel, where each sub-step of the CFD time step is carried out simultaneously with n DEM time steps. Interaction forces are then transferred semi-implicitly from DEM to CFD. Updated fluid properties are sent back from the CFD to the DEM model. This entire process is repeated until the total simulation time is reached, continually updating fluid and particulate phase interactions.

Figure 1 below shows the solution algorithm for the ANSYS-Rocky[®] multiphase two-way coupling used during the pneumatic grain separation simulations.

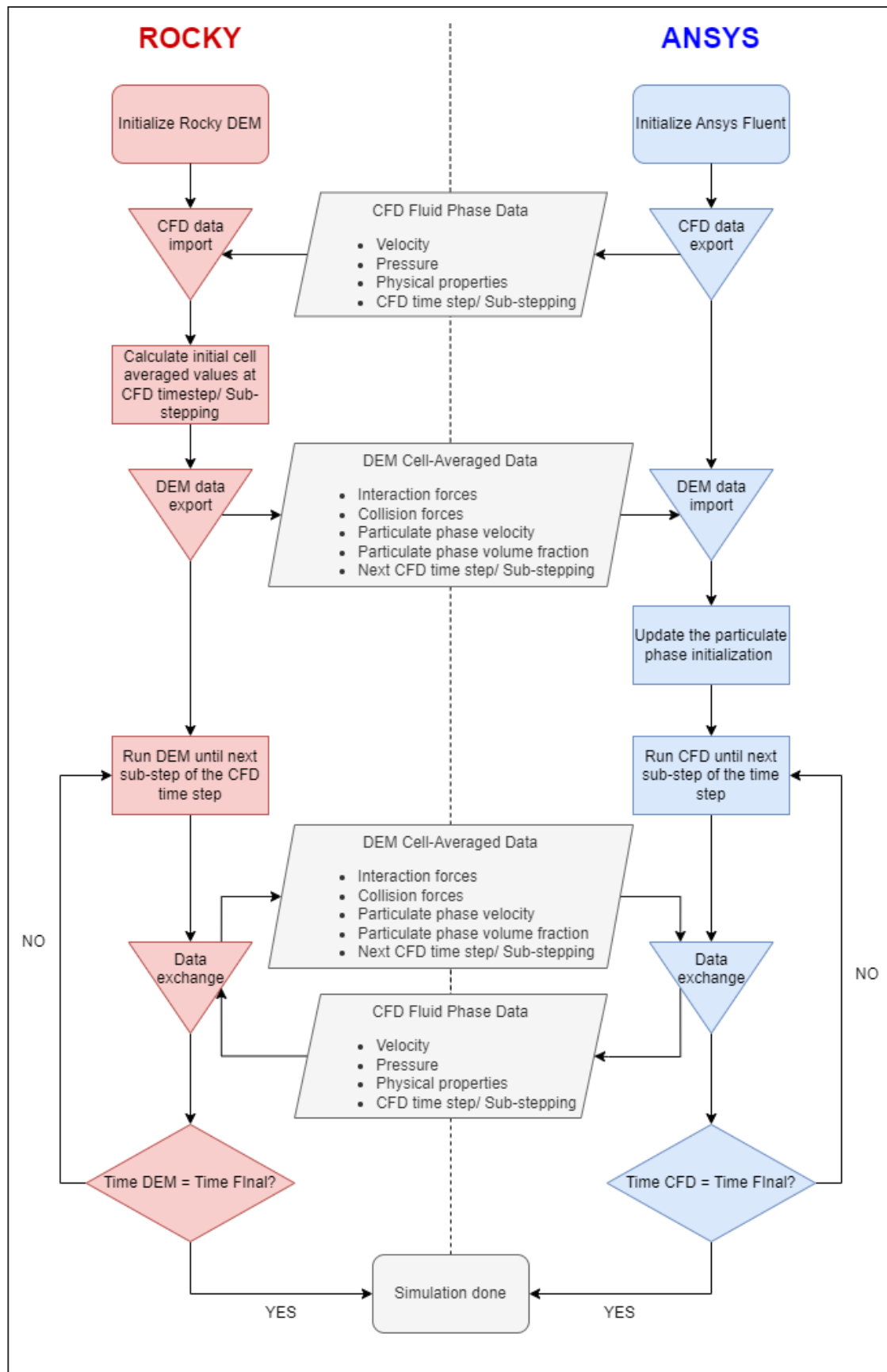


Figure 1: ANSYS-Rocky® solution algorithm for the grain aspirator, adapted from [3]

4.3.1 ANSYS-Rocky® coupling specifics for the grain aspirator

The ANSYS Fluent® and Rocky® DEM coupling procedure for the aspirator has specific aspects, limitations, and issues. The list below gives more insight into this phenomenon:

- The mesh resolution in the CFD domain may be insufficient for identifying the particle scale in the DEM simulation. The particle size in DEM should be less than the mesh cell size in CFD [3], [9], [25]; otherwise, the CFD cell will be mostly particle matter with little fluid. As a result, inaccurate assumptions regarding locally averaged values in a cell can be made [26].
- Since the boundary conditions in both simulations must be consistent, the ANSYS Fluent® "case-file" should be used as the geometry in Rocky® DEM.
- Tracking large numbers of particles in the coupled CFD-DEM simulation can be difficult. When removing outlet geometry from the model for particles to leave the domain, the simulation will automatically stop when all the particles leave the domain or when all the particles of a particular group leave the domain. This phenomenon may cause an early simulation stoppage.
- The simulation domain should closely match the geometry, as particles exiting the domain no longer consume resources, reducing the overall simulation time.
- The sub-stepping algorithm in the ANSYS-Rocky® coupling is essential as it allows for a bigger time-step in Fluent while still having an accurate simulation since the two programs communicate more often.
- A two-way simulation does not support the Dense Discrete Phase Model (DDPM) [3].
- The turbulence option in ANSYS-Fluent® must be set to disperse for a two-way simulation [3].
- The volume and backflow volume fractions should be zero for the discrete phase in ANSYS Fluent® [3].
- The pressure velocity coupling should be set to Phase Coupled SIMPLE in ANSYS Fluent® [3].
- All the different particle sets in Rocky DEM® are combined as one equivalent Eulerian phase in ANSYS Fluent® [3].

4.4 Geometry model

Figure 2 (a) and (b) below show the process flow diagram of the grain aspiration system during operation and the 3D CAD model, respectively.

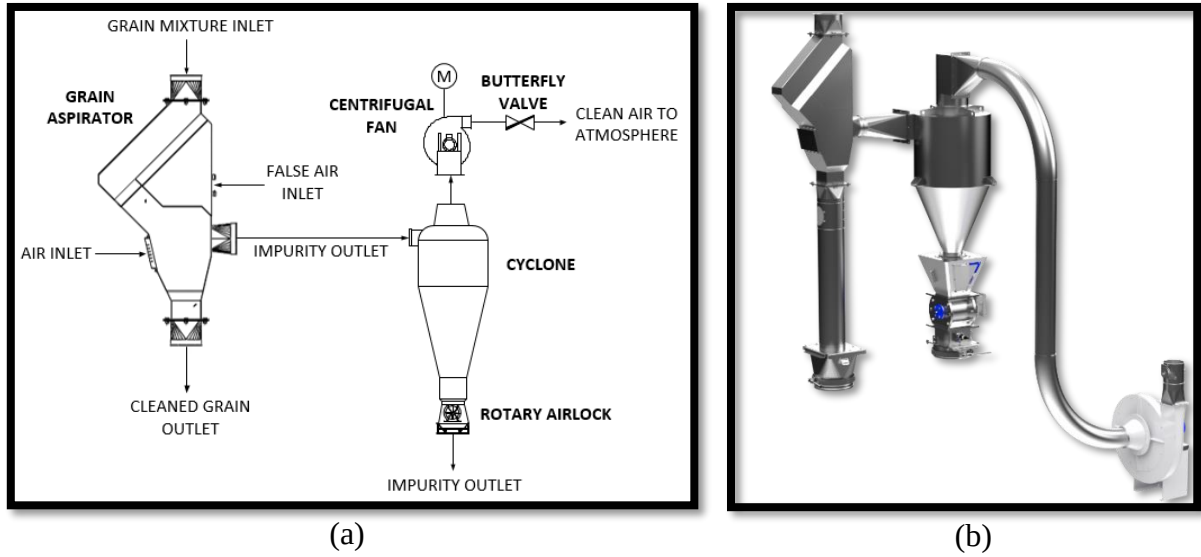


Figure 2: Grain aspiration system (a) Process flow diagram (b) Rendered 3D model

4.5 Experimental procedure

Figure 3 below shows the grain aspirator system's designed and manufactured experimental setup, which will be used to validate the numerical model. The grain is fed into the aspirator system with a disk chain conveyor. A bag-off for the "cleaned grain" is positioned beneath the grain aspirator, while an impurity "bag-off" is below the cyclone. During the testing phase of the grain aspirator, the term "cleaning efficiency" refers to the measured percentage indicating the successful aspiration of impurities from the grain stream. In contrast, "cleaning loss" denotes the measured proportion representing the unintentional aspiration of valuable endosperm particles during the cleaning procedure.



Figure 3: Grain aspiration system experimental setup

The experimental setup featured a disk chain conveyor, grain aspirator, cyclone, rotary airlock, and fan. The experiments were carried out with 25 [kg] samples of the maize mixture at a throughput rate of 7 [tph]. The test mixture consists of corn kernels, broken corn kernels, and corn husks. Prior to testing, the maize mixture entering the aspiration system was analysed; the mixture contained 93.55% degermed maize particles and 6.45% husks, which translates to 23.39 [kg] maize fractions and 1.61 [kg] of husks in each sample of the tests. To ensure accurate and consistent results, the conditions within the experimental setup were maintained at a constant level throughout the testing process. Several experimental tests were conducted to reduce human error, and the calculations used the average. The samples from the impurity outlet first required the removal of maize fractions, and then the husks and maize fractions were weighed separately with high-precision laboratory scales. This procedure allowed the determination of the cleaning efficiency and cleaning loss, which is shown in Eqs. (25) and (26) below.

$$\text{Cleaning Efficiency} = \frac{\text{Mass of husks aspirated}}{\text{Mass of husks in mixture}} \quad (25)$$

$$\text{Cleaning Loss} = \frac{\text{Mass of maize particles aspirated}}{\text{Mass of maize particles in mixture}} \quad (26)$$

The data collected from the experiments revealed that achieving the optimal cleaning efficiency of husk particles and negligible cleaning loss of maize fractions occurs when the airflow through

the aspiration system is controlled at a rate of 1017 [m³/h]. The coupled CFD-DEM simulations will be configured to reflect these exact conditions; consequently, the results will be validated and used for design optimisation. The simulation aims to replicate real-world airflow circumstances and determine its ability to predict the experimental aspiration efficiency, flow patterns, velocity profiles, pressure distribution, particle behaviour, and transient responses. Our previous research paper [27] elaborates on the development of the grain aspirator and provides an in-depth explanation of its functioning.

Observations present in the experimental tests that can be validated in the coupled CFD-DEM simulations:

- The air recirculation increases when grain particles enter the domain.
- Upon closure of the false air inlet, air recirculation increases.
- An increased aspiration rate leads to smaller maize fractions aspirating with impurities.
- The aspiration system functions perfectly, but a few impurities fall through the cleaned grain outlet upon shutdown, suggesting recirculation.
- The particle distribution can be improved, as the aspirator's sides have fewer particles than the middle section.

4.6 Model Implementation

4.6.1 ANSYS Fluent® (CFD) model description

The ANSYS Fluent® simulation meshing process was done using the automatic method while incorporating face refinement where necessary. The tetrahedron element type was chosen, resulting in a mesh having 650,674 elements. Maintaining mesh quality was critical throughout the procedure. The mesh had the lowest orthogonal quality of 0.15, which ensured acceptable element shapes and reduced distortion. Furthermore, the highest skewness was 0.87, showing excellent mesh distribution; the mesh independence was verified in [27]. A minimum element size of 7 [mm] and a maximum of 40 [mm] were maintained to balance computational efficiency and accuracy. The mesh element size is at least three times the diameter of the largest grain particle in areas where the airflow and grain interact, which is in accordance with the guidelines for a coupled CFD-DEM simulation [3], [9], [28]. This ensures that the fluid has an adequate area in the mesh cell to interact with the grain. Figure 4 below shows the tetrahedral mesh on the grain aspirator.

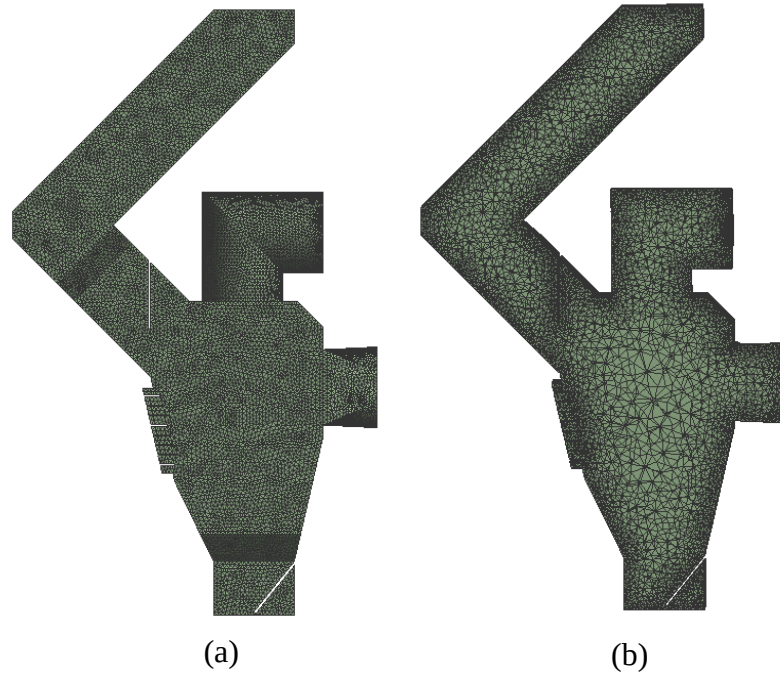


Figure 4: Meshing preview of grain aspirator (a) Front view (b) Section view

Table 1 below shows the various properties chosen during the setup phase of the ANSYS Fluent[®] model and why it was chosen to represent the grain aspirator best.

Table 1: ANSYS Fluent model description

ANSYS Fluent [®] Model		
Property	Description	Reasoning
Time	Transient	To account for changes in the fluid and discrete phase over time.
Multiphase	Eulerian	Continuous phase (air) and discrete phase (grain particles).
Turbulence model	RNG k- ϵ	This model overcomes the shortages of the k-epsilon model, as it is accurate for high internal velocities with swirling and turbulence [11].
Turbulence option	Dispersed	To accurately account for particulate phase effects on continuous phase [3].
Pressure-velocity coupling scheme	Phase Coupled SIMPLE	To allow for more accurate and stable multiphase flows [3].

Spatial discretisation	Second Order	To allow for improved accuracy, convergence, and stability within the simulation.
Transient discretisation	First order	The transient scheme in the coupled ANSYS-Rocky [®] simulation has to be first order [3].
Time step	0.001 s	By using the sub-stepping algorithm in Rocky [®] DEM, the ANSYS Fluent [®] time-step can be increased without sacrificing coupling accuracy [3].
Iterations	2000	To allow for two seconds of simulation.
Convergence criteria	0.0001	The CFD simulation residuals and monitors must converge sufficiently before sending data to Rocky [®] DEM.

The boundary conditions of the simulation were configured to match the experimental conditions. "Pressure Inlet" conditions were assigned to both the airflow inlet and the false air inlet, while a "Pressure Outlet" condition was assigned to the impurity outlet with a set pressure drop of 139 [Pa] to simulate the fan's suction effect. Due to the disk chain conveyor's configuration and the sealed bag-off section, "Wall" type boundary conditions were applied to the grain mixture inlet and the cleaned grain outlet, preventing air inflow. Additionally, all system walls were modelled using "Standard no-slip" conditions to ensure a good approximation of the walls' fluid velocity, aligning closely with the experimental setup. These boundary conditions, which were verified in prior research [27], proved highly effective in simulating the aspirator's vacuum effect generated by the fan. The pressure outlet was configured to yield an airflow rate of 1017 [m³/h], consistent with the specific parameters chosen during experimental testing.

4.6.2 Rocky[®] DEM model description

The following modifications were made to the Rocky[®] DEM model to decrease the simulation duration:

- The Modulus of Elasticity (E) can be reduced by two or three orders of magnitude, which will reduce the overall simulation duration without significantly influencing the accuracy, according to [28]. Thus, Young's modulus was reduced by one order of magnitude, as shown in Table 2 below.

- The numerical softening factor used in the investigation for the discrete phase was 0.8; this decreased the overall stiffness without compromising the simulation's accuracy or stability.
- The rolling resistance model was disregarded since it would lengthen the simulation while having little or no effect on impurity separation accuracy due to airborne particles in the airflow.

The mechanical properties of the maize mixture vary depending on factors like humidity, moisture content, variety, and growth stage. The material properties and interactions presented in Table 2 and Table 3 below are based on data from the literature [29]-[34], and minor changes were performed to represent better the realistic grain mixture used in the experimental setup.

Table 2: Rocky® DEM material properties

	Poisson's ratio	Young's Modulus (MPa)	Reduced Young's Modulus (MPa)	Bulk density (kg/m³)
Maize	0.4	280	28	790
Husks	0.4	100	10	230

Table 3: Rocky® DEM material interactions

Material Interactions				
	Restitution coefficient	Static friction coefficient	Dynamic friction coefficient	Adhesive force fraction
Maize-Maize	0.25	0.5	0.4	0
Maize-Wall	0.6	0.3	0.25	0
Husks-Husks	0.3	0.5	0.4	0.2
Husks-Wall	0.4	0.3	0.25	0.2
Maize-Husks	0.2	0.5	0.4	0.2

Table 4 below elaborates on the setup details for the DEM simulation regarding the particles, while Table 5 provides further details on the setup for the CFD-DEM coupling.

Table 4: Rocky[®] DEM simulation setup details

Property	Description	Unit	Reasoning
Particle input	Continuous injection	-	The continuous injection of particles represents the experimental setup better than a “volume fill”.
Maize particles shape	Polyhedron	-	The polyhedron shape parameters accurately represent the maize particles, ensuring accurate simulation results and good computational efficiency [35].
Husk particles shape	Custom polyhedron	-	A custom-modelled husk shape is used, which will improve the accuracy of impurity aspiration.
Maize throughput	6.55	[tph]	As measured in the experimental mixture.
Husks throughput	0.45	[tph]	As measured in the experimental mixture.
Maize particle size	1.5 – 9.76 sieve size	[mm]	As measured in the experimental mixture.
Husk particle size	1.5 – 9 sieve size	[mm]	As measured in the experimental mixture.

Table 5: ANSYS-Rocky[®] CFD-DEM simulation setup details

Property	Description	Unit	Reasoning
CFD coupling	Two-way Fluent	-	A two-way simulation is needed to visualise the change in airflow due to the grain particles.
Sub-stepping	30	-	To allow for a more tight and accurate coupling between ANSYS [®] and Rocky [®] DEM, data will be exchanged 25 times between each CFD time step.
Mapping method	Volumetric diffusion	-	Volumetric diffusion is more computationally expensive, but accuracy is needed to fully capture the interaction between the airflow and various grain particle types and sizes.
Drag law	Ganser	-	The drag force on non-spherical shaped particles with fluctuations is well predicted by Ganser's law [24], [26].
Virtual mass force	Paladino	-	The force is a function of the volume fraction of the fluid phase and accounts for particle shape [5].
Simulation duration	2	[s]	The simulation duration is equivalent to the ANSYS Fluent [®] simulation time.
Fluent outputs multiplier	1	-	The Rocky [®] DEM and ANSYS Fluent [®] data will be saved after each time step.

The turbulent dispersion model in Rocky[®] DEM was enabled for the maize and the husk particles, so each particle's path is modified by sampling turbulence, and the system's overall turbulence is derived through statistical averaging across multiple particles.

Table 6 below presents the shape and size parameters for the maize particles used in the simulation. The shape parameters of the maize particles in the simulation were obtained from [35] allowing an accurate representation of the particles while ensuring good computational efficiency.

Table 6: Maize particle shape and count for each equivalent diameter



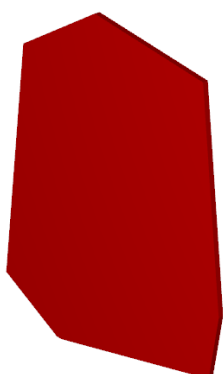
MAIZE			
Polyhedron Shape Parameters		Equivalent Diameter	Particle Count
Vertical aspect ratio	0.62	8.45 - 9.76	171
		7.85 - 8.45	359
Horizontal aspect ratio	1.36	7.22 - 7.85	369
		6.58 - 7.22	148
Number of corners	60	5 - 6.58	264
		2.5 - 5	326
Superquadratic degree	3.00	1.5 - 2.5	1373
		1.5	2681
			5691



Table 7 below presents the size parameters for husk particles used in the simulation. The shape used is a custom polyhedron imported into the simulation for increased accuracy.

Table 7: Husk particle shape and count for each equivalent diameter

HUSKS	
Equivalent Diameter	Particle Count
5.0 - 6.0	12292
4.0 - 5.0	2674
2.0 - 4.0	5570
2	1467
22003	



4.7 Results and discussion

4.7.1 ANSYS Fluent® CFD simulation

Figure 5 below shows the ANSYS Fluent® airflow simulation through the grain aspirator without particle interaction (one-way). The two solvers use this initial flow field when executing in parallel.

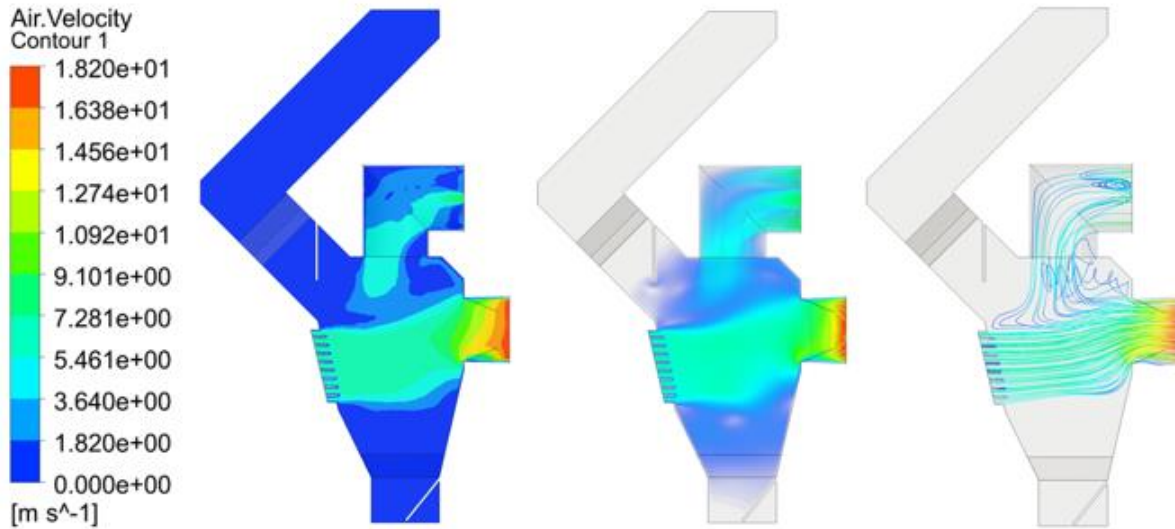


Figure 5: ANSYS Fluent® simulation results

The ANSYS Fluent® CFD simulation model used in this work was thoroughly verified, as described in [27]. The verification process included a thorough evaluation to ensure the simulation model met the set criteria and standards. The CFD simulation shows an elegant and uniform air crossflow without much recirculation in the aspirator.

4.7.2 Rocky® DEM simulation

Figure 6 below shows the grain particles moving through the grain aspirator without any airflow acting on it.

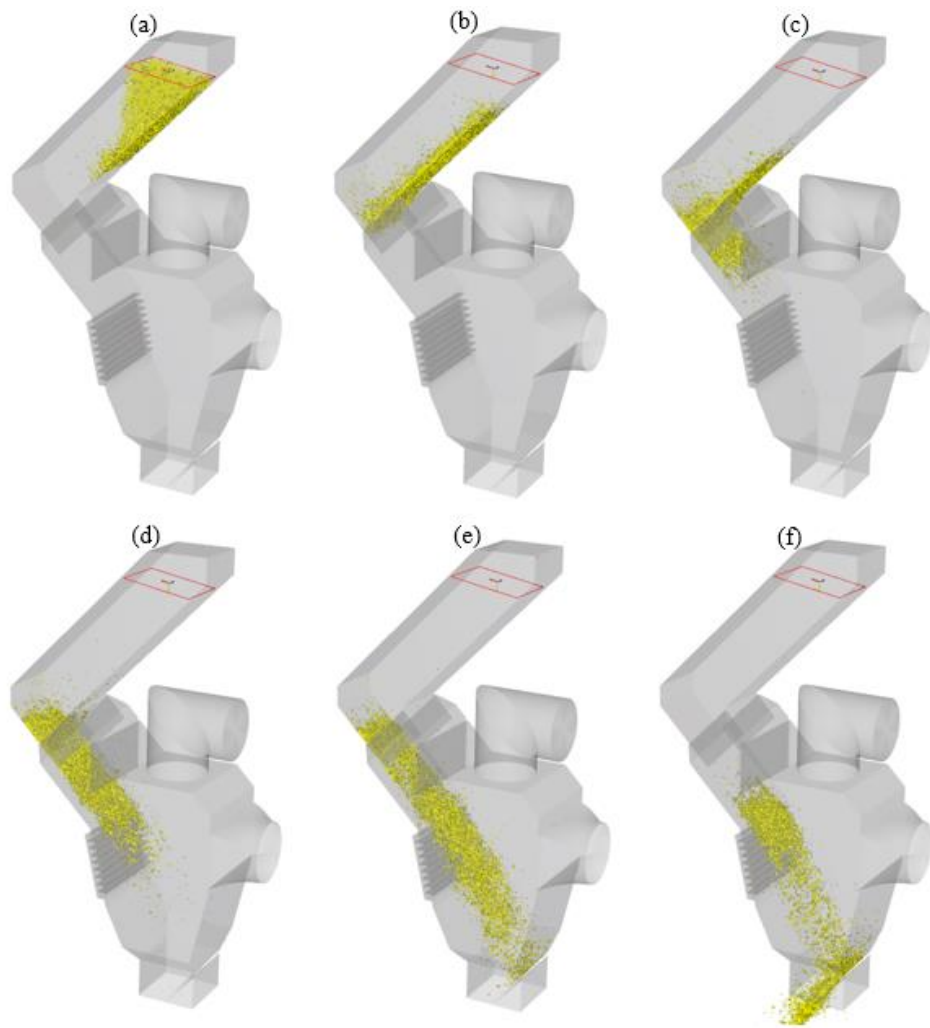


Figure 6: Rocky® DEM simulation of the maize mixture through the aspirator

As the particles flow through the aspirator from section (a) to (f) in Figure 6 above, it is clear that the particles move gently, and the particles will not choke in the aspirator upon continuous operation. Figure 7 below shows the particle distribution of the aspirator during operation.

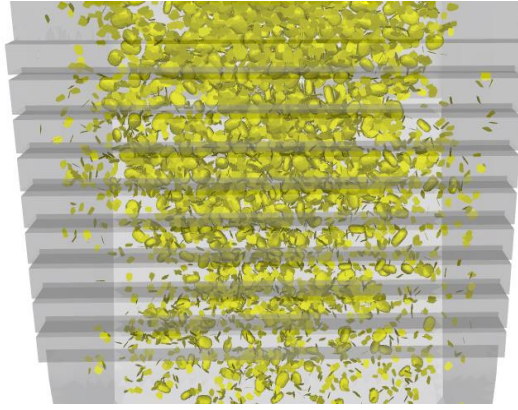


Figure 7: Rocky® DEM simulation of the maize mixture distribution

It is noted, however, that the particles are not evenly distributed over the entire width of the aspirator, which corresponds with the experimental observations. The performance of the aspirator can be improved drastically if the particle spread is even, as it will allow the airflow to draw through the grain curtain evenly.

Figure 8 and Figure 9 below elaborate on the particle flow characteristics gained from the DEM simulation.

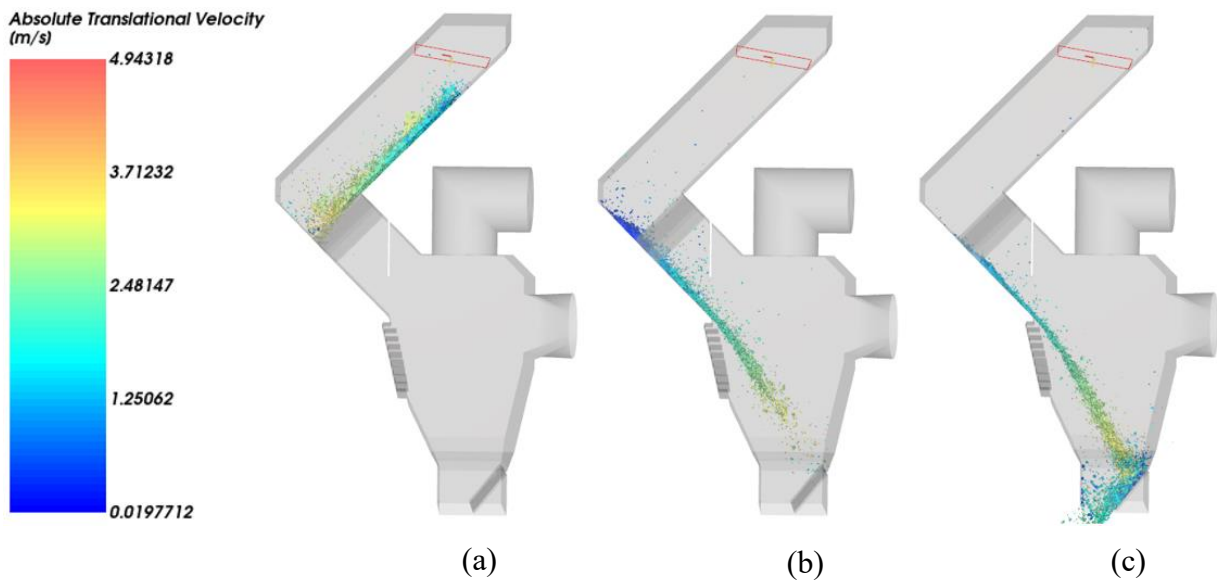


Figure 8: Particle translational velocity in DEM simulation

The translational velocities of the maize particles in section (a) are high but are reduced upon impact with the wall when changing direction. As a result, the particles attain a velocity of approximately 2.2 [m/s] while free-falling through the aspiration section, which is acceptable. Decreased particle velocity is crucial, as excessive particle translational velocity through the aspiration section would give the fan less time to aspirate the impurities.

Figure 9 below shows the trajectory of the maize particles moving through the aspirator.

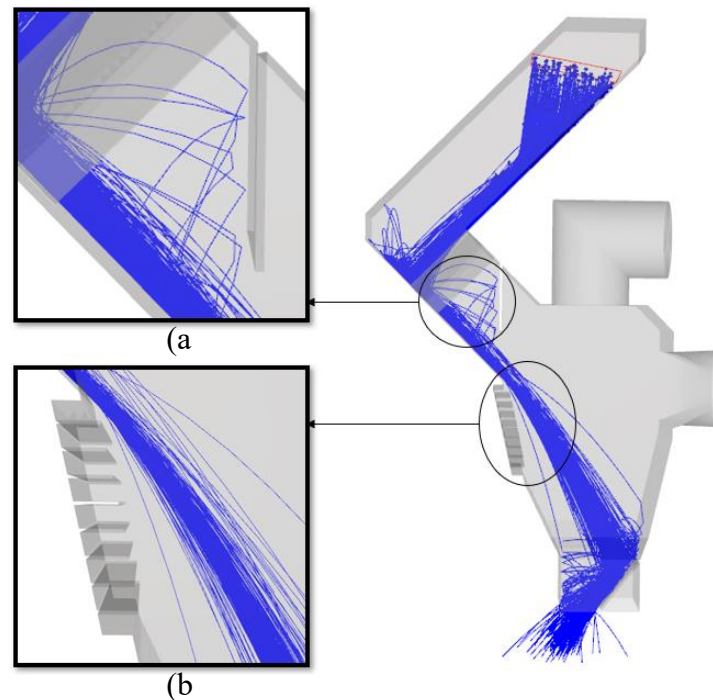


Figure 9: Maize particle trajectory in DEM simulation

The particle deflector plate shown in section (a) of Figure 9 above functions well as it prevents particles from entering the aspiration section with the wrong trajectory. Section (b) of Figure 9 illustrates that the particles will not contact the inlet vanes without airflow. Consequently, there is no risk of particle accumulation on the inlet vanes, reducing the likelihood of clogging over time.

4.7.3 Coupled ANSYS-Rocky® simulation

4.7.3.1 One-way vs. two-way airflow

Figure 10 below shows how the initial one-way fluid airflow transitions to two-way airflow when the grain particles fall through the moving airstream.

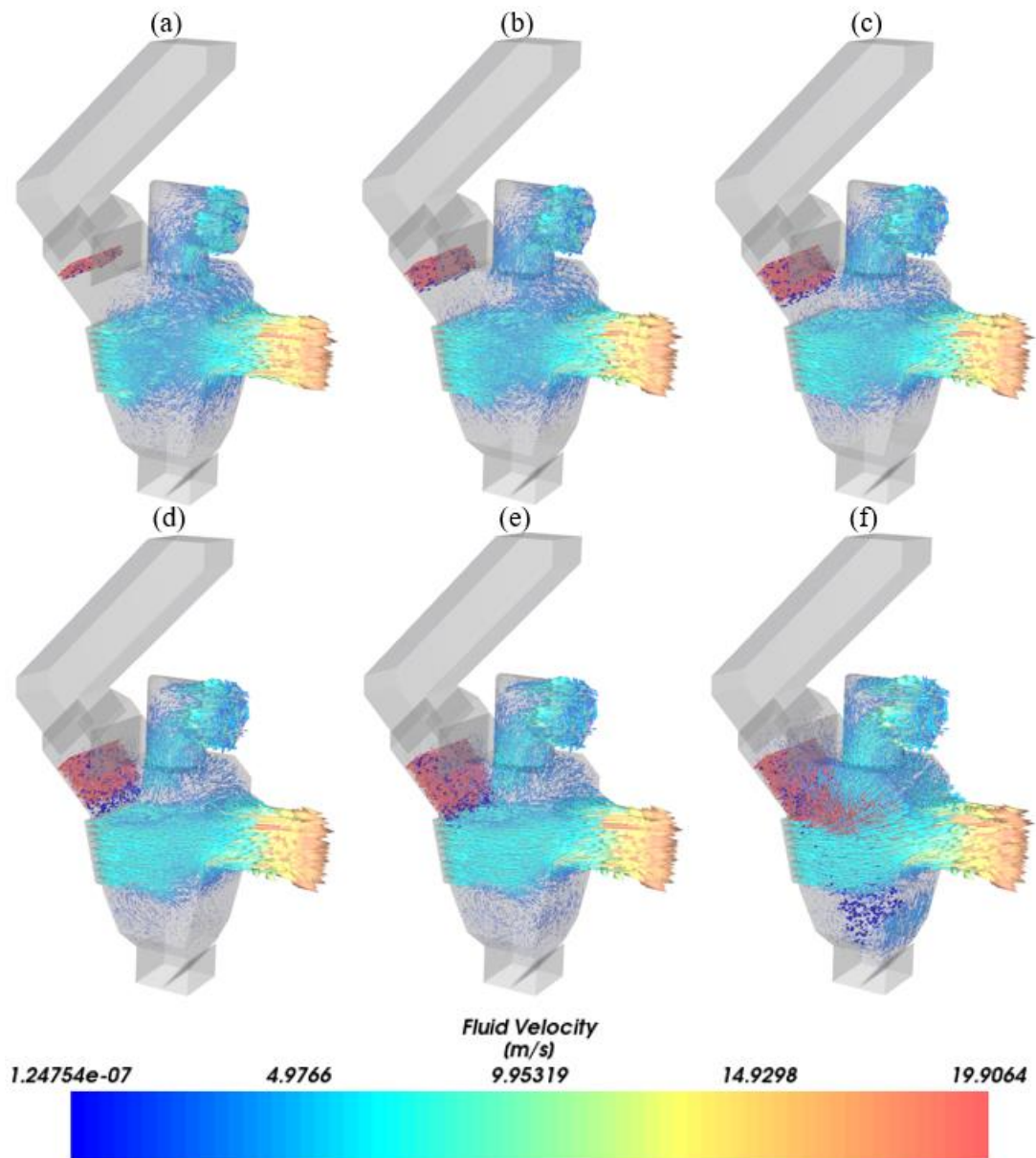


Figure 10: One-way to two-way airflow transition in the grain aspirator

It is evident in Figure 10 above that the grain particles falling through the grain aspirator significantly alter the initial one-way CFD airflow, which emphasises the importance of coupled CFD-DEM simulations when simulating pneumatic grain separation processes as it can accurately replicate the real-world airflow. The crossflow of air increases as the grain particles fall through the aspirator, and the recirculation increases.

Figure 11 below shows that if the velocity vectors in the CFD-DEM simulation are exaggerated, it clearly shows the increased recirculation areas observed in the experiments.

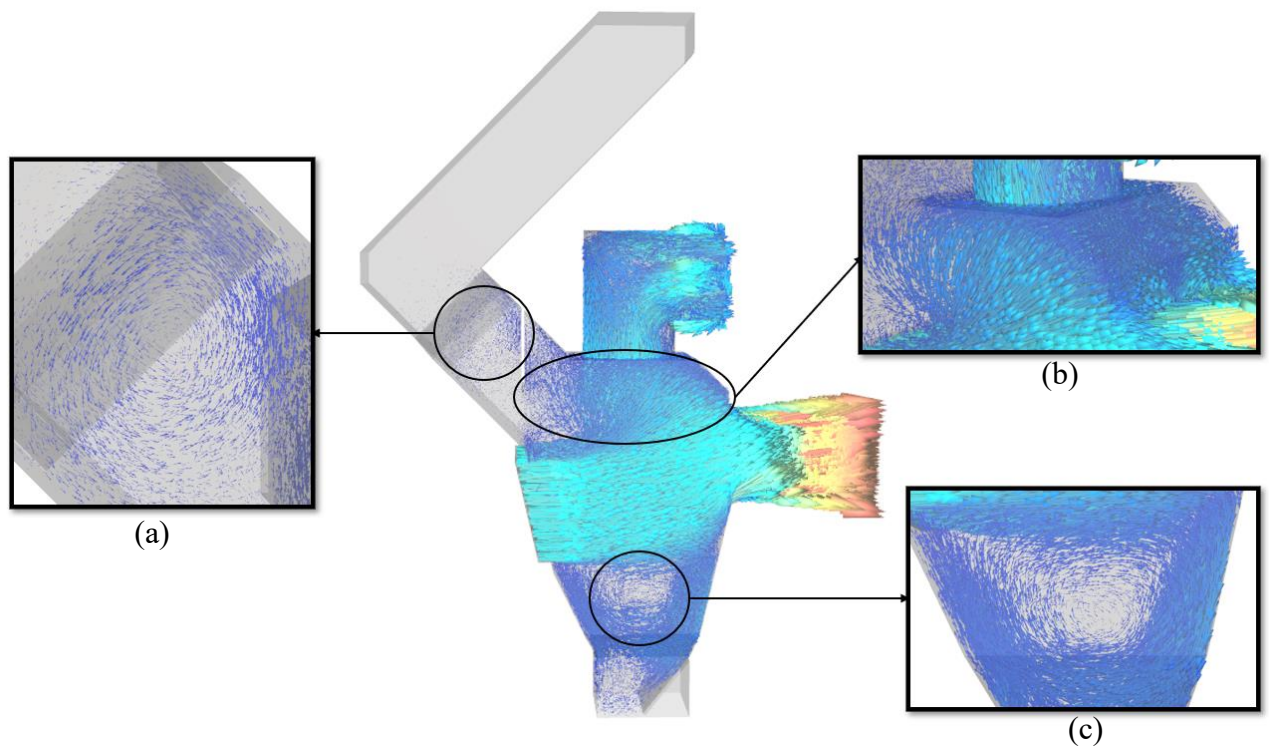


Figure 11: Increased air recirculation visualisation of the two-way airflow

The air recirculation area in section (a) of Figure 11 is the phenomenon that causes some impurities to fall through the cleaned grain outlet when the system is shut down in the experimental tests. Recirculation area (b) in Figure 11 above increases the time it takes to remove the impurities from the aspirator; if this recirculation area can be reduced, the cleaning efficiency and the rate at which the impurities are being aspirated will increase. The recirculation propagates from the side walls of the aspirator to the middle of the top section. The recirculation in areas (a) and (b) can be avoided by adding guide plates for the airflow, which guides the airflow into the impurity outlet and restricts it from recirculating. Recirculation in section (c) will not be easily avoidable, but it will not have a detrimental effect on the efficiency of the aspirator as it is below the aspiration area.

Closing the false air inlet reduced cleaning efficiency, likely due to the recirculation of impurities, as evidenced by experimental observations. Figure 12 below shows the difference between the initial CFD flow field and the developed CFD-DEM airflow through the aspirator while the false air inlet is completely closed.

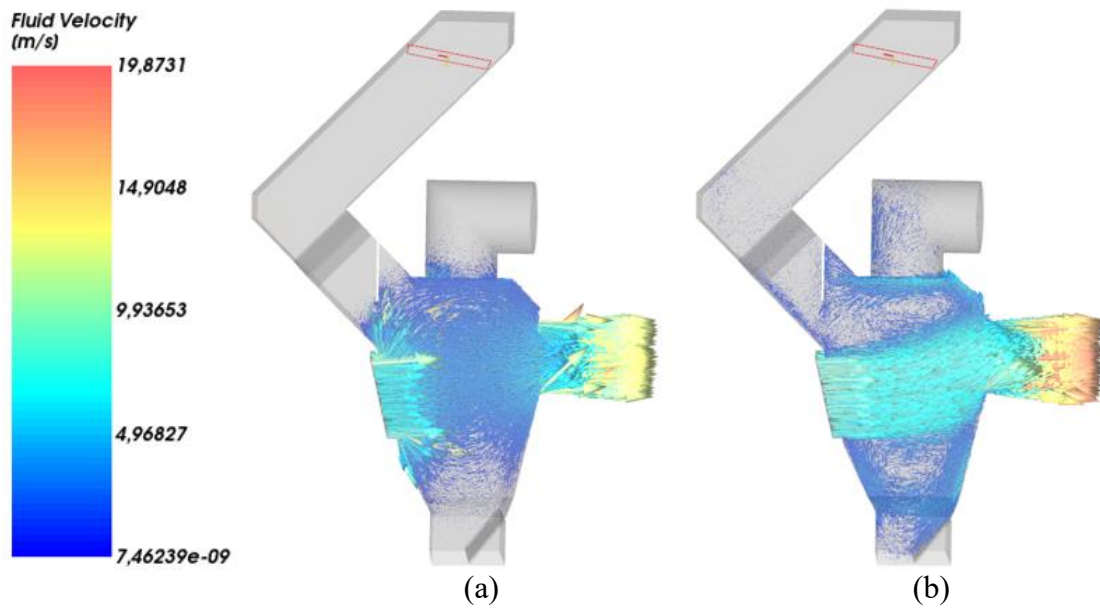


Figure 12: Increased recirculation when grain is injected (a) Initial CFD airflow (b) Developed two-way coupled airflow

The two-way coupled CFD-DEM simulation of Figure 12 (b) provides further insight that corresponds with the experimental observations. However, ANSYS Fluent® CFD simulations indicate no recirculation, as seen in section (a) of Figure 12. This discrepancy suggests grain particles may disrupt the CFD airflow visualised in section (b) of Figure 12 through a two-way coupled CFD-DEM airflow analysis.

4.7.3.2 Coupled CFD-DEM grain aspirator

Figure 13 below shows the various time steps of the coupled CFD-DEM simulation, showing how the grain mixture of maize (blue) and husks (red) particles move through the grain aspirator during operation.

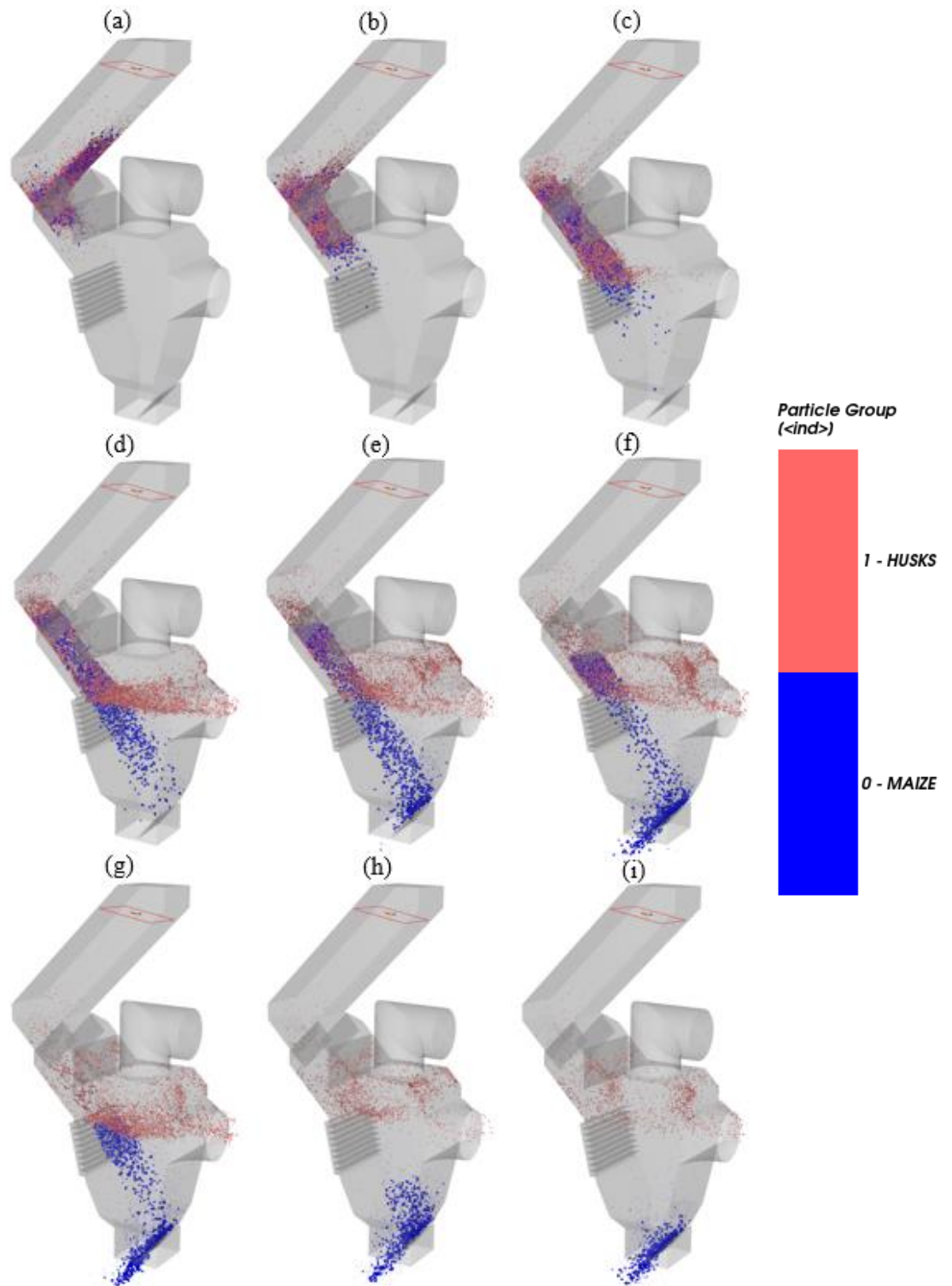


Figure 13: ANSYS-Rocky® coupled CFD-DEM simulation of the maize mixture through the aspirator

As the maize mixture moves through the aspirator, the airstream immediately picks up the impurities (husks). The husks follow the exact path of the airstream, and some of the particles get captured in the recirculation areas on the way out.

Figure 14 below confirms the phenomena experienced in the experiments: the smaller maize particles will be aspirated before the bigger particles.

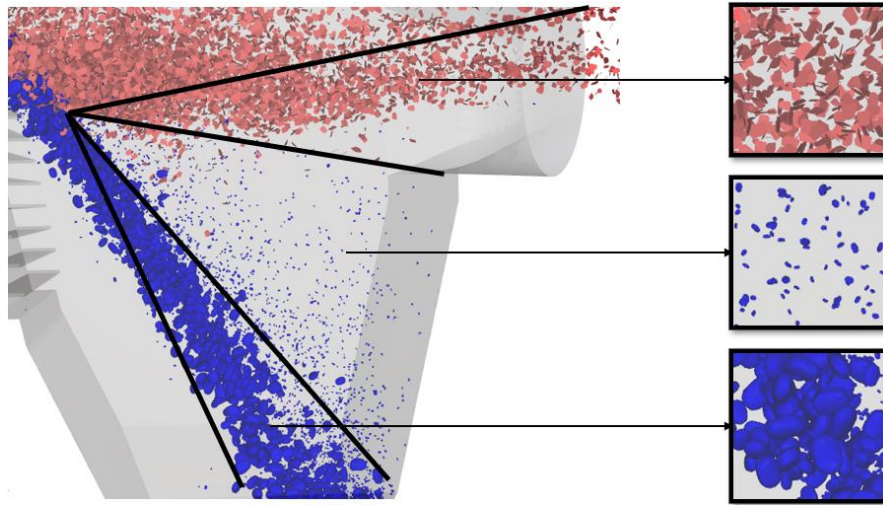


Figure 14: Particle classification streams

This feature of the aspirator can be leveraged to its advantage by incorporating multiple sections at the bottom outlet. This modification would enable the aspirator to remove lighter impurities and potentially allow for the classification of the cleaned mixture into distinct categories.

The coupled CFD-DEM simulations corresponded with all the experimental observations, which was previously impossible with only CFD simulations. While conducting a coupled CFD-DEM simulation as opposed to solely relying on CFD analysis, several vital distinctions were observed:

- The aerodynamic behaviour near the aspirator's sidewalls undergoes a noticeable change, exhibiting an increased airflow rate that instigates recirculatory motion close to the impurity outlet.
- Unlike in the CFD-only simulations, where it was absent, there is a marked elevation in airflow recirculation within the aspirator in various sections, affecting its fluid dynamics properties.
- The coupled simulation delivers a precise representation of the trajectories followed by injected particles within the airflow, effectively capturing their dynamic behaviour.
- Notably, the coupled CFD-DEM simulation outcomes showed a high degree of correspondence with experimental data.

The insights derived from the coupled CFD-DEM offer a pathway for the optimisation of the aspirator with the following actionable improvements:

- The false air inlet ducting should be designed so that it progressively widens until it matches the aspirator's width, which will mitigate abrupt variations in airflow.
- Internal plates should be strategically placed in section (a) of Figure 11 to target and restrict air and impurity recirculation,
- To further curb the issue of airflow recirculation, an airflow guide plate is advised to be positioned in section (b) of Figure 11. This addition will redirect the airflow more efficiently and reduce the pressure drop across the aspirator, optimising its operational efficiency.
- The internal guide plates in section (a) of Figure 11 should be removed, allowing the particles to spread over the entire width of the aspirator more evenly.
- Extending the length of the square-to-round ducting at the impurity outlet may be beneficial. This is because the current design, where airflow transitions from a broader section to a narrower outlet, unintentionally increases the velocity at the sides, leading to airflow recirculation.

The aspirator's functionality is expected to improve because of these adjustments, proving the value of using the coupled CFD-DEM technique for comprehensive system analysis.

Figure 15 below shows the particle count of the maize and husks throughout the simulation.

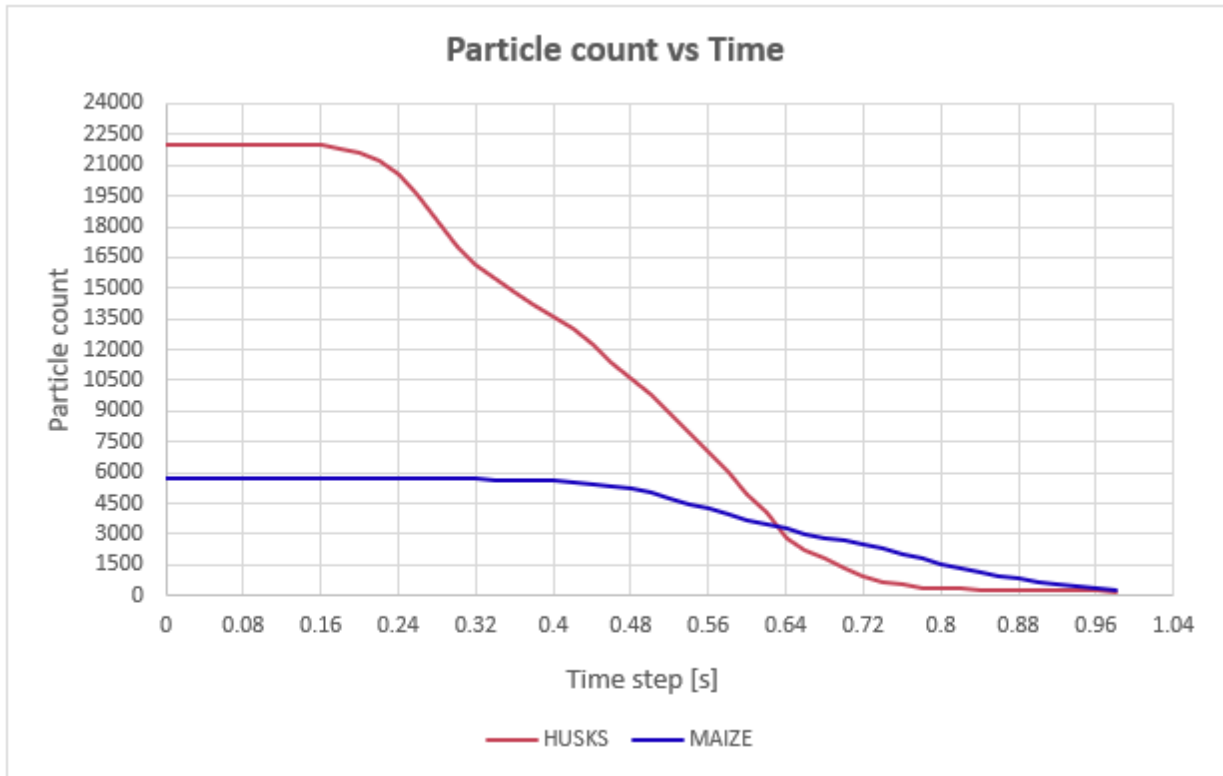


Figure 15: Maize and husk particle count throughout the simulation

The husks are being aspirated out of the system much faster than the maize particles leave the system, which suggests it may be possible to achieve similar results at an even higher throughput rate.

Figure 16 below shows the mass of the maize particles at the impurity outlet during the simulation.

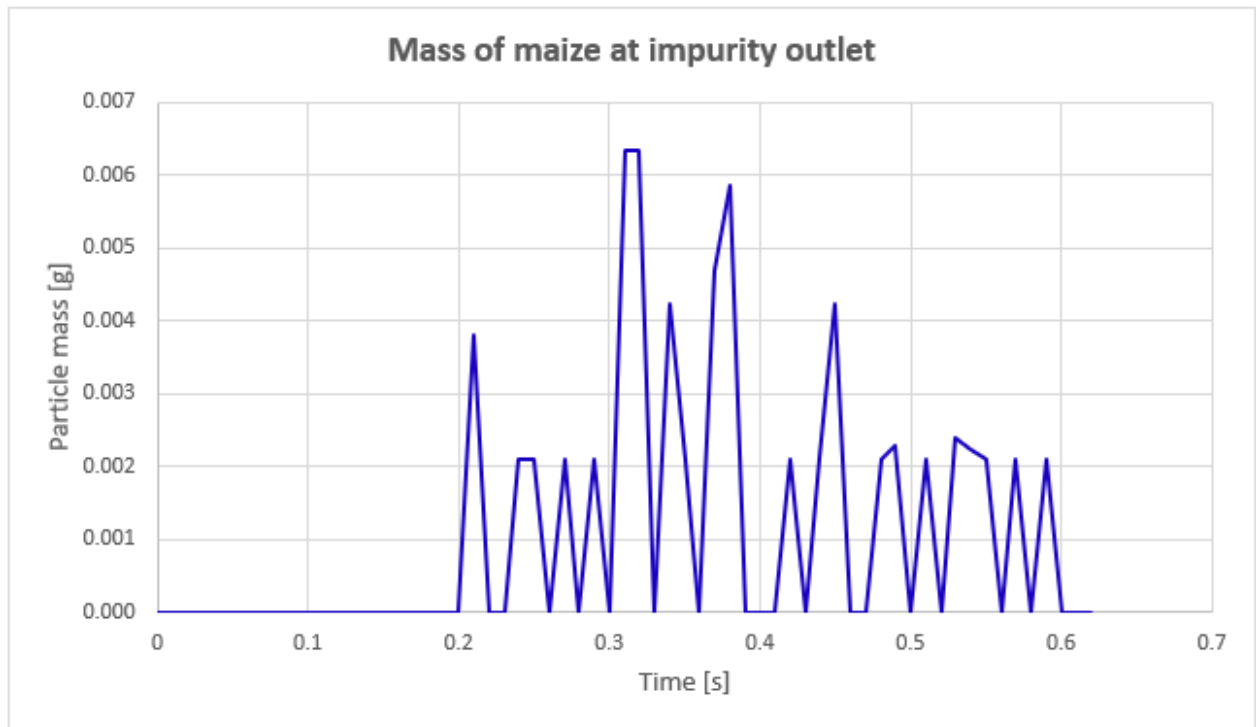


Figure 16: Mass of maize at impurity outlet

The total mass of the maize particles that leave the impurity outlet during aspiration determines the cleaning loss.

Figure 17 below shows the mass of the husk particles at the cleaned outlet during the simulation.

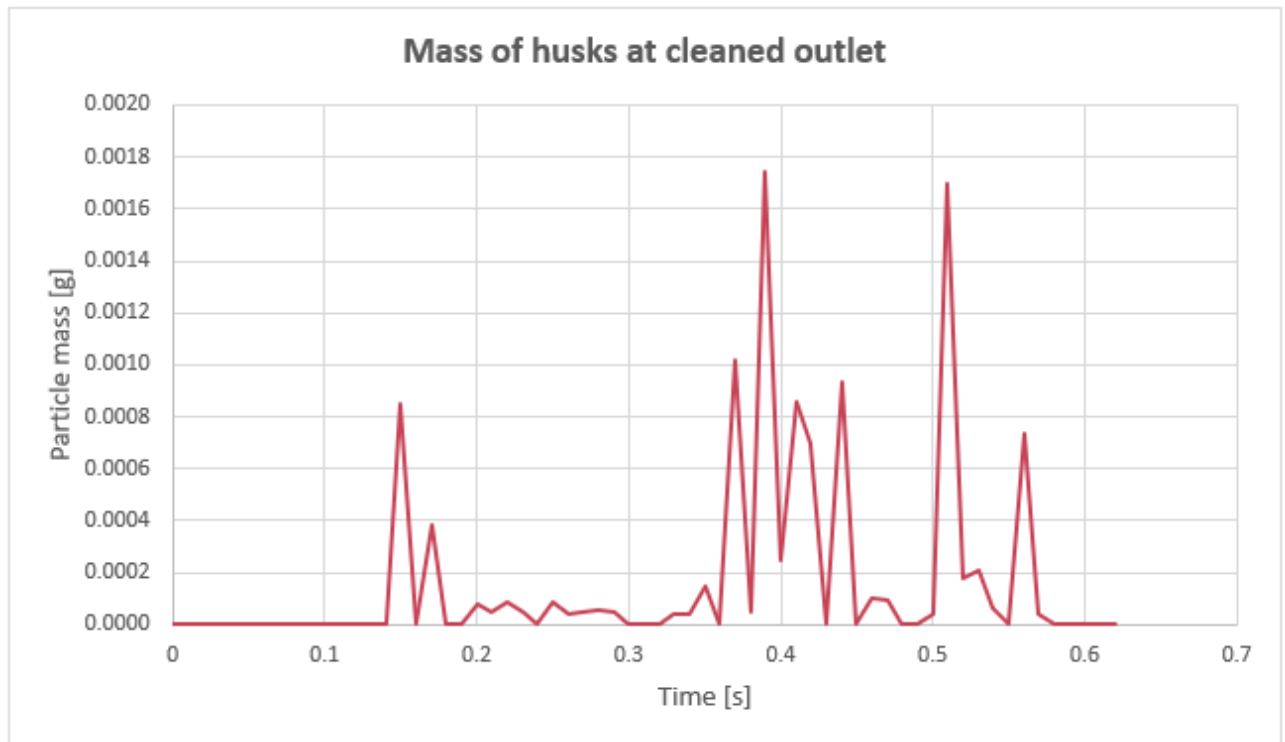


Figure 17: Mass of husks at the cleaned outlet

The total mass of husks that remain in recirculation, which can be seen at the end of the line graph in Figure 15, together with the data below, is used to calculate the cleaning efficiency of husks.

Table 8 and Table 9 below represent the results obtained from the experiments and simulation.

Table 8: Experimental results

Experimental Results				
	Husk mass cleaned outlet [g]	Cleaning Efficiency	Maize mass impurity outlet [g]	Cleaning loss
Run 1	1559.58	96.87%	5.4087	0.0231%
Run 2	1505.12	93.49%	4.5358	0.0194%
Run 3	1479.23	91.88%	3.9897	0.0171%
Run 4	1506.54	93.57%	4.6547	0.0199%
Average	-	93.95%	-	0.0199%
Standard deviation	-	2.10%	-	0.0025%

Table 9: Coupled CFD-DEM simulation results

ANSYS-Rocky® Simulation	
Cleaning Efficiency	Cleaning loss
98.36%	0.0186%

The error percentage between the experiments and the simulation was calculated using Eq. (27) below; it uses the experimental results as a benchmark to determine the percentage error present in the simulation.

$$\text{Simulation Error Percentage} = \frac{|\text{Experimental value} - \text{Simulation value}|}{\text{Experimental value}} \quad (27)$$

Table 10 below summarises the error percentages between the experimental setup and the simulation.

Table 10: Error percentage between the experiments and the simulations

Experiments and simulations error percentage	
Cleaning efficiency	4.69%
Cleaning loss	6.18%

The cleaning efficiency and loss observed in the experiment show minor variations compared to the simulation. The simulation has excellent correspondence with the experimental data; however, the simulation requires a lower volume flow rate to achieve the same results than in reality. The simulation aspirated more husks and endosperm pieces at the same volume flow of air when compared to experiments. These differences may be attributed to various factors like:

- The simulation is too short, not enabling the airflow to stabilise.
- The simulation's particles' drag coefficient differs from the actual drag coefficient.
- The unpredictable physical characteristics and quality of the grain particles in the experiments.

4.8 Conclusion

In this study, a two-way coupled CFD-DEM numerical model was developed to analyse and optimise a grain aspirator. The simulation met the validation benchmarks by closely matching the experimental data, with a cleaning efficiency error of 4.69% and a cleaning loss error of 6.18%. The simulation also accurately replicated the observed experimental phenomena, validating its predictive capabilities in both quantitative and qualitative dimensions. The simulation achieved validation and served as an invaluable asset for further optimisation of the grain aspirator system. Using CFD-DEM to simulate realistic pneumatic grain separation systems is highly advantageous since it provides essential insights into complex mechanics, easing the design process and providing significant time and cost savings.

Recommendations for future work to improve simulation accuracy:

- Compare different CFD meshing types, such as hexahedron and polyhedral.
- A semi-resolved coupled CFD-DEM simulation might be more accurate.
- Simulating the aspirator, cyclone, and fan together as an integrated system rather than focusing solely on the aspirator will be more computationally demanding but will yield more accurate results for both flow profiles and system pressure drop.
- Increase the simulation duration.
- Conduct simplified preliminary simulations using various physical models and drag laws to accurately determine which correlations most closely represent the characteristics of the grain mixture.

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Author contributions PG: Writing- Original draft, Methodology, Software, Validation, Investigation. OK: Conceptualisation, Writing: Review & Editing, Resources, Supervision. LJG: Funding Acquisition, Resources, Writing: Review & Editing, Supervision.

Conflict of interest The authors declare no conflicts of interest relevant to this study.

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CHAPTER 5 – CONCLUSION AND RECOMMENDATIONS

5. Conclusion and Recommendations

Motivated by the various advantages of pneumatic grain separators, a compact, energy-efficient and low-maintenance pneumatic grain separator was developed and thoroughly evaluated. In the industry, the design process generally relies heavily on trial-and-error methods, which, while functional, lack the precision offered by numerical modelling techniques like Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM). Numerical modelling techniques such as CFD and DEM offered several advantages while developing the pneumatic grain separation system.

A horizontal crossflow pneumatic grain separator (aspirator) that meets the specified requirements has been successfully developed. CFD simulations were crucial in shaping the aspirator's concept and specifying the system's components. The final design of the aspirator was developed with an experimental setup where the CFD simulations could be successfully validated. Efficiency tests on the system were conducted using mixtures of maize and husks and soybeans and hulls. These tests also accounted for varying conditions like moisture levels and grain or seed varieties. The system achieved a high cleaning efficiency of up to 96.87%, with a minimal cleaning loss of 0.02%. Further evaluation of the aspiration system in an industrial setting confirmed its effectiveness and adaptability.

Another experimental setup was created to allow for easy control and adjustment of all parameters. For further optimisation of the aspirator, it was crucial to analyse the internal two-way airflow in conjunction with the particles passing through the system. A coupled CFD-DEM simulation was carried out using ANSYS-Rocky[®], which provided valuable insights. This simulation identified several areas where improvements could be made, particularly concerning airflow and particle movement. The coupled simulation effectively captured the particles' behaviour in the airflow, and its results were validated quantitatively by comparing with experimentally measured efficiencies and qualitatively through experimental observations.

This study demonstrates the feasibility of conducting coupled CFD-DEM simulations on a grain aspiration system. It also confirms that the simulation results closely match real-world behaviour and tendencies. Additionally, the study outlines fundamental principles to consider when

developing pneumatic grain separation systems. The parameters for both particles and setup are fully documented, providing a basis for future research.

The following recommendations can be made for future research in similar fields:

- Coupled CFD-DEM simulation approaches are advised for developing and analysing pneumatic grain cleaning systems.
- Investigate and predict the wear and tear within grain cleaning systems with coupled CFD-DEM simulations.
- Utilise coupled CFD-DEM simulations to conduct an energy consumption analysis in machinery with particle dynamics and airflow.
- The development process for a pneumatic grain separation system that uses coupled CFD-DEM simulations may become computationally intensive and complex if there are too many particles. An alternative approach could be to run CFD and DEM simulations iteratively but separately instead of coupling them. This method may yield valuable insights while reducing computational costs and complexity.

ANNEXURES

This section presents data not included in the research articles, detailing the instrumentation, experimental setup, machinery, and manufacturing techniques. It covers the prototype, industry, and soybean mixture testing from the first article and data for validating the CFD simulation.

- Appendix A- Experimental Instrumentation
- Appendix B- Manufacturing
- Appendix C- System component breakdown
- Appendix D- Article 1
- Appendix E- CFD validation
- Appendix F- Rocky DEM calibration

APPENDIX A- EXPERIMENTAL INSTRUMENTATION

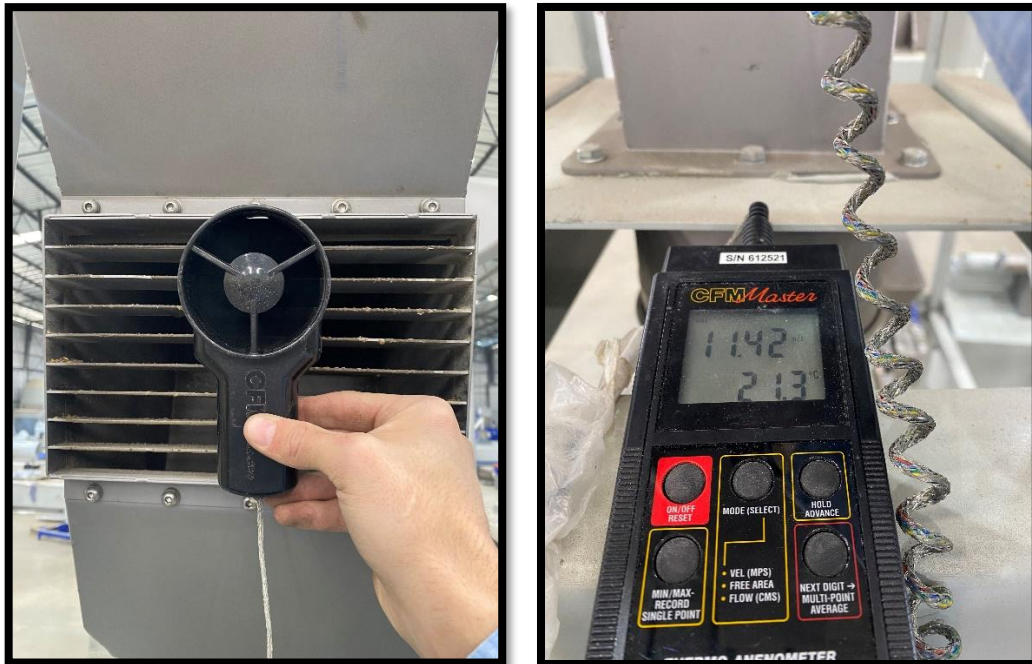
A "Radwag AS 110/C/2" digital scale was used to weigh the samples between 0.001 [g] and 110 [g], with a readability of 0.0001 [g].



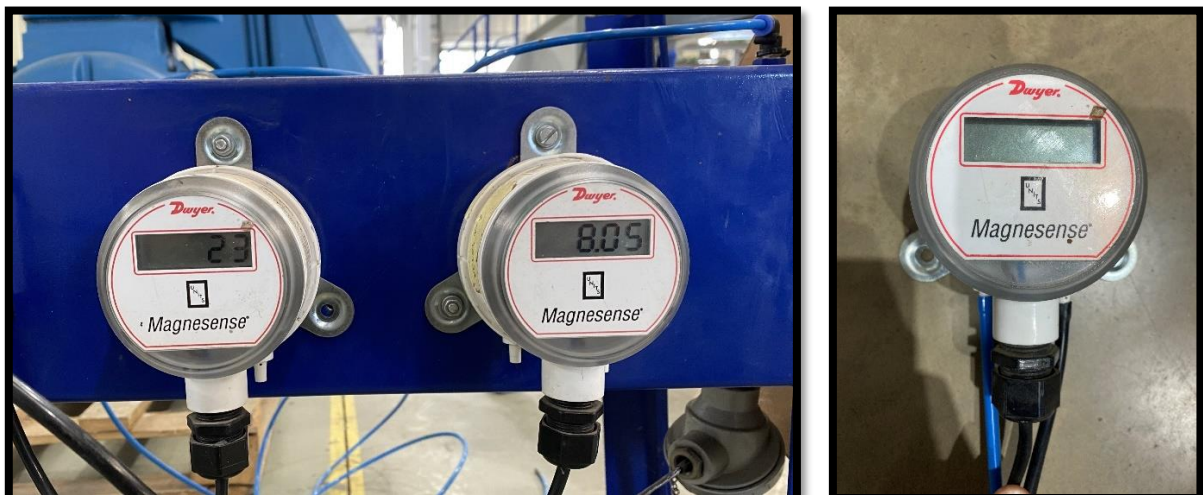
A "Mettler Toledo New Classic MF – MS603S" digital scale was used to weigh the samples that were between 110 [g] and 620 [g], with a readability of up to 0.001 [g].



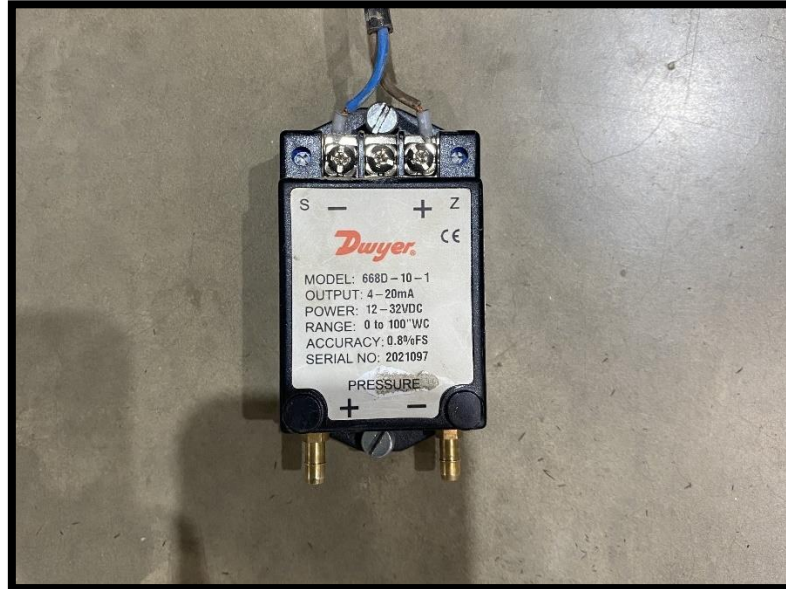
A "CFM Master" anemometer was used to measure airflow velocity during validation and testing in areas where the pitot tube is not accessible.



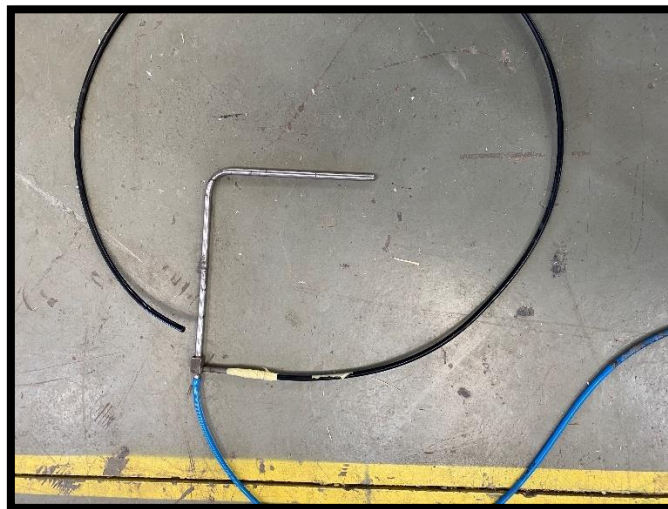
The "Dwyer Magnesense Differential Pressure Transmitter" can measure air pressure and velocity. The Dwyer Magnesense sensors were used in areas with a differential pressure below 1250 [Pa]. Both sensors are the "MS-111*" model with a selectable range of 250, 500, or 1250 [Pa], with an accuracy of ± 1 [%] and response time of 0.5 [s].



A "Dwyer Differential Pressure Transmitter" model "668D-10-1" has a unidirectional range from 0 – 100" [WC], which is equivalent to 24900 [Pa], at an accuracy of $\pm 0.8\%$ FS. This sensor was used in areas where the total differential pressure exceeded 1250 [Pa].



A pitot tube measured the airflow velocity in the system's piping. The static and dynamic pressure obtained with the pitot tube was then converted to velocity using the "Dwyer Magnesense" sensor.



An Allen-Bradley 1700P Integrated Display Computer was used to capture the data the "Dwyer" pressure and velocity sensors read.

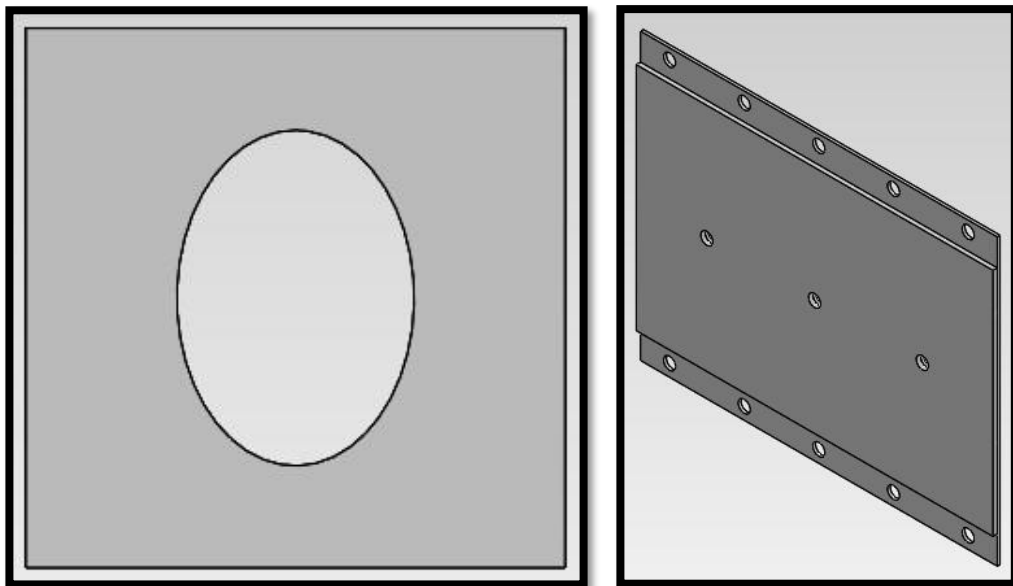
APPENDIX B- MANUFACTURING

Material

The material selected for the aspirator is 3CR12 Stainless Steel, as it provides corrosion resistance, strength, and ease of manufacturability. The inlet vanes sub-assembly consists of 1.5mm 3CR12 stainless steel, as the structural integrity of this sub-assembly is not essential. The entire aspirator body consists of 2mm 3CR12 to ensure the body is rigid and capable of withstanding wear. The flanges comprise 4mm 3CR12 stainless steel to ensure the coupling to other systems is rigid, which will also prevent air leakage.

Jigs

All grain aspirators should be dimensionally equivalent where the components fit together as designed; therefore, jigs were designed to help keep the body in place while welding to achieve the required tolerances. The figures below are examples of some of the manufacturing jigs used. The figure on the left shows the jig that ensured that any two pipes were precisely 45 degrees, and the figure on the right shows the jig that ensured that the inlet vane sub-assembly fit into the body of the aspirator.



Fabrication

Fabrication of the grain aspirator consisted of various stages ranging from profiling, boilermaking, welding, and finishing operations. According to the drawings, the sheet metal parts were laser-cut and bent during the profiling stage. During the boilermaking stage, the whole aspirator body was tack-welded together using a tungsten-inert-gas (TIG) welder. The whole aspirator body is designed with tabs and slots to ensure all parts are in the correct position, angle, and orientation before being welded into place. The welding stage occurred next, where laser welding was used for the long seams to prevent warpage on the sheet metal parts. Finally, the grain aspirator's welded assemblies underwent finishing operations consisting of deburring and glass bead blasting. Glass bead blasting was performed on the entire body of the aspirator to remove all the surface imperfections and give it an aesthetic appearance.



APPENDIX C- SYSTEM COMPONENT BREAKDOWN

The various components utilised during the development of the aspiration system will be described briefly below:

Auger feeder

An auger feeder was used to convey the grain/ seed mixture into the aspirator during the development of the prototype.



Tubular disk conveyor

A tubular disk cable conveyor was used to convey the grain/ seed mixture into the aspirator. The tubular disk conveyor has equally spaced plastic disks fastened onto a cable in the steel pipe that pushes the product forward. The tubular disk conveying system has a driving, tensioning, and disk cleaning section.



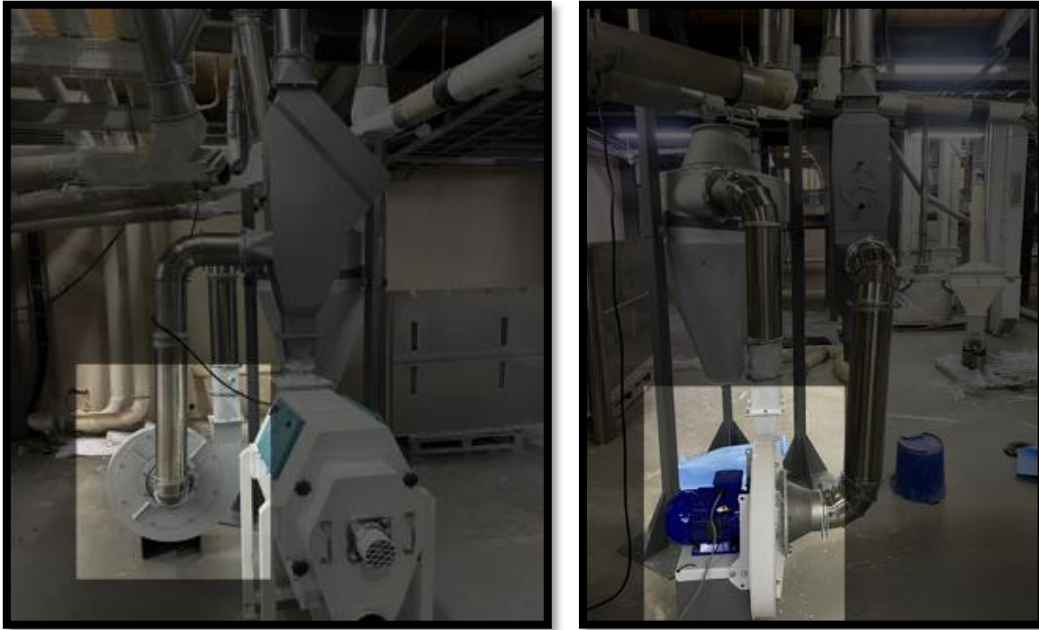
Cyclone

A cyclone separator was used in the aspiration system to separate the impurities and airflow from each other, enabling the system to be placed indoors.

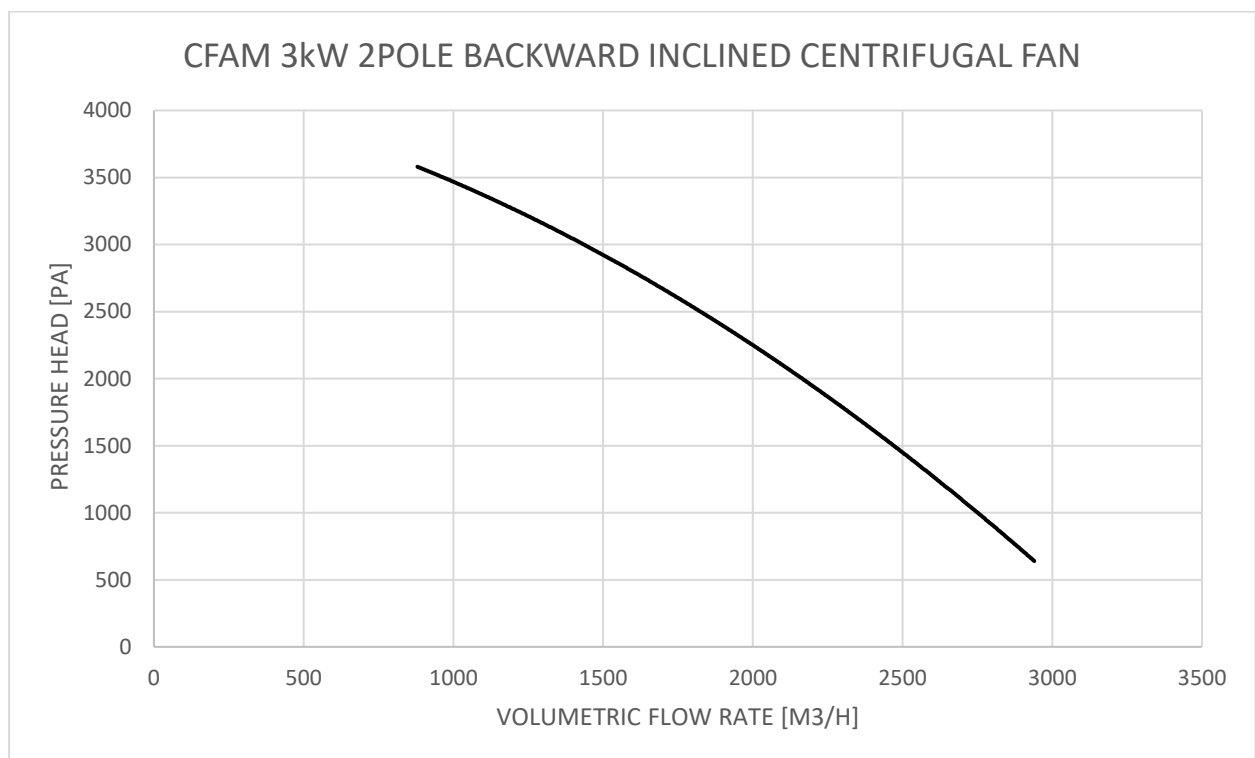


Centrifugal fan

A centrifugal fan was used in the aspiration system since the impurities might need to be conveyed upwards or a long distance while travelling through the cyclone. The operating point of the centrifugal fan was regulated via a butterfly valve on the fan outlet and a false air inlet on the aspirator; this way, the correct volumetric airflow through the system could be achieved.



The characteristic curve of the 3kW Centrifugal fan that was used for the system is shown below.



Rotary airlock

The configuration of the fan and cyclone determines whether a rotary airlock is required at the bottom exit of the cyclone. A rotary airlock is specifically needed while the fan draws air out of the cyclone but not when blowing air into it.

The rotary airlock allows the impurities to leave the cyclone without air escaping.



Turbo sifter

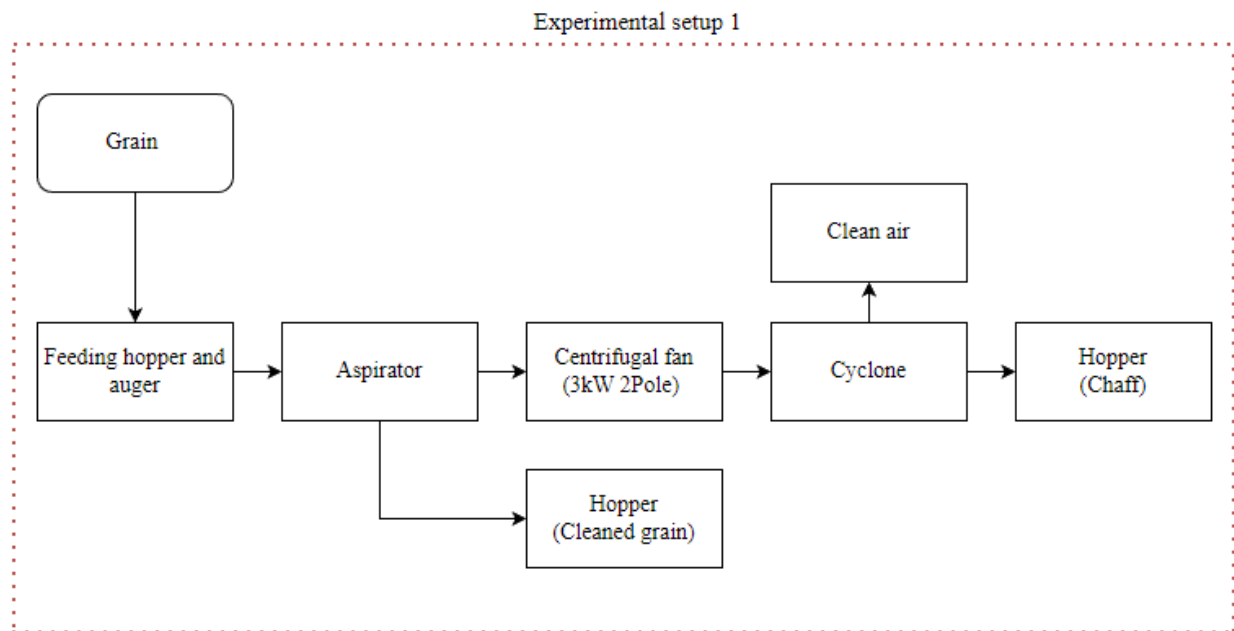
While testing the aspirator in the industry, a turbo sifter was connected to the cleaned outlet of the aspirator. The turbo sifter was used to help measure the efficiency of the cleaning process and determine the percentage of fines in the mixture.



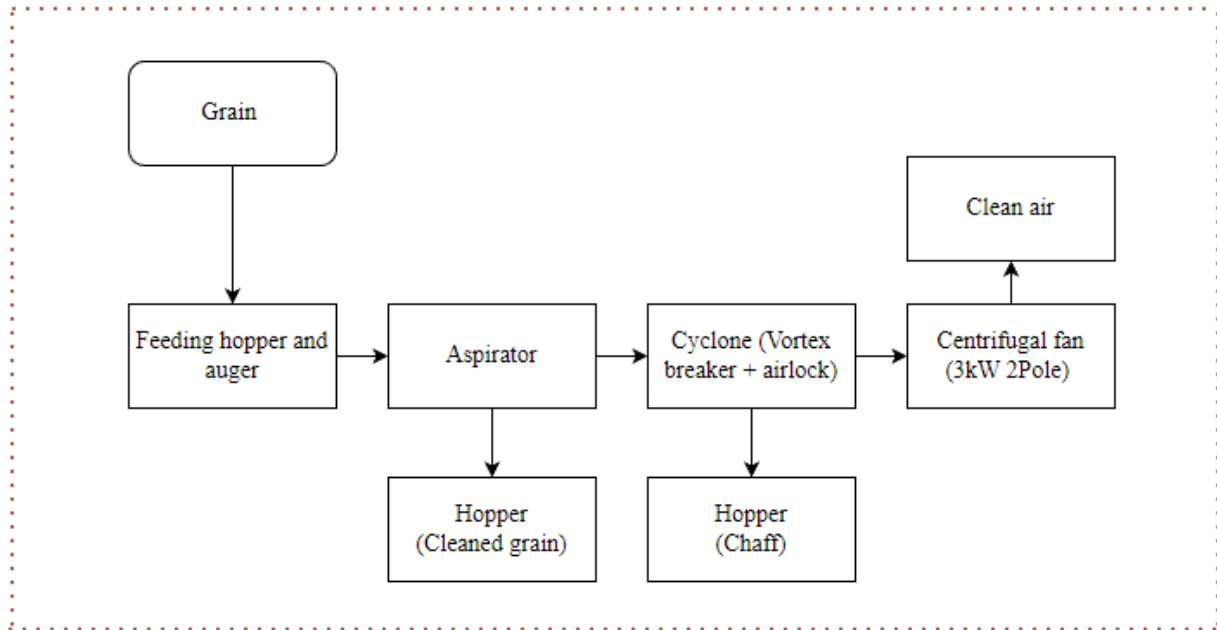
APPENDIX D- ARTICLE 1

Prototype testing

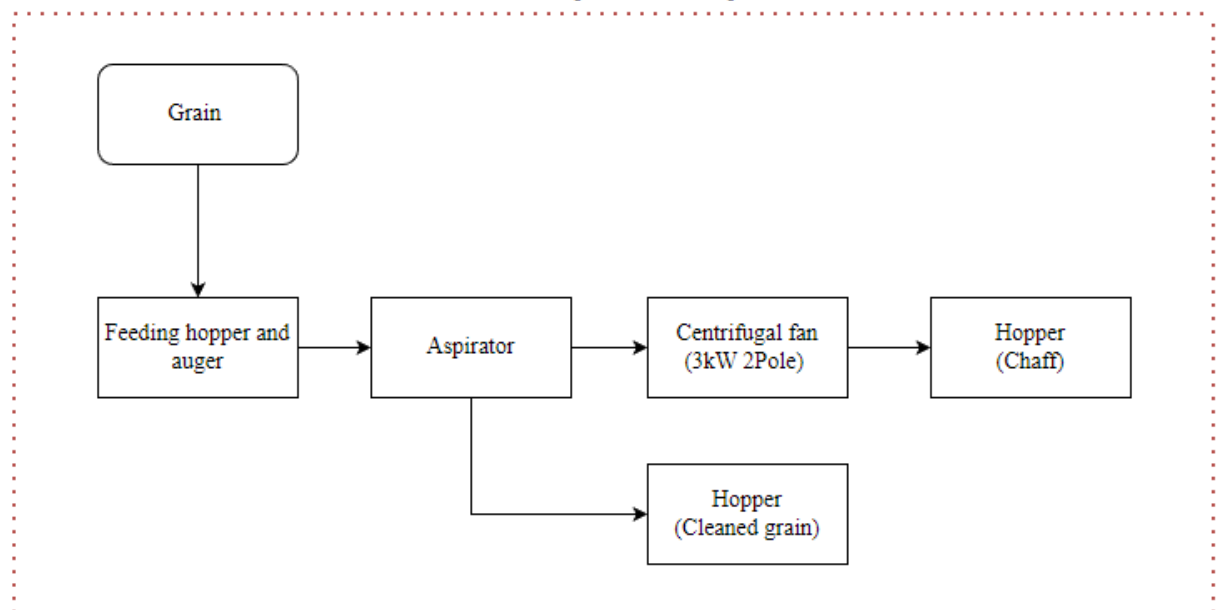
During the development of the grain aspirator, a prototype was first built to verify the concept and test the system in different configurations. The process flow diagrams of the various configurations evaluated can be seen below.



Experimental setup 2



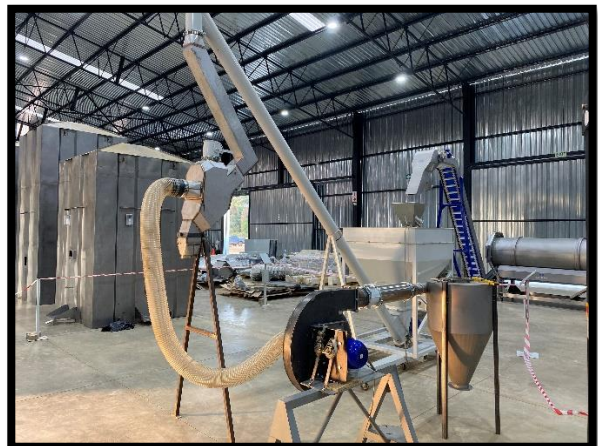
Experimental setup 3



The figures below show the prototype grain aspirator that was developed.



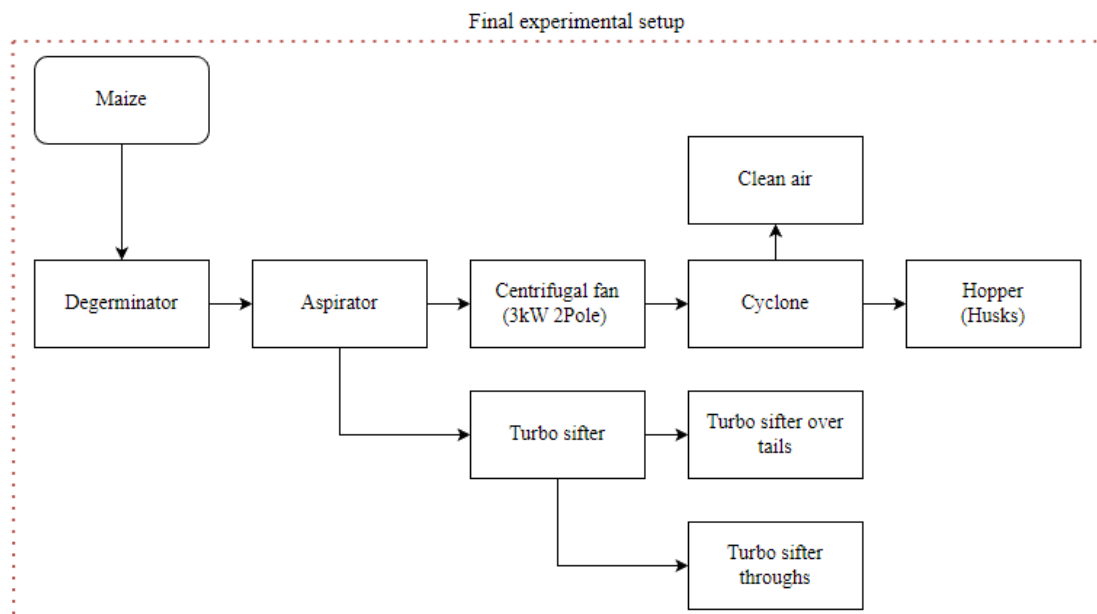
The figures below show the testing phases of the prototype grain aspirator, which was used to verify that the concept works as intended.





Industry testing

The process flow diagram below shows the system's configuration when it was tested in the milling industry.



The figures below show the setup used while testing the grain cleaning system at a milling plant.



Soybean testing

The figure below shows the experimental setup of the grain cleaning system used for soybean and hull separation, also known as a dehulling system in the oil seed extraction industry.



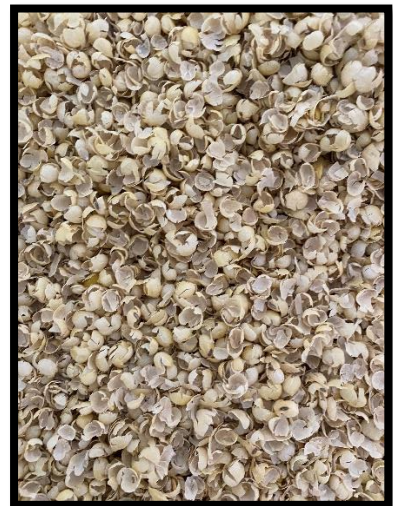
The figures below show the results of the grain cleaning system with soybeans.



Initial Soybeans Mixture



Cleaned Soybeans

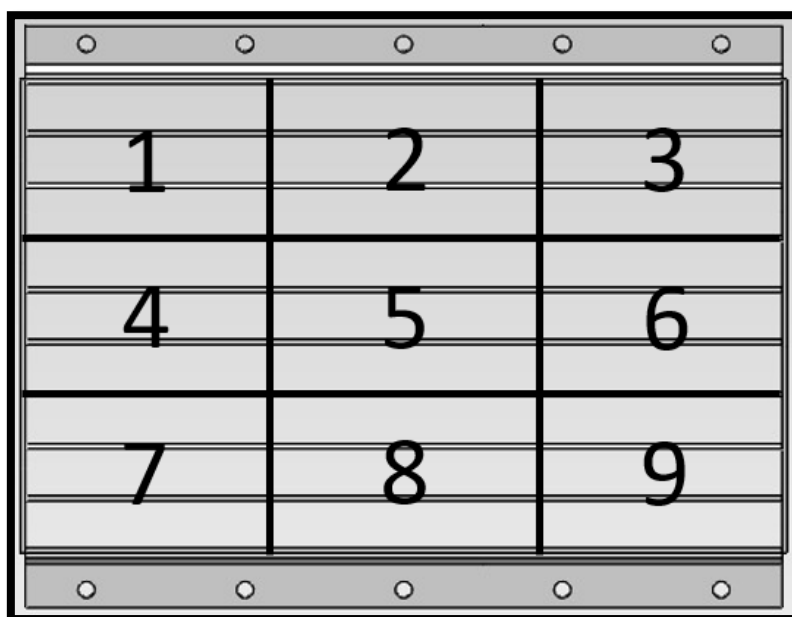


Aspirated Hulls

APPENDIX E- CFD VALIDATION

The CFD simulations run on ANSYS Fluent® were the basis of the coupled CFD-DEM simulations performed in ANSYS Rocky®. The CFD simulations had to be validated to ensure valid and reliable results for further simulations.

The CFD simulations were validated by comparing the airflow through the inlet vanes in nine different places with the experimental airflow, as seen in the figure below.



The tables below show the velocity at each section when the aspiration system was regulated at a volumetric airflow of 1000 [m³/h].

Simulation Velocity [m/s]		
1- [8.75]	2- [8.70]	3- [8.73]
4- [7.58]	5- [7.82]	6- [7.59]
7- [7.34]	8- [7.21]	9- [7.39]

Experimental Velocity [m/s]		
1- [8.71]	2- [8.70]	3- [8.73]
4- [7.28]	5- [7.41]	6- [7.32]
7- [7.10]	8- [6.89]	9- [7.15]

The tables below show the velocity at each section when the aspiration system was regulated at a volumetric airflow of 1500 [m³/h].

Simulation Velocity [m/s]		
1- [13.11]	2- [13.08]	3- [13.10]
4- [11.65]	5- [11.74]	6- [11.65]
7- [11.10]	8- [10.96]	9- [11.16]

Experimental Velocity [m/s]		
1- [13.06]	2- [13.06]	3- [13.10]
4- [11.29]	5- [11.42]	6- [11.31]
7- [11.11]	8- [10.77]	9- [11.12]

The simulated and experimental airflow data shows similar results when compared to each other, with the following similarities:

- Overall velocity readings are similar.
- The velocity decreases from the top to the bottom row.
- The velocity reading in the bottom row centre column (block 8) is the lowest.

The experimental velocity readings are a fraction lower than the simulated values. This phenomenon is due to a small leakage on the fan's volute casing and the piping system between the fan, cyclone, and aspirator.

APPENDIX F- ROCKY DEM CALIBRATION

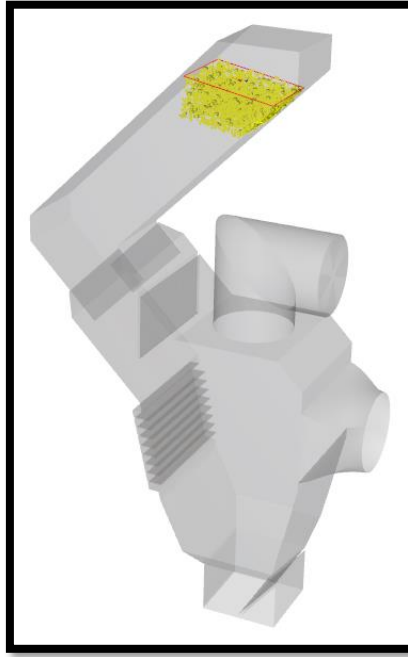
Various material properties should be known when performing a DEM simulation; some of them are:

- Poisson's ratio
- Youngs Modulus
- Bulk density
- Restitution coefficient
- Static friction coefficient
- Dynamic friction coefficient
- Rolling resistance coefficient
- Adhesive force fraction

It is important to note that the maize and husk particles have different properties. The material properties of the maize and husk particles have been found in literature, as shown in Chapter 4; however, each mixture is different. Various factors influence the properties of the mixture, like varieties, moisture, stage of growth, etc. Thus, the DEM simulation was first calibrated before a coupled CFD-DEM simulation was performed.

The particle spread through the aspirator during the experiments was used as a reference to calibrate the mixture's properties in the DEM simulation.

The figure below shows the inlet position of the mixture, which matches how the mixture enters the aspirator in the experimental setup with the auger and tubular disk cable conveyor.



The figure below shows the experimental particle spread, which is used as a reference for the DEM mixture's calibration process.



The figure below shows the simulated particle spread in Rocky[®] DEM, and after calibrating the property values obtained from the literature, the simulation closely matches the experimental observations.

