Proceedings of the 9th World Congress on Mechanical, Chemical, and Material Engineering (MCM'23)
Brunel University, London, United Kingdom - August 06-08, 2023
Paper No. ICMIE 141
DOI: 10.11159/icmie23.141

Design and Testing of a Pneumatic Grain Aspirator for Efficient Separation of Impurities

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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

1. Introduction
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.

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

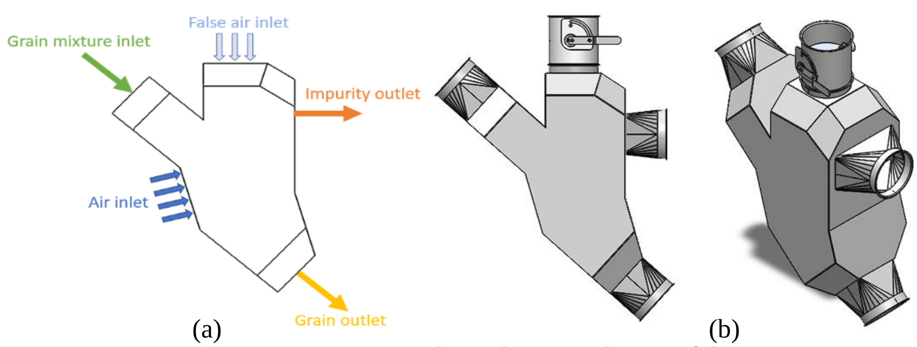
Parameter	Description
System design	Compact, energy-efficient, inline design
Throughput rate	7 tonnes/hour with various grain types
Material	Stainless steel (3CR12) is used to comply with the food industry standards
System regulation	A butterfly valve is implemented on the fan outlet to adjust the operating 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

2. Design and development

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

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.



(a) (b)
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.

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.

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.

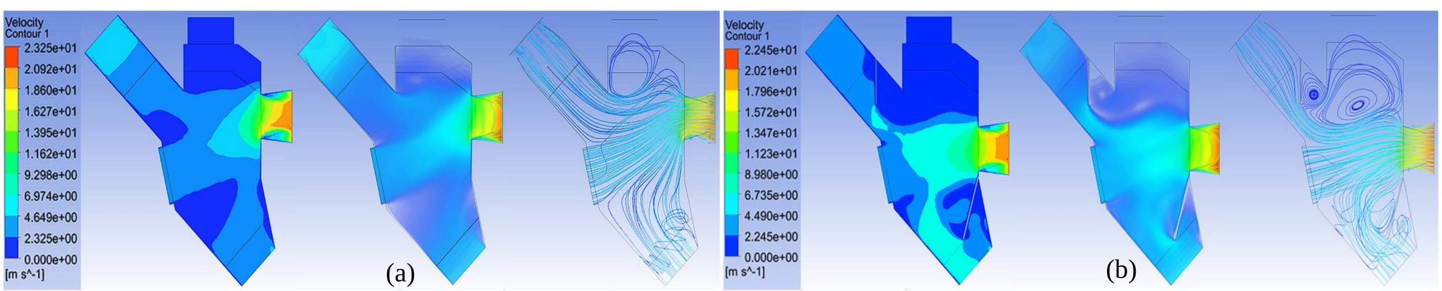


Figure 2: Ansys Fluent simulations on the preliminary design (a) Iteration 1; (b) Iteration 2

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.

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.

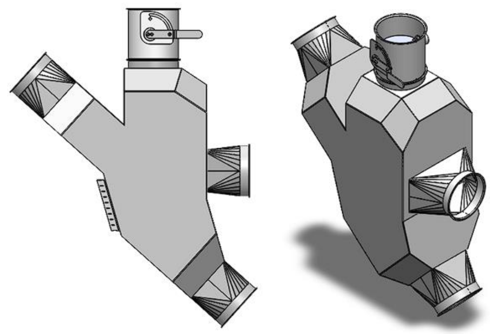


Figure 3: Improved preliminary design

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.

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 [m^3/h] and a minimum pressure of 640 [Pa] at a maximum volume flow rate of 2940 [m^3/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 [m^3/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 [m^3/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.

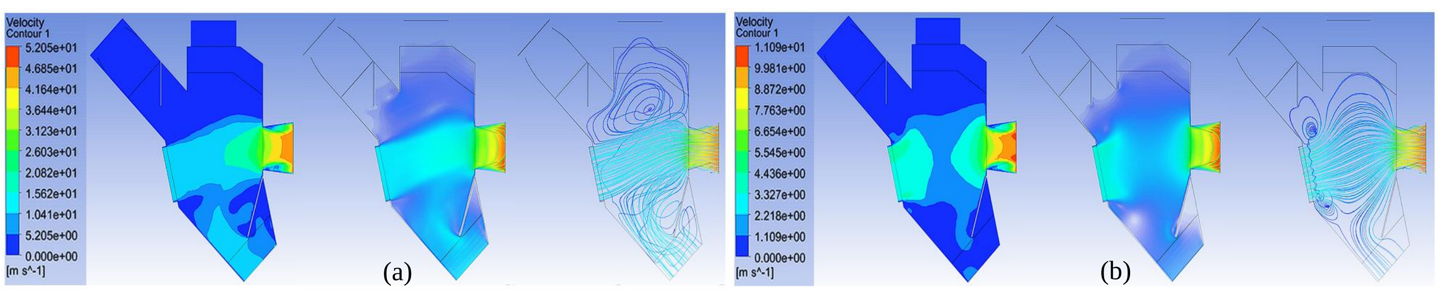


Figure 4: (a) Maximum airflow, (b) minimum airflow

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.

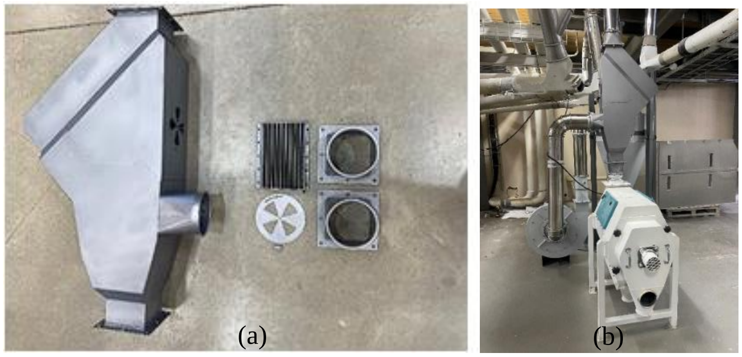


Figure 5: (a) Manufactured final design; (b) Final design experimental setup

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.

<u>Prototype experimental setup</u>

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.

<u>Final design experimental setup</u>

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. Results and discussion

3.1 Prototype

The prototype test results can be seen below, where Figure 6(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.

3.2 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.

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

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

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.

5. Acknowledgements

The authors are thankful for CFAM Technologies, which provided assistance regarding manufacturing, testing facilities, and funding for this work. Thank you, Prof LJ Grobler, Dr OC Koekemoer, and Mr D Vorster, for the various assistance rendered during the research. Thank you, Jan van der Walt, for your help with the experimental tests.

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