

Full Length Article

Optimized design and fabrication of a wind-sifter separator for enhanced dry beneficiation of high-ash coal

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ABSTRACT

The high mineral content in coal exacerbates environmental pollution, therefore, reducing the ash content is essential. This study reports the effectiveness of an optimized wind-sifting separator in upgrading high ash coal based on size and density through computer simulations employing the Lagrangian particle tracking method. This new separator was designed using Autodesk-Inventor and assessed with and without particle collecting bins via simulation using STAR-CCM+TM software. Three particle sizes ($-6.7 + 3.35$ mm, $-3.35 + 1$ mm, $-1 + 0.2$ mm) were tested experimentally at different airstream velocities to ascertain optimal velocities (cut point of 1.6 g/cm³) for each size fraction. The investigation into the impact of particle shape on separation efficiency revealed that shape affects the separation of larger particles significantly, with this effect diminishing as particle size decreases. The laboratory-scale separator effectively reduced the ash content in the feed coal from 37.38 % to 24.11 %. The findings imply that the optimized separator holds promise for upgrading the quality of coal and various minerals within the mineral processing sector, thereby contributing to a cleaner and more sustainable energy future.

1. Introduction

Energy resources play a vital role in fostering social, economic, and industrial development, with coal serving as a cornerstone, particularly for nations rich in this resource. Coal is instrumental in power generation and finds extensive use in metallurgical applications [1–3]. Coal remains indispensable for over 80 countries, catering to electricity and heat production (Future [4]). It fuels process energy and underpins essential industries such as steel manufacturing (70 %), cement production (90 %), and aluminium production (61 %). The International Energy Agency (IEA)[5] reported that coal contributed a staggering 36 % of the world's total electricity generation in 2022 and trajectory suggests it will continue to dominate the electricity landscape globally by 2040. Despite being the most abundant energy source globally and relatively cost-effective, the scarcity of high-grade coal necessitates the utilization of low-grade variants to meet modern civilization's energy demands [6].

Coal is the primary energy source in the Southern African region, playing a pivotal role in driving economic advancement. In South Africa, coal serves nearly all electricity generation demands, constituting 70 % of installed power generation capacity [7]. Minister Mantashe's report

in 2022 [8]underscores the significance of the coal sector, indicating it as the highest revenue generator among all mined minerals, contributing approximately 21.4 % to the total mining revenue. Additionally, this sector is the third largest employer in the mining industry, providing jobs for 20.48 % of the industry's workforce. From a long-term availability perspective, South Africa boasts abundant coal reserves, estimated to last over a century at current rates of usage and production [9,10]. However, high-quality coal is needed to ensure its suitability for critical sectors such as power generation and metallurgical industries. The decline in South Africa's coal quality has spurred research into effective beneficiation techniques for producing clean coal meeting diverse customer specifications [11–13]. Jeffrey et al. [14] noted that high-grade coal with ash content below 15 % is mainly exported, whereas lower-grade coal is used domestically. This differentiation is achieved through either wet or dry coal beneficiation processes, wherein coal's inorganic minerals are separated from organic components, ensuring optimal coal quality for various applications.

Wet beneficiation processes have garnered significant attention in the mineral processing industry due to their ability to yield high-quality products with excellent recovery rates [15–17]. Techniques such as dense medium cyclone, spirals, froth flotation, and wet jig have been widely employed to achieve high-quality coal products [18–20].

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Nomenclature*Mathematical abbreviation and vocabulary (with units)*

F_{ap}	The total force of interaction between the fluid and the particles per unit volume of air ($N, \text{orkgm/s}^2$)
p	Particle
P	Air pressure ($Pa, \text{or } N/m^2$)
j	Sample
φ	Sphericity factor of the particle (—)
ρ	Fluid density (kg/m^3)
ρ_j	Mass density of the particle of the number of equivalent-volume-diameter in sample “j” present in the airstream (kg/m^3)
$f_{ap,j}$	The force of interaction for individual particles ($N, \text{orkgm/s}^2$)
d_v	Diameter of the volume equivalent sphere of the particles (mm)
d_s	Diameter of the particles (mm)
S_w	Powder-specific surface area determined using gas adsorption (m^2/g)
∇	Standard derivative for multidimensional domain
α_{sv}	Shape factor (—)

u	Fluid velocity (m/s)
e	Specific energy of the fluid ($Nm/kg \text{orm}^2/s^2$)
t	Time (s)
g	Acceleration due to gravity (m/s^2)
μ	Dynamic viscosity ($Pa.s, \text{or } N.s/m^2$)
d_{vj}	The equivalent volume diameter of particles in sample j (mm)
a	The fluid (air)
V	Volume of particle (mm^3)
F_B	Buoyant force ($N, \text{orkgm/s}^2$)
F_W	Weight ($N, \text{orkgm/s}^2$)
F_D	Drag force ($N, \text{orkgm/s}^2$)
m	Mass of particle (g)
A	Cross-sectional area (mm^2)
d_L	Diameter of the lighter particle (mm)
d_H	Diameter of the heavier particle (mm)
ρ_L	Density of the lighter particle (kg/m^3)
ρ_H	Density of the heavier particle (kg/m^3)
C_D	Coefficient of drag (—)
Σ	Summation

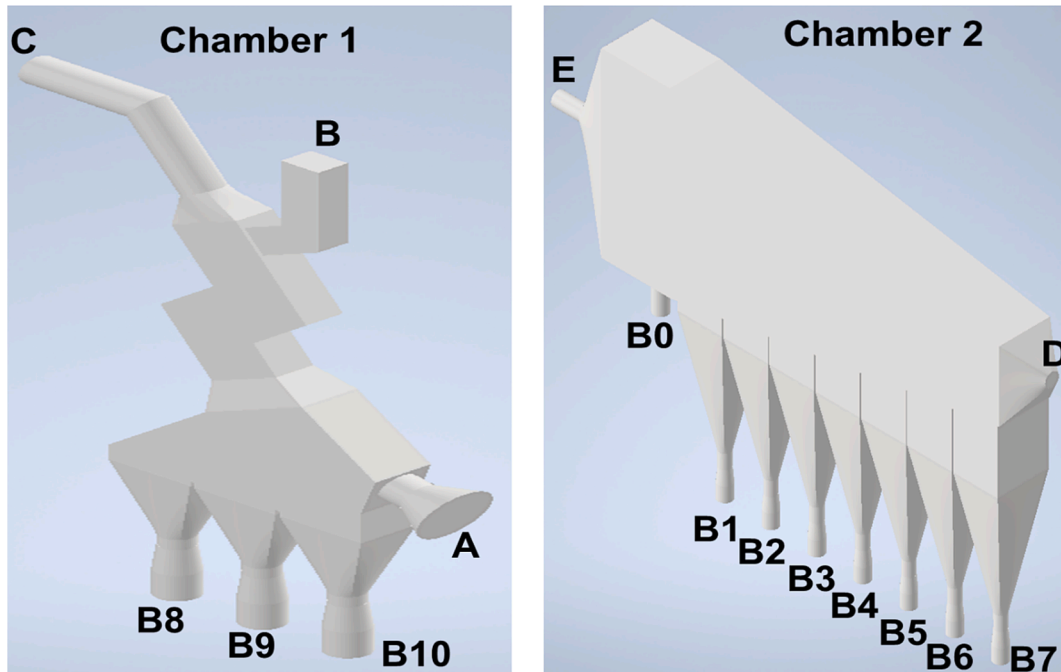


Fig. 1. Flow boundaries of the first and second chambers (chambers 1 and 2) with their collection bins.

However, water scarcity, effluent management, and substantial capital investment are significant hurdles for these wet beneficiation methods. As a result, dry beneficiation is emerging as the preferred alternative, driving ongoing research efforts to enhance its efficiency, especially in upgrading smaller coal particles [21,22]. Dry beneficiation techniques exploit differences in the physical properties of coal and its inherent mineral matter, encompassing factors such as shape, density, size, magnetic susceptibility, lustrous nature, and electrical conductivity to facilitate separation [23–26]. Diverse dry beneficiation methods have been explored, including air tables, pneumatic separation, air-dense

medium fluidized bed, tribo-electrostatic separators, and air jigging, [27–30]. An exhaustive review was conducted by Zhao et al. [31] on different dry beneficiation methods and the size fractions of coal that were effectively beneficiated by Zhao et al. [31]. Some innovative approaches have also been explored like the planar air jet principle among others [32–35]. These dry diverse beneficiation techniques offer promising avenues for efficiently upgrading coal without the logistical challenges associated with wet beneficiation processes.

The application of the air jet principle for coal beneficiation was carried out by Yang et al. [32]. In this study, a planar air jet separator

Table 1

The assigned particle diameters for each particle size fraction per density fraction.

Relative Density	(−6.7 + 3.35) mm	(−3.35 + 1.0) mm	(−1.0 + 0.2) mm
1.3	3.35	1.00	0.20
1.4	3.80	1.40	0.35
1.5	4.60	1.80	0.40
1.6	5.40	2.30	0.55
1.7	6.10	2.70	0.70
1.8	6.35	2.90	0.85
1.9	6.70	3.35	1.00

was built to upgrade (−6 + 2 mm) size fraction coal. This technique capitalizes on the difference in coal particle densities as they traverse the planar air jet flow field horizontally. The study produced promising

results, showing a clean coal yield of 56.75 % with an ash content of 16.61 %, starting from feed coal with 26.92 % ash content. In another study, Dong et al. [36] introduced an innovative approach to beneficiate coal by integrating two separators. This involves the use of an air-dense medium fluidized bed (ADMFB) and a Fuhe-Ganfa-Xuanmei (FGX) dry separator connected in series to beneficiate coal particles of varying sizes (−100 + 50 mm) and (−50 mm). ADMFB produced coal with an ash content of 7.86 % and a yield of 90.96 % at an optimal separation efficiency of 0.11 m/s. The FGX separator demonstrated separation performance at a vibration frequency of 18 Hz and amplitude of 2.2 mm, producing a clean coal product of 13.28 % ash content and a yield of 90.30 %.

Wind-sifting separation techniques have been utilized in a range of applications and for recycling various materials. A recent review by Alade and Bada [37] examined various applications, types,

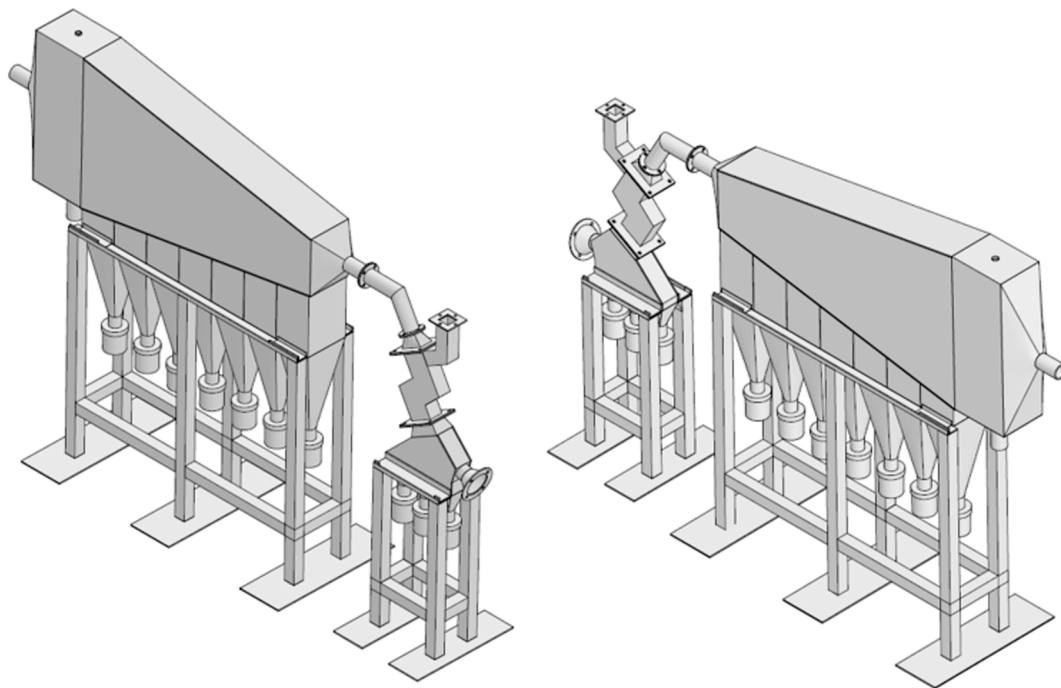


Fig. 2. The optimized wind-sifter separator assembly design (without auxiliaries).

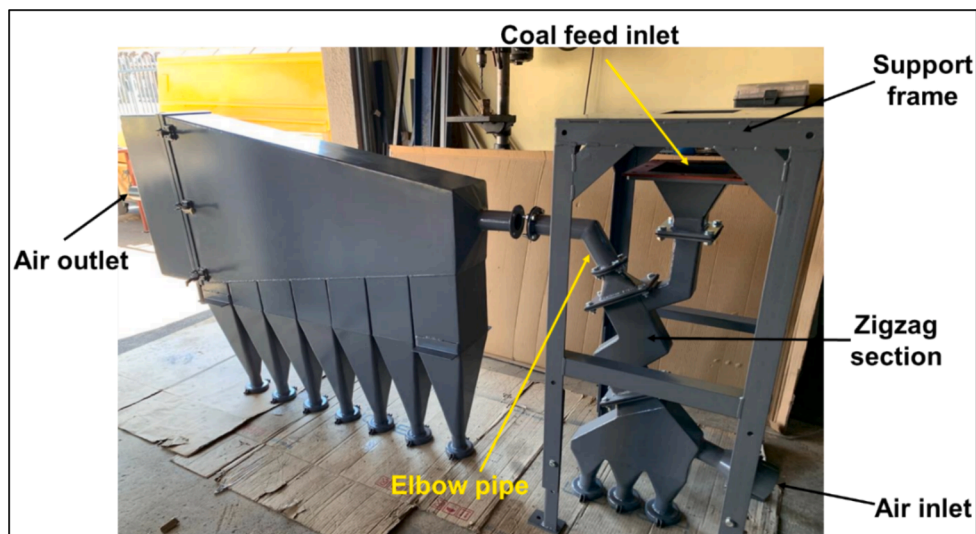


Fig. 3. The fabricated optimized wind sifter separator.

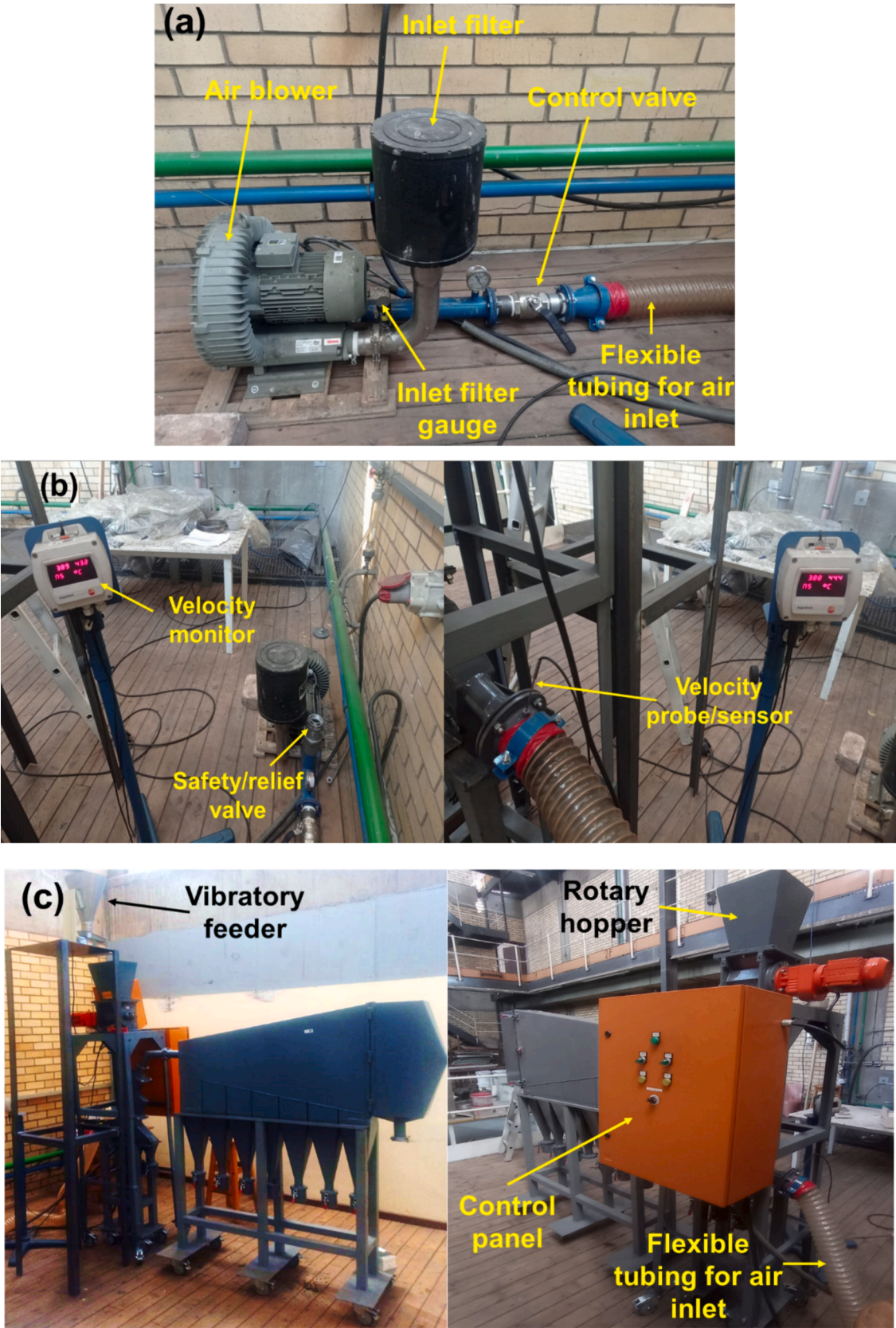


Fig. 4. a, b & c: images showing auxiliaries of the installed separator assembly set-up on its cradles.

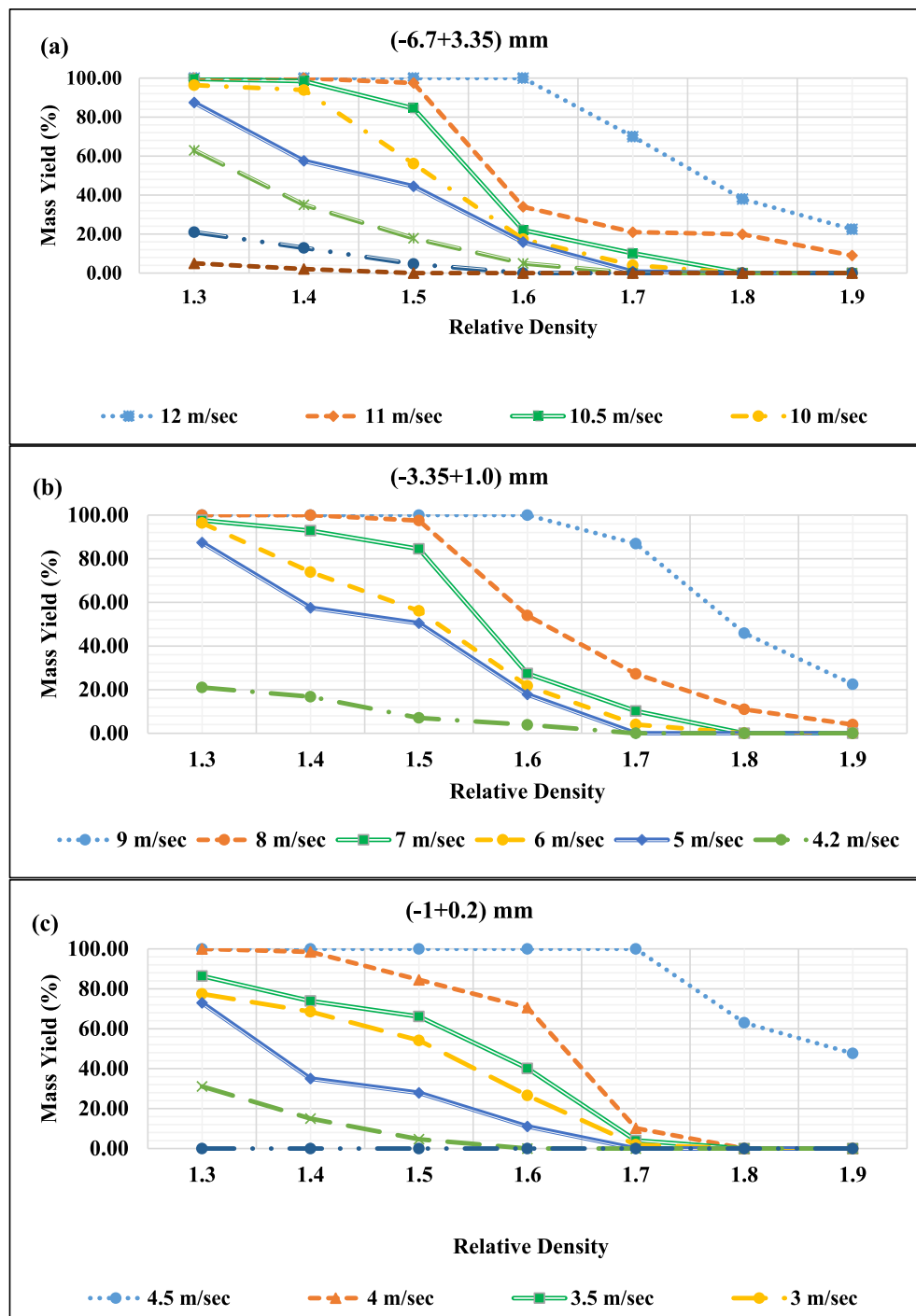


Fig. 5. a, b & c: optimal velocity determination for all three size fractions (without bin).

configurations, and the fundamental working mechanism of this technique. Some of these areas of applications of this technique include electronic waste (e-waste), municipal solid wastes, food, furniture, pharmaceuticals, minerals, chemicals, and metallurgical, and, recently, in the field of coal processing [38–44]. The principle of wind-sifting was also applied in recent studies by Alade [45] and Alade et al. [44] to beneficiate high ash coal of -6.7 mm. The top size of 6.7 mm was used owing to the ample proportion generated in millions of tons due to mechanized mining in South Africa [45]. The author fabricated a laboratory-scale wind-sifter separator marking the first applied prototype in dry coal beneficiation. The separator effectively upgraded feed coal with an ash content of 30.28% and a calorific value of 21 MJ/kg

into clean coal, reducing the ash content to 16.75% and increasing the calorific value to 27.00 MJ/kg. However, some drawbacks were observed in this prototype, leading the authors to redesign and optimize the separator. One of these drawbacks is the particles' stickiness to the separator's walls, which led to poor separation performance on the finest particle size fraction. In this paper, an optimized version of the old separator was presented, and the model applied accounts for the variations in the morphology of coal particles. These variations are characterized by factors such as the sphericity factor and shape factor, as exemplified in Section 2.1. The simulation results were presented considering the separator's response to different set parameters. This paper also presents a preliminary experimental laboratory investigation

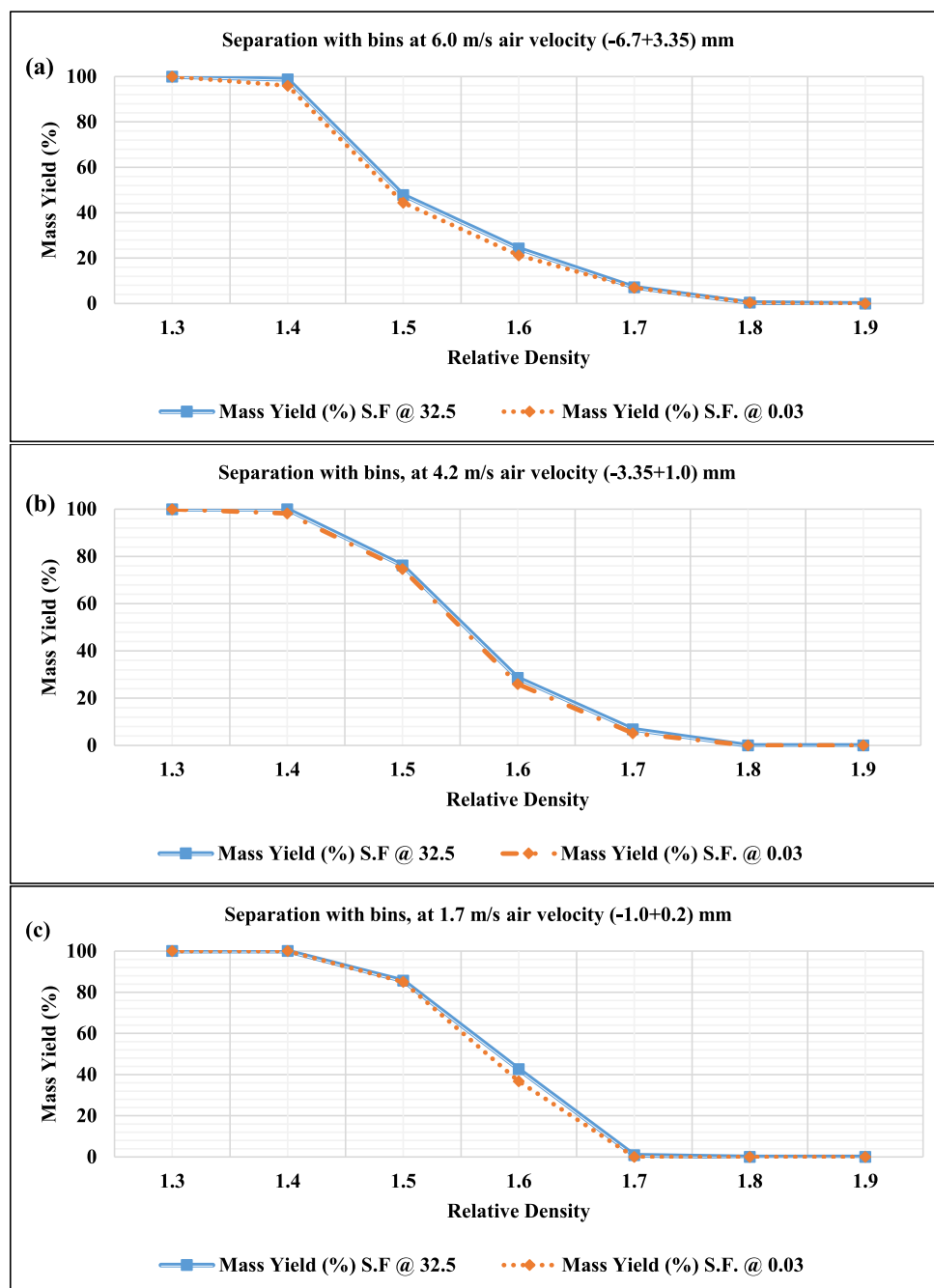


Fig. 6. a, b & c: particle recoveries of the three particle size fractions for both particle shape factors (with bins).

of the separator's performance, and further experimental studies are currently underway to ascertain its overall efficiency.

2. Materials and methods

2.1. Geometry design

For this study, the simulation test runs were conducted utilizing the Lagrangian particle tracking method. However, the fluid body of the wind-sifter separator was initially generated using Autodesk Inventor and subsequently exported into STAR-CCM+. Several factors were meticulously considered during the design phase of the separator, including the air-jet angle, velocity of the air stream, particle density and size, buoyancy, drag force, gravity, and friction on the wall of the separator. The minimum mass flow rate of 36 g/min applied in the old

design [45] was also used to simulate the feed rate of particles into the new separator. This feed rate minimizes particle-to-particle and particle-to-wall interactions within the flowing airstream, leading to a diluent phase. The gas phase (airstream) was treated as a steady-state continuous phase and the force resolution was done for a single moment in time at a single point in space. This means that any spatial variations are considered irrelevant and as such, the fluid density does not vary. Equations 1 – 3 serve as the guiding model(s) for describing the forces experienced by the particles at any location within the separator. The fundamental equation that forms the basis of our modelling approach is derived from the Euler equation.

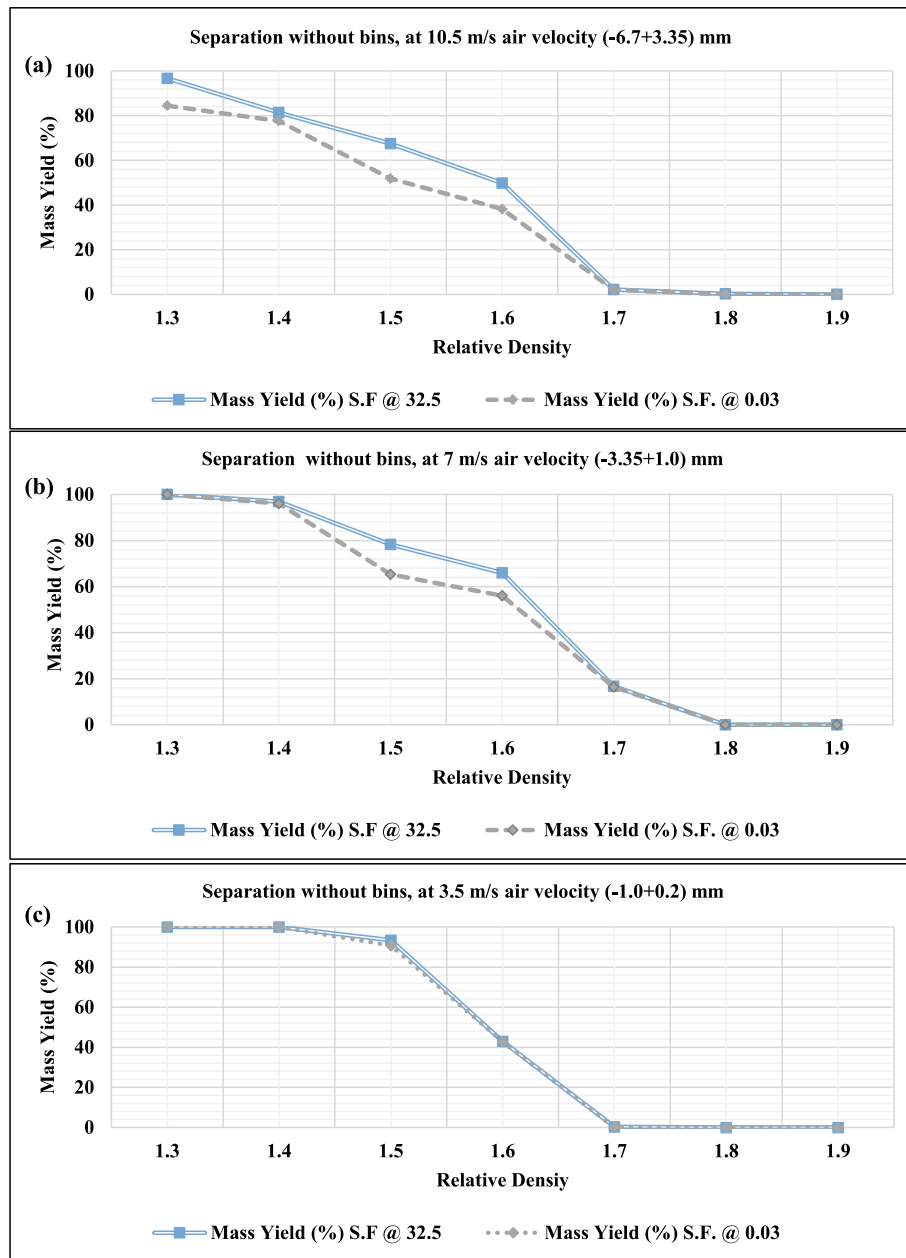


Fig. 7. a, b & c: particle recoveries of the three particle size fractions for both particle shape factors (without bins).

$$\begin{cases} \left(\frac{d\rho}{dt} = -\rho \nabla \cdot u \right) (\text{Equation 1}) \\ \left(\frac{du}{dt} = -\nabla \left(\frac{P}{\rho} \right) + \mu \nabla^2 u + g \right) (\text{Equation 2}) \\ \left(\frac{de}{dt} = -\left(\frac{P}{\rho} \right) \nabla \cdot u \right) (\text{Equation 3}) \end{cases} \quad (1-3)$$

When written in their derived material form, Equations 1 – 3 show the conservation of mass, impulse, and energy, respectively. Given that the flow is assumed to be steady-state, the velocity remains constant, and $\nabla u = 0$. Consequently, terms such as $\frac{d\rho}{dt}$ and $\frac{de}{dt}$ become zero. Furthermore, the air temperature is assumed to be 20 °C, leading to the dynamic viscosity (μ) of air 1.6×10^{-5} Pa.s infinitesimal and considered negligible (tending to zero). Hence, Equations 1 – 3 can be reformulated as follows to Equations 4 – 5.

$$\begin{cases} \left(\frac{d\rho}{dt} = -\rho \nabla \cdot u = 0 \right) (\text{Equation 4}) \\ \left(\frac{du}{dt} = -\nabla \left(\frac{P}{\rho} \right) + g \right) (\text{Equation 5}) \\ \left(\frac{de}{dt} = -\frac{P}{\rho} \nabla \cdot u = 0 \right) (\text{Equation 6}) \end{cases} \quad (4-6)$$

This means that $\frac{d\rho}{dt}$ and $\frac{de}{dt}$ become zero, leaving the “ $\frac{du}{dt}$ ” component. Therefore, the above equation becomes $\left(\frac{du}{dt} = -\nabla \left(\frac{P}{\rho} \right) + g \right)$. Multiplying all through with ρ yield Equation (7).

$$\left(\rho \frac{du}{dt} = -\nabla P + \rho g \right) \quad (7)$$

When further elaborated, Equation (7) can be expressed as Equation (8).

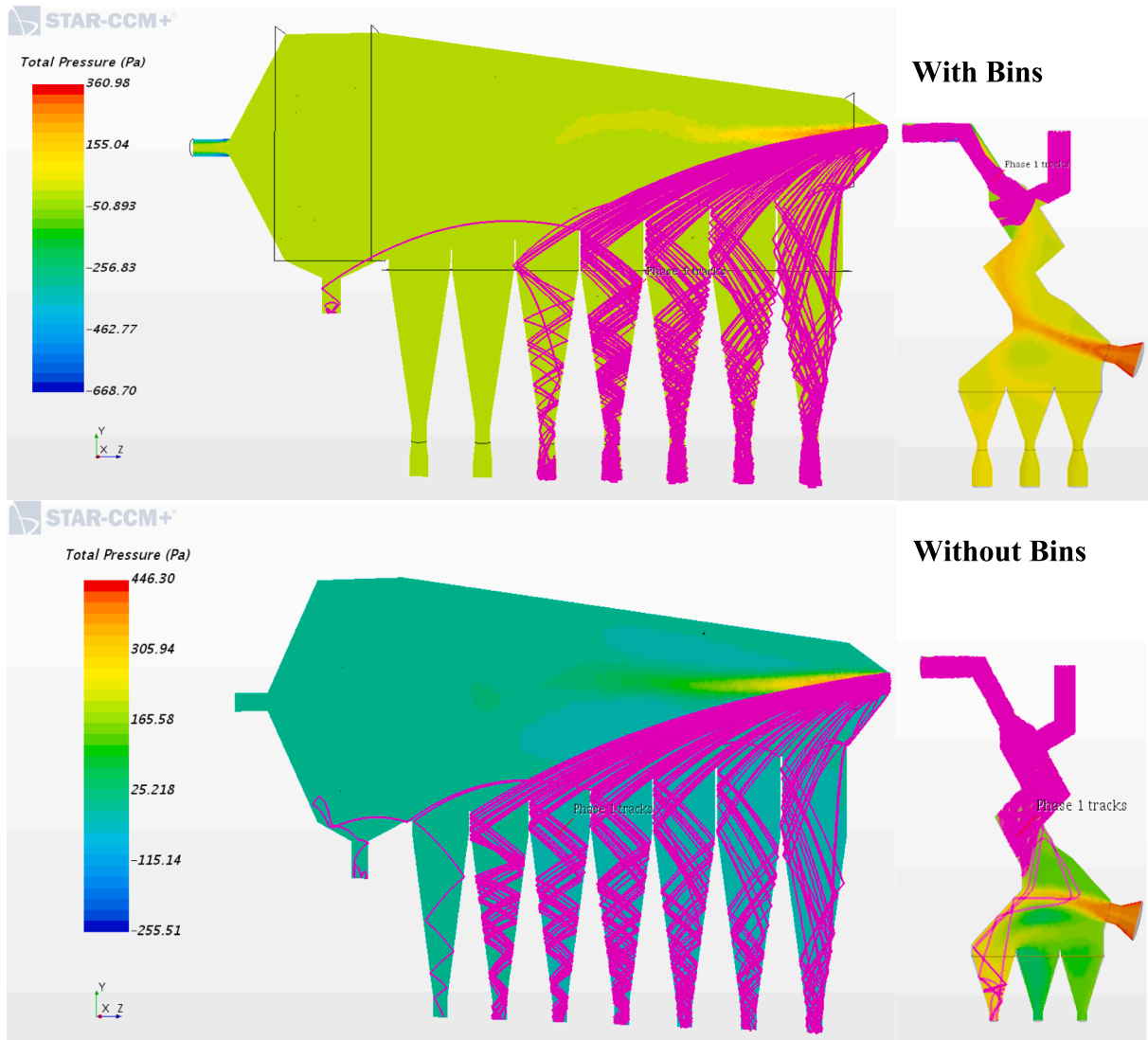


Fig. 8. Particle tracks for the $(-6.7 + 3.35)$ mm size fraction at 1.3 relative density in both chambers at 6.0 m/s (with bins) and 10.5 m/s (without bins).

$$\left(\frac{\partial(\rho u)}{\partial t} \right) + \nabla(\rho u u) = -\nabla P + \rho g - F_{ap} \quad (8)$$

where ρ represents the fluid density, u denotes the fluid velocity, e is the specific energy of the fluid, P is the air pressure, t is time, g is the acceleration due to gravity and F_{ap} is the total force of interaction between the fluid and the particles per unit volume of fluid (air).

The expression of F_{ap} is given in Equation (9):

$$F_{ap} = \sum_{j=1}^n \frac{f_{ap,j}}{V} \quad (9)$$

where a represents the fluid (air), p,j represents the particle “ j ”, n is the number of particles considered, V is the volume of particle “ j ” and $f_{ap,j}$ is the force of interaction for individual particles, which is shown in Equation (10).

$$f_{ap,j} = F_B - F_w - F_D \quad (10)$$

According to Equations (11) and (12), F_B is represented as the buoyant force, ρ is the density of the fluid (air), V is the displaced body volume of the fluid (this is also the volume of the particle since it is fully immersed in the air), and g is the acceleration due to gravity.

$$F_B \geq F_w + F_D \quad (11)$$

$$F_B = \rho V g \quad (12)$$

$$F_w = m \times g \quad (13)$$

F_w in Equation (13) represents the weight of the particle, m is the mass of the particle, and g is the acceleration due to gravity.

$$F_D = \left(\frac{C_D \times A \times \rho \times u^2}{2} \right) \quad (14)$$

F_D in Equation (14) is the drag force on the particle. C_D denotes the drag coefficient of the particle, A is the cross-sectional area, ρ is the density of the fluid (air), and u is the flow velocity relative to the air. When $F_B > F_w + F_D$, the particles are being transported in the airstream, and when $F_B = F_w + F_D$, implies that $f_{ap,j}$ is zero, the particle velocity in the airstream terminates, and the particles fall at constant velocity. Notably, it is crucial to consider the particle settling ratio when addressing dry particle separation, particularly when utilizing air as the separating medium. This ratio represented in equation (15) (adapted from [46]), defines the limiting ratio of diameters of particles that may be separated by free settling.

$$\text{Free settling ratio} = \frac{d_L}{d_H} = \frac{\rho_h - \rho}{\rho_l - \rho} \quad (15)$$

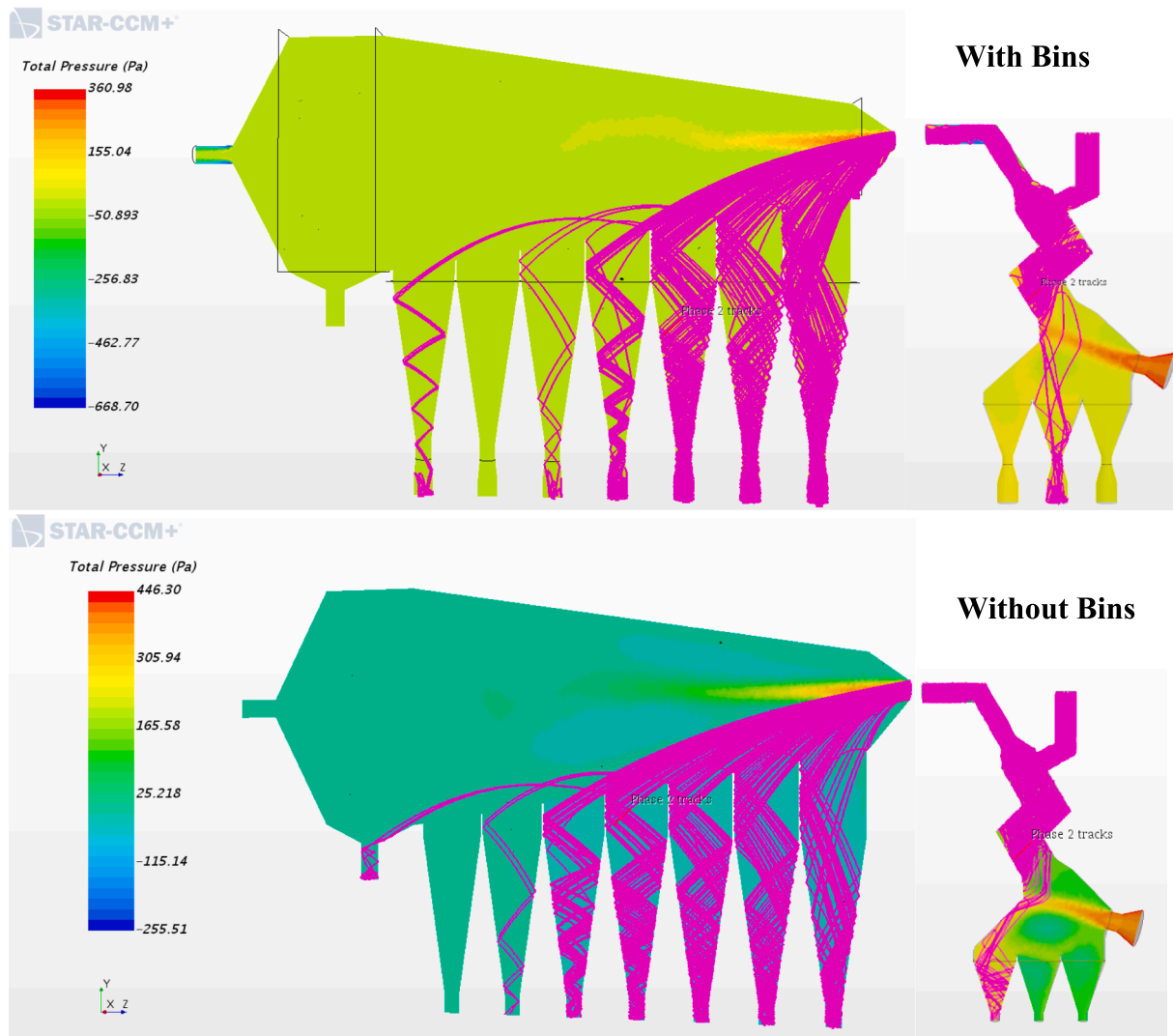


Fig. 9. Particle tracks for the $(-6.7 + 3.35)$ mm size fraction at 1.4 relative density in both chambers at 6.0 m/s (with bins) and 10.5 m/s (without bins).

where, d_L = diameter of the lighter particles; d_H = diameter of the heavier particles; ρ_L = density of the lighter particles; ρ_H = density of the heavier particles; ρ = density of the separating medium (air).

These equations were applied to design and fabricate the initial prototype wind-sifter separator assembly [44,45] and are also utilized to design the new/optimized separator but with slight modifications in some components. The irregularities in coal's shape and how it influences shape factor were examined in this new design, unlike the previous design where particles were assumed to be perfectly spherical. Thus, the influence of particle shape was investigated in this study, and the results are shown in Sections 3.1 and 3.2. Equations (16)–(18) were applied to adjust the coefficient of drag and drag force to reflect the effects of particle shape variations. Equations (16) – (18) are formulas for obtaining sphericity factor, shape factor, and powder-specific surface area, respectively.

$$\varphi = \frac{\text{Surface area of volume equivalent sphere of the particle}}{\text{Surface area of the particles}} = \frac{\pi \times d_v^2}{\pi \times d_s^2} = \frac{d_v^2}{d_s^2} \quad (16)$$

where φ is the sphericity factor of the particle; d_v and d_s are the diameters of the volume equivalent sphere of the particle(s) and the diameter of the particle(s) respectively and is expressed in Equation (17) as:

$$\varphi = \frac{\pi \times d_v^2}{\alpha_{sv} \times d_s^2} = \frac{\pi}{\alpha_{sv}} \quad (17)$$

where α_{sv} is the shape factor adapted from Barreiros et al. [47] and is expressed in Equation (18) as:

$$\alpha_{sv} = S_w \times \rho_j \times \frac{\pi}{6} \times \frac{\sum n_i \times d_{vj}^3}{\sum n_i \times d_{vj}^2} \quad (18)$$

where S_w (m^2/g) is the powder-specific surface area determined using gas adsorption; ρ_j is the mass density of the particle of the number of equivalent volume diameter in the sample j ; d_{vj} is the equivalent volume diameter of particles in sample j ; n is the number of particles; i is the size class (particle size distribution).

Equation (19) (adapted from Hölzer and Sommerfeld, [48], represents the coefficient of drag (C_D) which incorporates considerations of shape variation.

$$C_D = \frac{8}{Re} + \frac{1}{\sqrt{\varphi}} + \frac{16}{Re \times \sqrt{\varphi}} + \frac{4 \times \varphi}{\sqrt{Re}} + 0.4210^{0.4(-\log \varphi)} \quad (19)$$

The optimal separator design as per the derived mathematical model was achieved through the following steps:

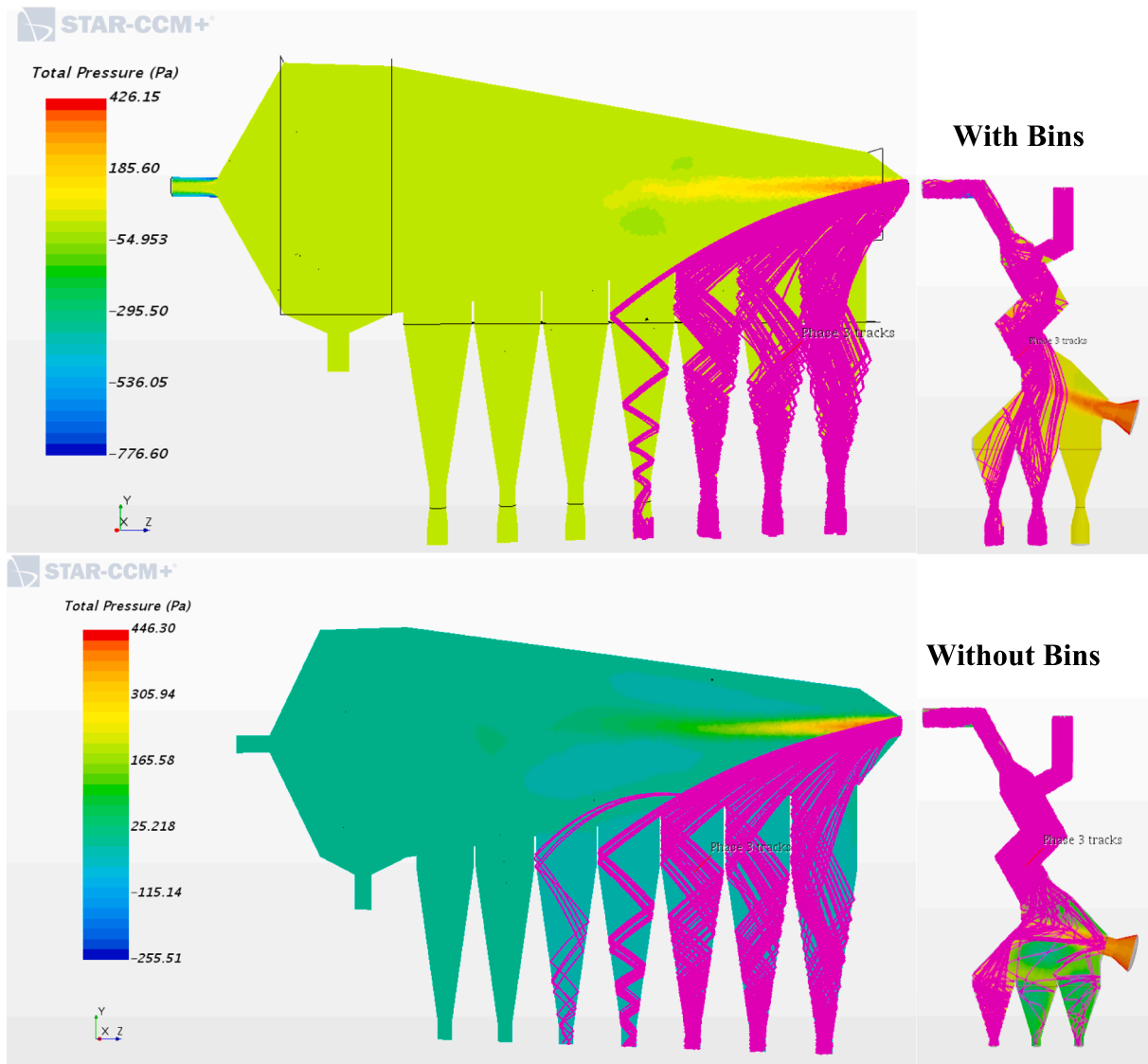


Fig. 10. Particle tracks for the $(-6.7 + 3.35)$ mm size fraction at 1.5 RD in both chambers at 6.0 m/s (with bins) and 10.5 m/s (without bins).

- i. The first chamber of the separator assembly was designed using the Autodesk Inventor software and then imported into the simulation software.
- ii. A simulation test was conducted using the assumptions listed in Section 2.1 while varying the airstream velocity as shown in Section 3.1.1. for all size fractions when running the separator with and without the bins.
- iii. The particle trajectories for each relative density (RD) were carefully observed, with adjustments made to operational parameters to assess the separation effectiveness of each design at the specified cut-point of 1.6 RD, mirroring the prototype conditions.
- iv. Iterative refinements were undertaken guided by the observed flow trajectories from each design iteration until an optimal separation outcome was achieved within the first chamber.

The second chamber was designed using steps similar to those outlined for the first chamber. These steps, guided by the optimal results attained through particle tracking, culminated in designing the optimized separator assembly. To achieve the dilute phase, the simulation study was carried out according to the study by Santos et al. [49], where 6.0 to 11 g of particles were used in an airflow airstream. The density of

air used during the simulation process was 1.204 g/cm^3 , assuming room temperature conditions (20°C). Equation (20) was used to determine the mass yield of the separator.

$$\text{Mass yield (\%)} = \frac{100 \times M_o}{M_I} \quad (20)$$

where M_o represents the mass of the lighter particles at a cut-point of 1.6 g/cm^3 , flowing from the first chamber into the second chamber. M_I is the total mass of the particles fed into the separator through the separator coal feed inlet. Following the condition from the study by Santos et al. [49], the mass flow rate of the particles was determined using Equations (21) and (22).

$$\text{Air mass flow rate} = \rho_{\text{air}} \times u \times A \quad (21)$$

where ρ_{air} is the density of air at 20°C , u is the velocity of air entering the separator. The diameter of the cross-sectional area of the air inlet channel was 100 mm.

$$\text{Particle mass flow rate} = \text{Air mass flow rate} \times \frac{\text{6g of particles}}{\text{11g of air}} \quad (22)$$

Equation 23 was used to calculate the wind-sifter separator's recovery.

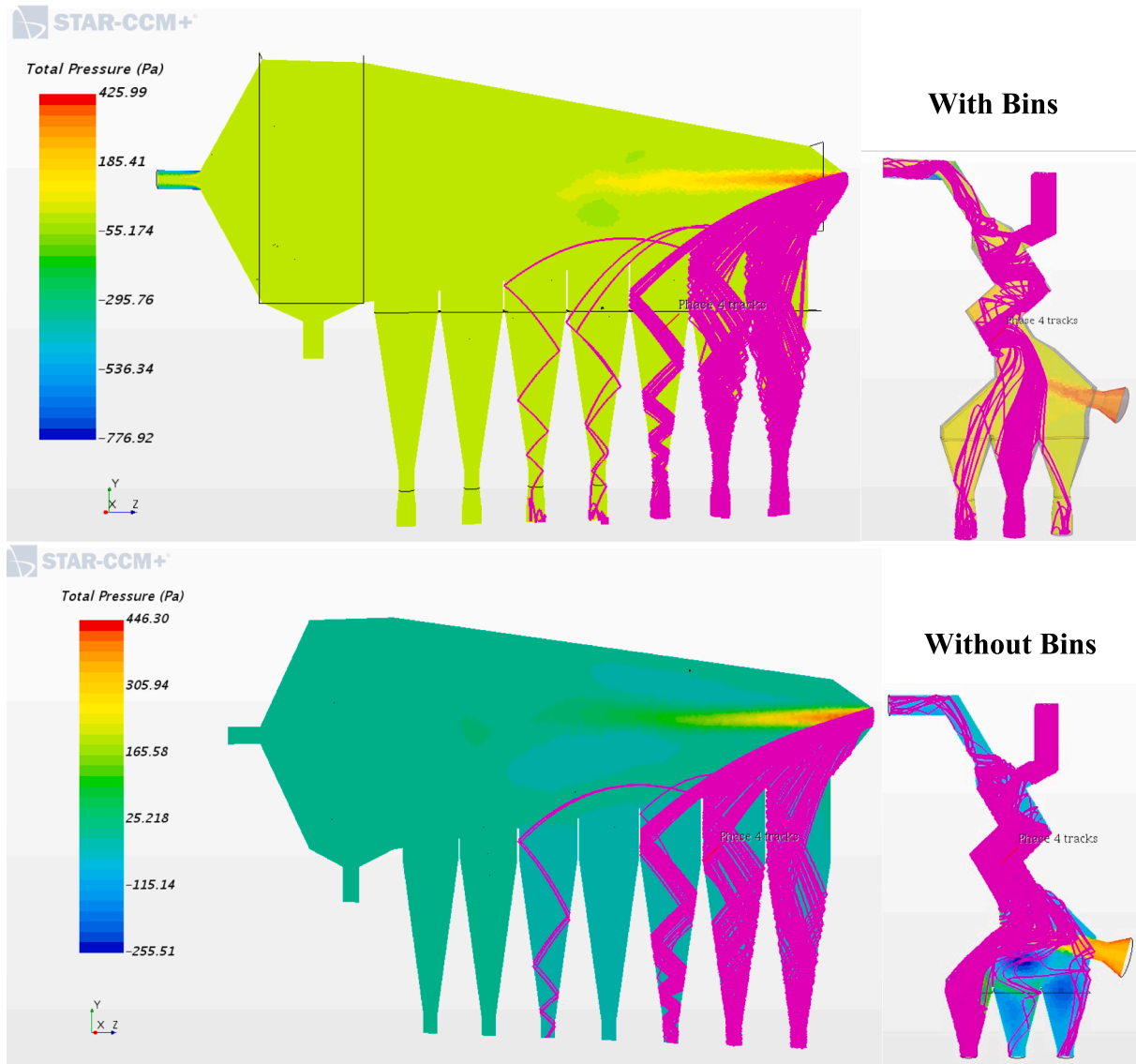


Fig. 11. Particle tracks for the $(-6.7 + 3.35)$ mm size fraction at 1.6 RD in both chambers at 6.0 m/s (with bins) and 10.5 m/s (without bins).

$$\% \text{Yield} = \left(\frac{\text{Total mass of coal collected in the coal bins of the second chamber}}{\text{Total Mass of Coal feed}} \right) \times 100 \quad (23).$$

Fig. 1 illustrates the layout of individual chambers along with their respective boundaries. A represents the air supply inlet into the separation chamber in chamber 1, while B denotes the particle inlet into the separation chamber. C is the outlet of the clean coal particles carried away by the airstream from the first chamber. B8, B9, and B10 correspond to the coal bins 8, 9, and 10 for collecting gangue material particles. D denotes the inlet of the partitioned particles in chamber 2, through which the lighter particles are transported into the second chamber. E is the air outlet from the separator. B1, B2, B3, B4, B5, B6, and B7 represent the particle collection bins 1, 2, 3, 4, 5, 6, and 7, respectively, while B0 is the collection point for particles that bypass B1. The design of the separator was meticulously conducted to ensure maximal recovery of coal, either as a product or discard. This design consideration aims to prevent sample retention within the separator, a challenge noted in prior designs [44,45].

Several modifications were implemented, including adjusting the air jet angle in the chamber, increasing the number of collecting bins, and adding a feature that allows operation with or without bins. The air inlet angle in chamber 1 of the old design was adjusted from 150° vertical to 165° in the optimized version. Another modification was the increase in

the coal collecting bins from 7 in the old design [44,45] to 10 in the optimized design. B0 is not a bin but collects coal that travels further than B1 in the optimized version displayed in Fig. 1. The mode of operation was also optimized in the new design. The optimized separator can operate with and without the sample's collecting bins, while the previous design can only operate with the bins fastened to the separator.

The following assumptions were made regarding the simulation test runs (for the new separator).

- The particle shape factors range from 32.5 to 0.03, encompassing a broad spectrum to represent various drag coefficients [47].
- The particle relative densities (RDs) are equally represented in terms of mass.
- Each particle's RD within the coal sample was represented in the simulator and assigned a size (mm) as outlined in Table 1. This is done to simplify the simulation process and ensure consistency with the particle sizes used in the simulation study of the previous design.
- A normal and tangential restitution coefficient of the boundary of the wind-sifter separator was assumed to be 0.7. This assumption accounts for the lining material, linatex-rubber-heavy-duty (HD)-

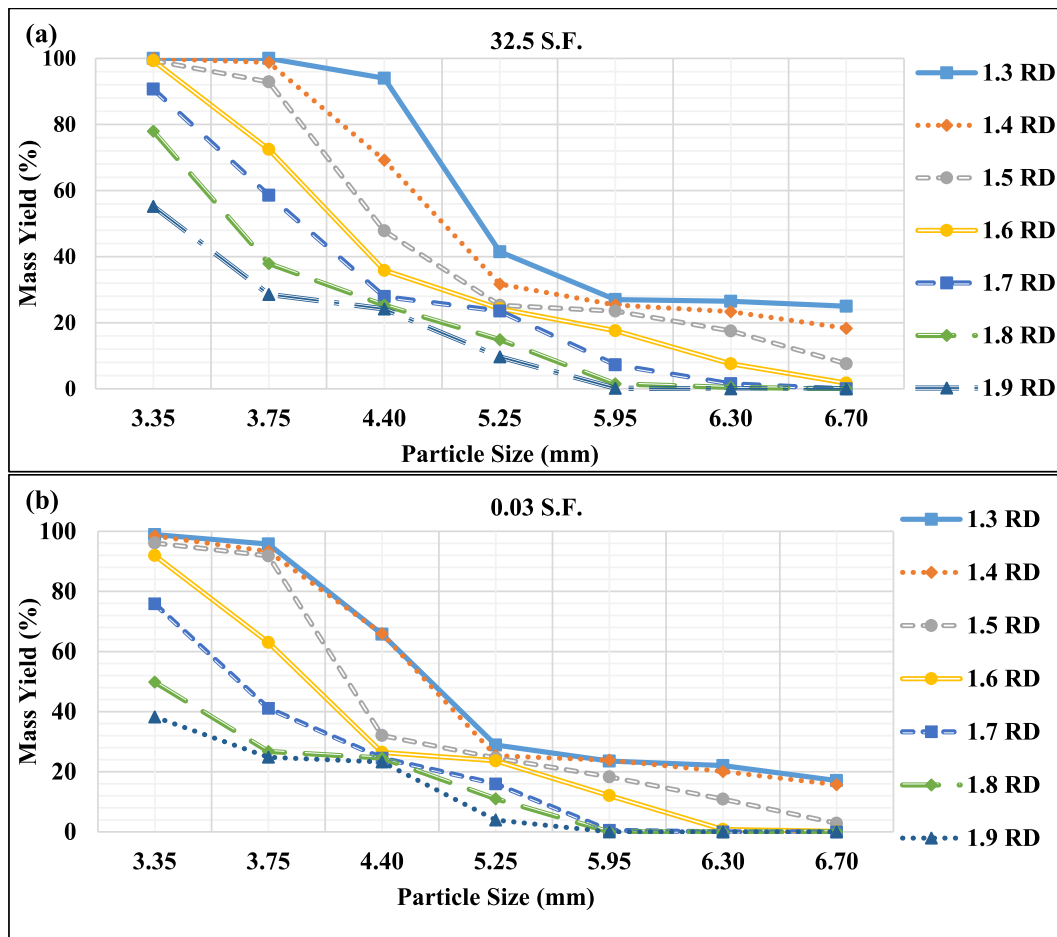


Fig. 12. a & b: mass yield(s) of individual particles in the particle size distribution of the $(-6.7 + 3.35)$ mm size fraction as a function of relative density (with bins) at 6.0 m/s.

60 used in the inner section of the separator. The lining aids in cushioning coal particles during transport within the airstream.

Table 1 presents the appropriate cut size for the finest size fraction in the separation process determined by correlating the indicated velocity with the observed flow tracks of the particles. Cut-size of 0.2 mm was selected based on the size associated with a smooth flow track. The particle sizes $(-6.7 + 3.35)$ mm, $-3.35 + 1.0$ mm, and $-1.0 + 0.2$ mm) were compared to investigate which particle size fraction would produce the best performance.

2.2. The wind-sifter separator

The optimized wind-sifter, including bins but excluding auxiliaries, occupies a footprint of 2.46 m in length, 1.30 m in height, and 0.2 m in width. The footprint extends to 4.0 m in length, 2.5 m in height, and 0.9 m in width with the inclusion of auxiliaries. The separator assembly is mounted on a cradle, allowing suspension from the ground for operational flexibility. It can be used with or without the bins depending on the operator's requirements. Fig. 2 depicts the complete assembly mounted on cradles without auxiliaries while Fig. 3 displays the fabricated separator.

2.2.1. Operating principle

The optimized wind-sifter separator, akin to its predecessor, functions to segregate lighter particles from heavier ones. The centrifugal air blower delivers air to the separator and enters the system through the inlet filter (Fig. 4a). The air blower uses centrifugal force generated by

the rotation of its impeller to move air. The impeller pulls air into the blower and then pushes it out through the outlet. Subsequently, the air passes through a control valve (ball valve) for regulation, with the regulated air directed into the separator via the flexible tubing. A pressure gauge indicates when the filter becomes clogged: higher pressure readings denote greater filter obstruction. The safety/relief valve is designed to depressurize the separator assembly if there is excessive pressure buildup (Fig. 4b). It works together with the control valve for velocity control by adjusting the percentage opening of the valve. Incoming air enters chamber 1, where its velocity is measured using a velocity probe/sensor. The airstream then progresses through the air inlet. Coal particles introduced into the separator through the coal feed inlet descend into the zigzag section. As particles bounce within this section, separation occurs due to their weight difference. Continuously flowing air further enhances separation in a counter-current manner, transporting lighter particles into the second chamber for collection. Differential drag acting on particles in the airstream facilitates their segregation based on size and density within this chamber (chamber 1). The chamber design follows the same principle as chamber 1 of its predecessor [44]. Coal feed is facilitated by a vibratory feeder assembly and a rotary hopper valve which aids direct particle feeding into the system. The rotary hopper valve also seals the coal-feed inlet and prevents it from serving as an outlet for the airstream. The vibratory feeder for the feed sample was calibrated, and mass flow rates during test runs were kept constant and low to maintain a dilute phase and minimize particle-to-particle interactions. Fig. 4c shows the installed separator with its vibratory feeder, the rotary hopper, and the control panel upon installation. The control panel powers the electric motor-driven rotary

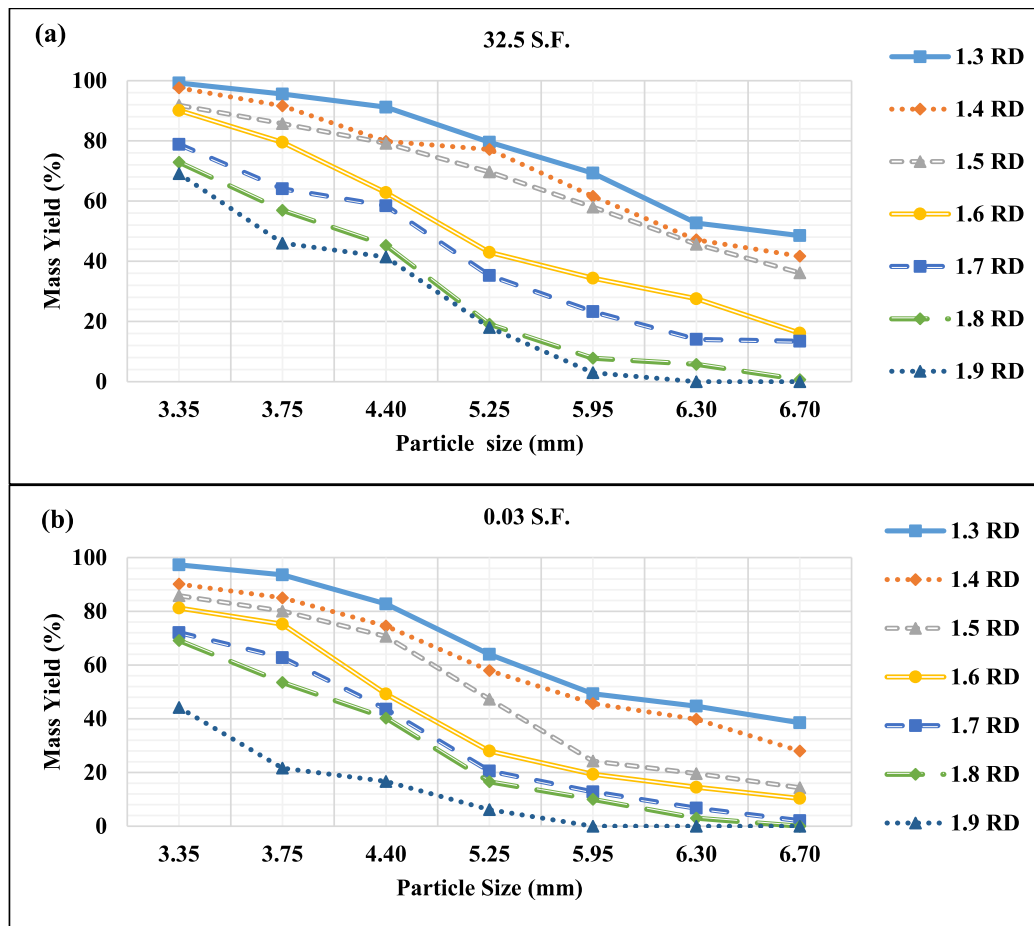


Fig. 13. a & b: mass yield(s) of individual particles in the particle size distribution of the $(-6.7 + 3.35)$ mm size fraction as a function of relative density (without bins) at 10.5 m/s.

hopper valve and the air blower.

2.3. Experimental test work

Experimental data obtained from the fabricated separator explored the impact of air velocity on separation performance and product ash contents using run-off-mine coal from Witbank Coalfield. The as-received coal was crushed and sized into the three particle size fractions $(-6.7 + 3.35)$ mm, $(-3.35 + 1.0)$ mm, $(-1.0 + 0.2)$ mm according to ASTM D 2013. The preliminary beneficiation study followed the operating principle described in Section 2.2.1. The proximate analysis for the raw and clean coal products was determined using a TGA 701 Leco equipment, following the ASTM D 5142 standard.

3. Results and discussion

3.1. Simulation results

The design and fabrication of the optimized wind-sifter separator were based on the findings from the simulation study. As stated in section 2.1., the forces acting in the separation process are the buoyant force, the drag force, and the weight of the particles. The buoyant force i. e., the force exerted by the airstream when transporting the particles while the summation of the drag force and the weight is the force exerted by the particle. As shown in Equation (11), the resolution of the forces determines if the particles are in motion and when they attain their respective settling velocities. Shape analysis was conducted for three size fractions under two conditions: with the separator's bins

closed (with bins) and open (without bins). In the simulation, the range of shape factors (0.03 – 32.5) corresponds to the drag coefficient, with 0.03 representing the highest and 32.5 the lowest. Airstream velocity's influence on three particle size fractions was evaluated at a cut point of 1.6 RD during the simulation tests. All tests were repeated multiple times with minimal differences in the results of each run.

3.1.1. Optimal velocity determination

The optimal airstream velocities for all particle size fractions when the bins were connected to the separator were obtained from the previous study conducted by Alade (2021). The new separator design in chamber 1 is not significantly different from the previous design, hence, the same air stream velocities were utilized. The airstream velocities were set at 6.0 m/s for $(-6.7 + 3.35)$ mm, 4.2 m/s for $(-3.35 + 1.0)$ mm, and 1.7 m/s for $(-1.0 + 0.2)$ mm size fractions at a cut point of 1.6 RD. Various airstream velocities were simulated to observe how particles separate and to identify the optimal velocity for each size fraction in open mode (without the bins). For the $(-6.7 + 3.35)$ mm size fraction, airstream velocities ranging from 6.0 m/s – 12 m/s were tested. It was observed that at 6.0 and 7.0 m/s, an insignificant yield was achieved. Higher airstream velocity led to an increase in yield due to enhanced buoyant force. The airstream velocity ranging between 9.0 and 10.5 m/s, resulted in an optimal mass yield of 29.46 – 44.97 % for this size fraction (Fig. 5a).

A similar investigation was also conducted for the $(-3.35 + 1.0)$ mm and $(-1.0 + 0.2)$ mm size fractions until their optimal mass yields were attained. The results shown in Fig. 5b & c indicate that the optimal mass yield of 30.47 – 44.65 % was obtained at 5.0 – 7.0 m/s for the $(-3.35 +$

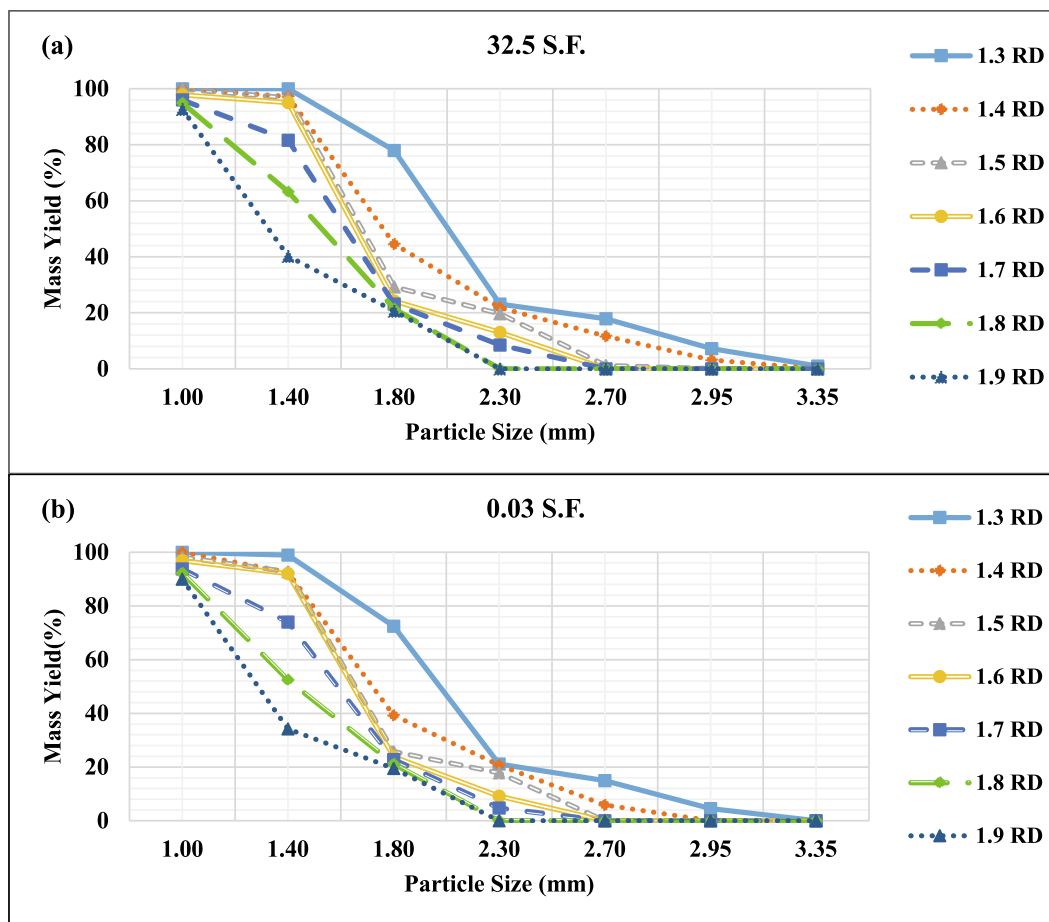


Fig. 14. a & b: mass yield(s) of individual particles in the particle size distribution of the $(-3.35 + 1.0)$ mm size fraction as a function of relative density (with bins) at 4.2 m/s.

1.0) mm at 1.6 RD. The velocity range attained for the $(-1.0 + 0.2)$ mm size fraction was between 3.5 – 2.5 m/s for the same cut-point, with the optimal mass yield of 21.00 – 38.65 %.

3.1.2. Effect of shape factor on particle separation

The simulation tests conducted based on the specified assumptions in Section 2.2 yielded insightful results. Figs. 6 & 7 depict the results at a shape factor of 32.5 and 0.03, representing the process separation efficiency. Fig. 6a, b & c showcased the washability or separation process with all the separator's outlet bins closed, while Fig. 7a, b, & c depicted the outcomes with open bins. Regardless of the shape factor, Fig. 6a revealed consistent yields for the $(-6.7 + 3.35)$ mm fraction across different relative densities (RDs) due to the highly effective airstream minimizing variations in particle recoveries. Conversely, open bins led to distinct yield differences attributed to decreased pressure and reduced air stream-tube effectiveness. From Fig. 7b & c for $(-3.35 + 1.0)$ mm and $(-1.0 + 0.2)$ mm size fractions respectively, a similar recovery trend for both shape factors was observed with closed bins. The variation in recoveries however was particularly pronounced in the coarsest size fraction $(-6.7 + 3.35)$ mm (Fig. 7a). The findings suggest that the shape factor's impact on mass yield is less pronounced when bins are closed than when operating without them. Furthermore, finer particle size fractions exhibited reduced influence of shape factor on particles and mass yield. This observation underscores the importance of operational conditions such as bin status in shaping separation efficiency outcomes across different size fractions and shape factors.

3.1.3. Particle tracks of different relative densities at constant airstream velocities with and without bins

The particle track analysis offered crucial insights into the particle flow pattern during separation. The analysis was conducted based on Table 1 and the assumptions described in Section 2.1. Fig. 8, 9, 10, & 11 depict the particle separation (flow tracks) with and without bins for $(-6.7 + 3.35)$ mm fractions of 1.3, 1.4, 1.5, and 1.6 RD. The findings reveal a higher recovery of lighter particles in chamber 2, particularly when using a shape factor of 32.5, characterized by lower drag force and longer travel distances compared to the 0.03 shape factor. Similar flow patterns were observed across the other size fractions. Fig. 8 demonstrates that 1.3 RD particles travelled the furthest in chamber 2 (with and without bins, respectively), attributed to delays in reaching their settling/terminal velocity upon entering the diffuser chamber. As the airstream channel expands, particle trajectories align with airflow trajectories, further transporting lighter particles. This explains why the 1.3 RD particles, the lightest for this study, were transported the furthest by the transporting airstream. Also, the kinetic energy of the airstream transporting the particles decreases as they enter the diffuser section of chamber 2. The same phenomenon was observed for the 1.4 RD particles, as shown in Fig. 9 (with and without bins, respectively). A decrease in particle yield was noted for 1.5 and 1.6 RD particles shown in Figs. 10 & 11 respectively (both with and without bins), indicating decreased sample recovery with increased density. Notably, operating the separator without the bins (open) resulted in higher particle recovery, attributed to increased airstream velocity and buoyant force enhancing particle elutriation into chamber 2. Overall, the particle track analysis provided valuable insights into the particle flow pattern during separation. This underscores the significance of particle density and shape

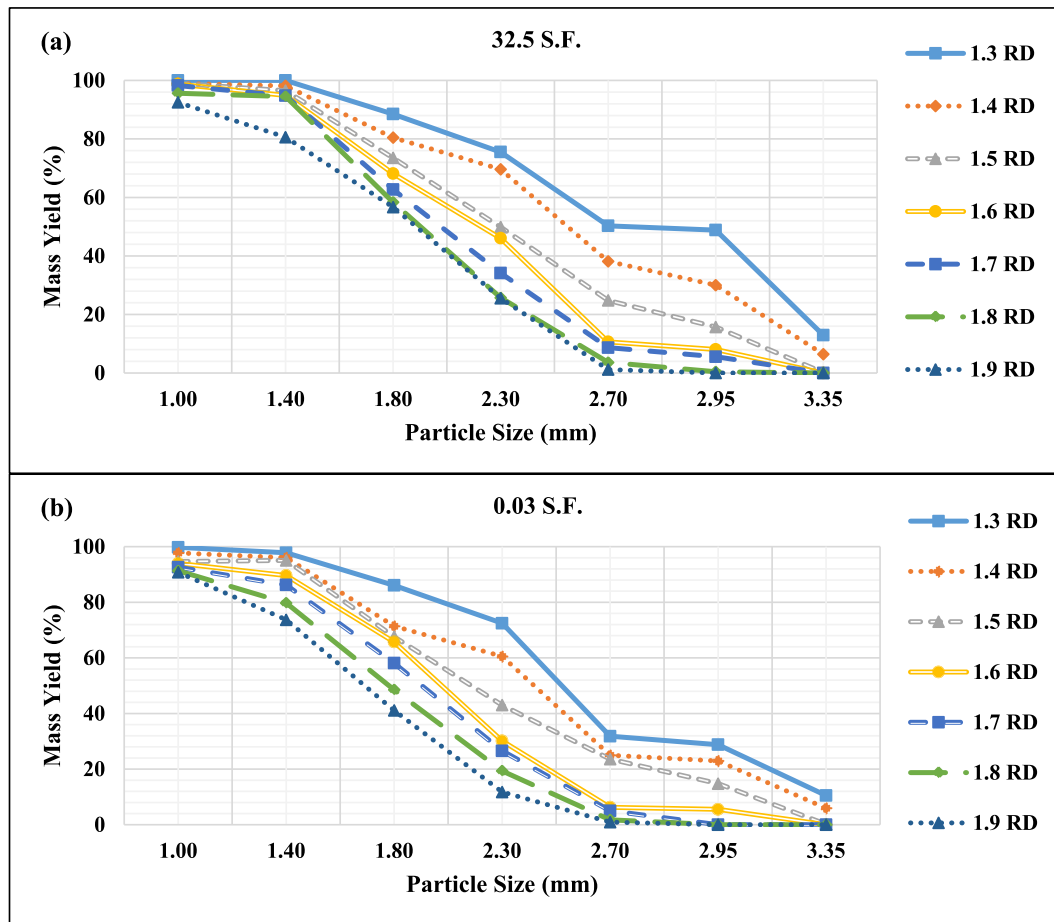


Fig. 15. a & b: mass yield(s) of individual particles in the particle size distribution of the $(-3.35 + 1.0)$ mm size fraction as a function of relative density (without bins) at 7.0 m/s.

factors in determining particle recovery efficiency.

3.1.4. Effect of shape factor on mass yield(s) of individual particles within $(-6.7 + 3.35)$ mm

From the computer simulator program, each relative density (RD) within the coal was assigned a size (mm) to simplify the simulation process (see Table 1). The aim was to investigate the influence of shape factors (32.5 and 0.03) on the mass yields of individual particles within the $(-6.7 + 3.35)$ mm size fraction, maintaining constant RD and velocity. Simulation results for the $(-6.7 + 3.35)$ mm size fraction at 6.0 m/s with closed bins are depicted in Fig. 12a & b for shape factors of 32.5 and 0.03, respectively. Fig. 13 demonstrates that particles sized 3.35 mm exhibited 100 % mass yield across RDs 1.3 to 1.6 for a shape factor of 32.5. Conversely, for a shape factor of 0.03, only 1.3 RD particles achieved 100 % mass yield, with decreasing yields observed for RDs 1.4, 1.5, and 1.6. Additionally, as individual sizes increased, mass yields for shape factor 32.5 surpassed those for shape factor 0.03 within the same size fraction. The higher mass yields observed for shape factor 32.5 compared to 0.03 indicate the greater influence of shape on the coarsest size fraction, attributed to the lower drag coefficient associated with the former.

Fig. 13 displays the simulation test results with the separator's outlets open (without bins) at a higher velocity of 10.5 m/s, accounting for observed pressure loss. A notable difference in mass yields between shape factors (32.5 and 0.03 for Fig. 13a & b respectively), is evident from the figure. For instance, the mass yields of the 3.5 mm particles at relative densities of 1.3 and 1.4 were 99.23 % and 97.6 %, respectively, for shape factor 32.5, whereas for shape factor 0.03, the yields were 97.29 % and 90.12 %, respectively. The trend was observed across other

relative densities in this size fraction. Tests conducted at a lower shape factor (0.03), indicative of a higher drag coefficient, resulted in lower yields than those at a higher shape factor (32.5) for the same particle size. The lower mass yield observed in the open bin circuit compared to the closed bin circuit in this study can be attributed to the higher pressure drop when the bins are opened, thus reducing the potency of the air stream tube. This will result in the presence of swirls in the stream tube, ultimately leading to a reduced buoyant force.

3.1.5. Effect of shape factor on mass yield(s) of individual particles within $(-3.35 + 1.0)$ mm

Figs. 14 & 15 depict simulation results for the $(-3.35 + 1.0)$ mm size fraction for closed and open bins, respectively. Fig. 14a & b illustrate outcomes for shape factors of 32.5 and 0.03, respectively, with a constant air velocity of 4.2 m/s and closed bins. Conversely, Fig. 15a & b present results under similar shape factor conditions but with bins open, at an air velocity of 7.0 m/s. Consistent with Fig. 12a & b, the trends observed in these results align with expectations. In Fig. 14a & b, higher recoveries are observed for all individual sizes at the 32.5 shape factor compared to the 0.03 shape factor. Additionally, the mass yields of the smallest particle size fraction (1.0 mm particle) in Fig. 14a & b surpass those of the smallest particle in the $(-6.7 + 3.35)$ mm fraction (3.35 mm particle) with closed bins (Fig. 12a & b). This discrepancy is attributed to the size difference; as particle size decreases, so does weight and drag force, facilitating easier transport by the airstream.

Fig. 15a & b illustrate the simulated results for the $(-3.35 + 1.0)$ mm size fraction with open bins (without bins), considering shape factors of 32.5 and 0.03. Notably, a significantly higher mass yield was observed for the 32.5 shape factor compared to the 0.03 shape factor. This trend

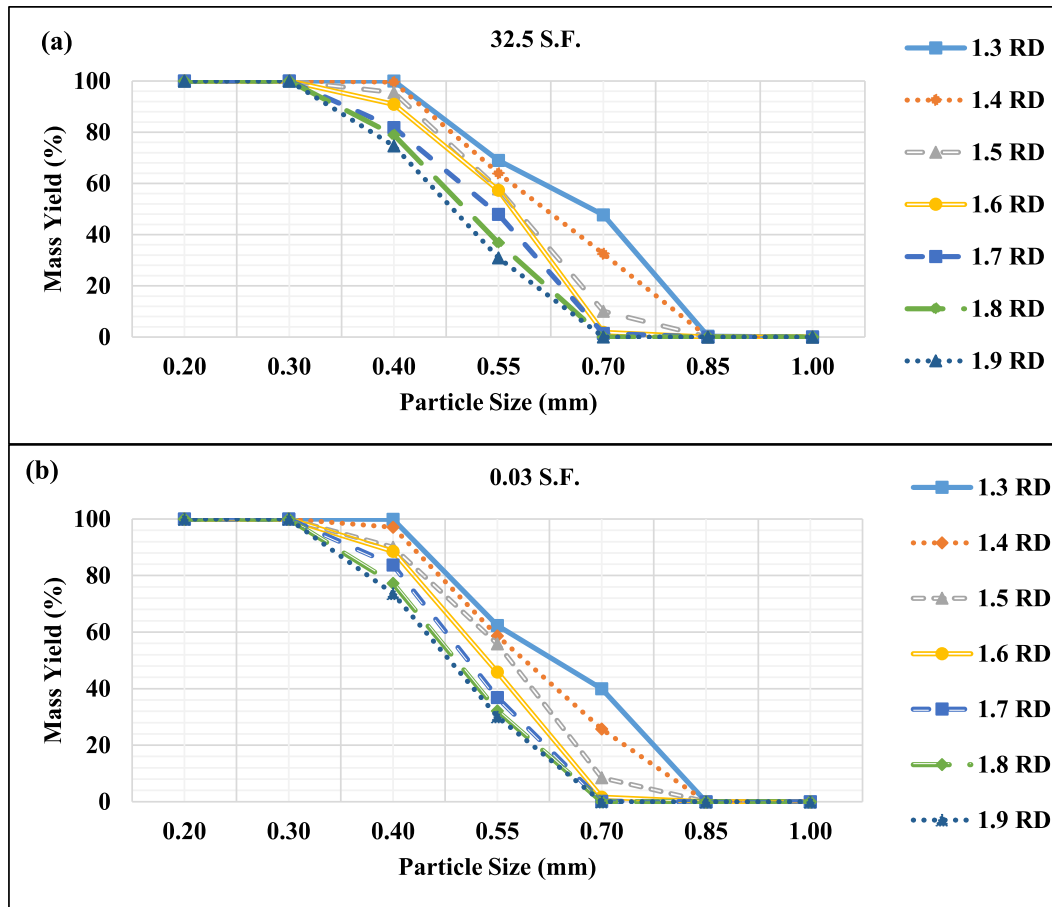


Fig. 16. a & b: mass yield(s) of individual particles in the particle size distribution of the $(-1.0 + 0.2)$ mm size fraction as a function of relative density (with bins) at 1.7 m/s.

mirrors the observations made for the $(-6.7 + 3.35)$ mm size fraction without bins, as depicted in Fig. 13. The impact of the shape factor on mass yield for this fraction is evident, although not as pronounced for the $(-6.7 + 3.35)$ mm fraction.

3.1.6. Effect of shape factor on mass yield(s) of individual particles within $(-1 + 0.2)$ mm

Fig. 16a & b and 17a & b display the simulation outcomes for the finest particle size fraction $(-1.0 + 0.2)$ mm. In Fig. 16a & b, results for shape factors of 32.5 and 0.03 respectively, are presented for closed bins at an air velocity of 1.7 m/s. Fig. 17a & b showcase simulation results without bins (open bin) at an air velocity of 3.5 m/s for shape factors of 32.5 and 0.03. Notably, Fig. 16a & b reveal a 100 % mass yield for particles sized 0.2 mm and 0.3 mm at 32.5 and 0.03 shape factors with closed bins. This is unlike Fig. 17a & b where there is a slight decrease in the 0.3 mm sized particles which emphasizes the pressure drop when the bins are opened.

Fig. 17a & b present the simulation results for the $(-1.0 + 0.2)$ mm size fraction without bins for shape factors of 32.5 and 0.03 respectively. The yield for the 32.5 shape factor exceeded that obtained for the 0.03 shape factor. Comparatively, the difference in mass yield for the $(-1.0 + 0.2)$ mm size fraction was smaller than that observed for the $(-3.35 + 1.0)$ mm size fraction. This can be attributed to the diminishing influence of particle shape as particle size decreases. Additionally, smaller particle size correlates with reduced weight and drag force, increasing the likelihood of particle elutriation by the flowing airstream.

These findings underscore the significant role of a particle's density and size in its transportation and separation within an airstream. Notably, the shape factor of particles has pronounced significance in the

separation of coarse particle size fractions, whereas its influence diminishes for finer particles. As particle sizes decrease, the impact of particle shape on separation efficiency and mass yield diminishes accordingly. It should be noted that these observations contrast with the sink-and-float method which partitions coal particles based on their relative densities, with minimal influence on particle shape.

3.2. Determination of the particle size fraction (cut-size) for the -1 mm particle size

The selection of the $(-1.0 + 0.2)$ mm particle size fraction for simulating the separator, instead of the -1.0 mm size fraction, was motivated by the substantial sample loss during coal beneficiation of the -1.0 mm size using a previous separator design. In this prior design, smaller particles within the -1.0 mm fraction were prone to constant entrainment in the airstream and adhering to the separator walls. To address these issues, it was imperative to identify a suitable cut size for the new separator design to minimize sample loss. To determine the optimal cut size for the -1.0 mm size fraction, simulations were conducted for cut sizes: 0.10 mm, 0.15 mm, and 0.20 mm representing particle size distributions: $(-1.0 + 0.1)$ mm, $(-1.0 + 0.15)$ mm, and $(-1.0 + 0.2)$ mm, at air velocities of 1.7 m/s for closed bins and 3.5 m/s for open bins. Particle tracks were analyzed to determine the appropriate cut size, with Figs. 18 to 20 illustrating particle flow tracks for the respective cut sizes. Throughout the experiments, a particle density of 1.3 relative density (RD) was maintained to observe the flow behavior of the smallest and lightest particles in the airstream.

Notably, Fig. 18b illustrates particle recirculation within the airstream, especially evident when the separator bins are open. Fig. 19

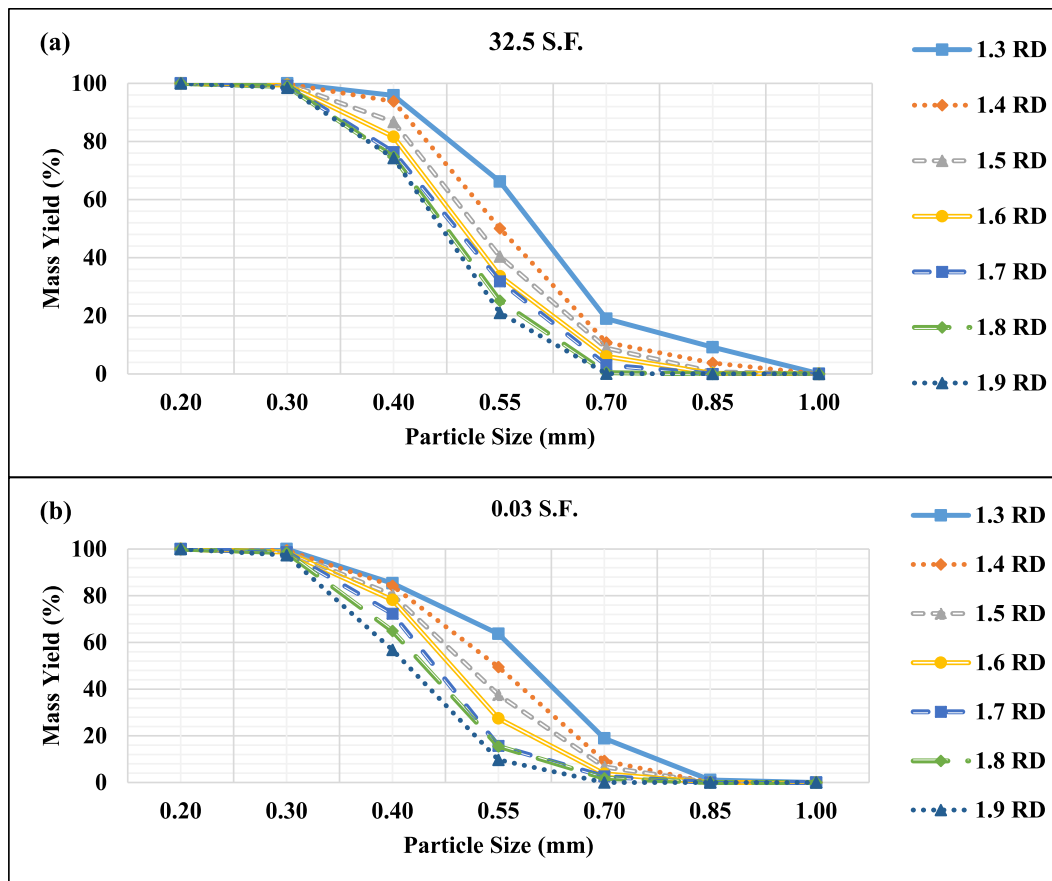


Fig. 17. a & b: mass yield(s) of individual particles in the particle size distribution of the $(-1.0 + 0.2)$ mm size fraction as a function of relative density (without bins) at 3.5 m/s.

demonstrates smoother particle flow tracks during the separation process, both with and without bins. Fig. 20 exhibits appropriately settled particle flow tracks, defining the cut size for the $(-1.0 + 0.2)$ mm particle size fraction.

3.3. Preliminary experimental results

3.3.1. Wind-sifting beneficiation (initial investigations)

An initial beneficiation study utilizing the separator was conducted across all three particle size fractions, utilizing its collecting bins to investigate the validation of the model(s). A constant mass flow rate of 36 g/min was maintained throughout the experiments, derived from a previous study [45].

3.3.1.1. Results for the $(-6.7 + 3.35)$ mm size fraction. 500 g of $(-6.7 + 3.35)$ mm size fraction of coal with 37.38 % feed ash content, 1.99 % moisture content and calorific value (CV) of 19.61 MJ/kg, was processed through the separator at airstream velocities of 6.0 m/s and 5.0 m/s. As depicted in Fig. 21, decreasing the air velocity led to a reduction in ash content, subsequently resulting in a decline in cumulative yield. At an airstream velocity of 6.0 m/s, the bins of chamber 2 produced a clean coal product with a cumulative ash content of 26.97 % and a cumulative yield of 77.40 %, from the feed coal. Conversely, when the velocity was reduced to 5.0 m/s, the clean coal product obtained from the bins of chamber 2 exhibited a lower cumulative ash content of 24.84 % and a reduced cumulative yield of 62.59 %. The cleanest coal products at 6.0 m/s was 25.93 % specific ash content and 23.48 MJ/kg, and 23.86 % specific ash content and CV of 24.52 MJ/kg at 5.0 m/s. The experimental results reported in this study show similar trends to those of the simulation results which validates the mathematical model used.

The performance of the optimized separator was assessed by comparing its cumulative yields with those of the old prototype design. In chamber 2, the old design yielded a 58.38 % cumulative yield at 6.0 m/s [44,45], whereas the optimized separator achieved a higher yield of 77.40 %. Notably, using a 500 g sample feed as a benchmark, the old design incurred a sample loss of 37.15 g (7.43 %).

3.3.1.2. Results for the $(-3.35 + 1.0)$ mm size fraction. The beneficiation of the $(-3.35 + 1.0)$ mm size fraction with 31.11 % feed ash content, 2.34 % moisture content and calorific value (CV) of 20.10 MJ/kg, was conducted at a constant mass flow rate of 120 g/min and under airstream velocities of 4.2 m/s and 3.0 m/s. The separation of coal's organic from inorganic components mirrored the trend observed in the $(-6.7 + 3.35)$ mm size fraction. At an airstream velocity of 4.2 m/s, a clean coal product with a cumulative ash content of 27.29 % and a cumulative yield of 83.39 % was obtained from the bins in chamber 2 (Fig. 22). Conversely, at a lower air velocity of 3.0 m/s, the cumulative ash decreased to 24.11 % with a corresponding decrease in cumulative yield to 71.63 %. The cleanest coal products at 4.2 m/s were observed to have 25.39 % specific ash content, 23.15 MJ/kg CV, and 23.86 % specific ash content and CV of 24.64 MJ/kg at 3.0 m/s. The results indicate that airstream velocity is the primary factor influencing separation efficiency in this separator.

3.3.1.3. Results of the raw coal for the $(-1.0 + 0.2)$ mm size fraction. The beneficiation process of the smallest size fraction in this study revealed easier upgrading using the optimized separator compared to its predecessor, albeit with some sample loss. Sample loss ranged from 11.23 to 35.31 g (2.25 % to 7.06 %) with the optimized design, a marked improvement over its predecessor where more than 50 % of the sample

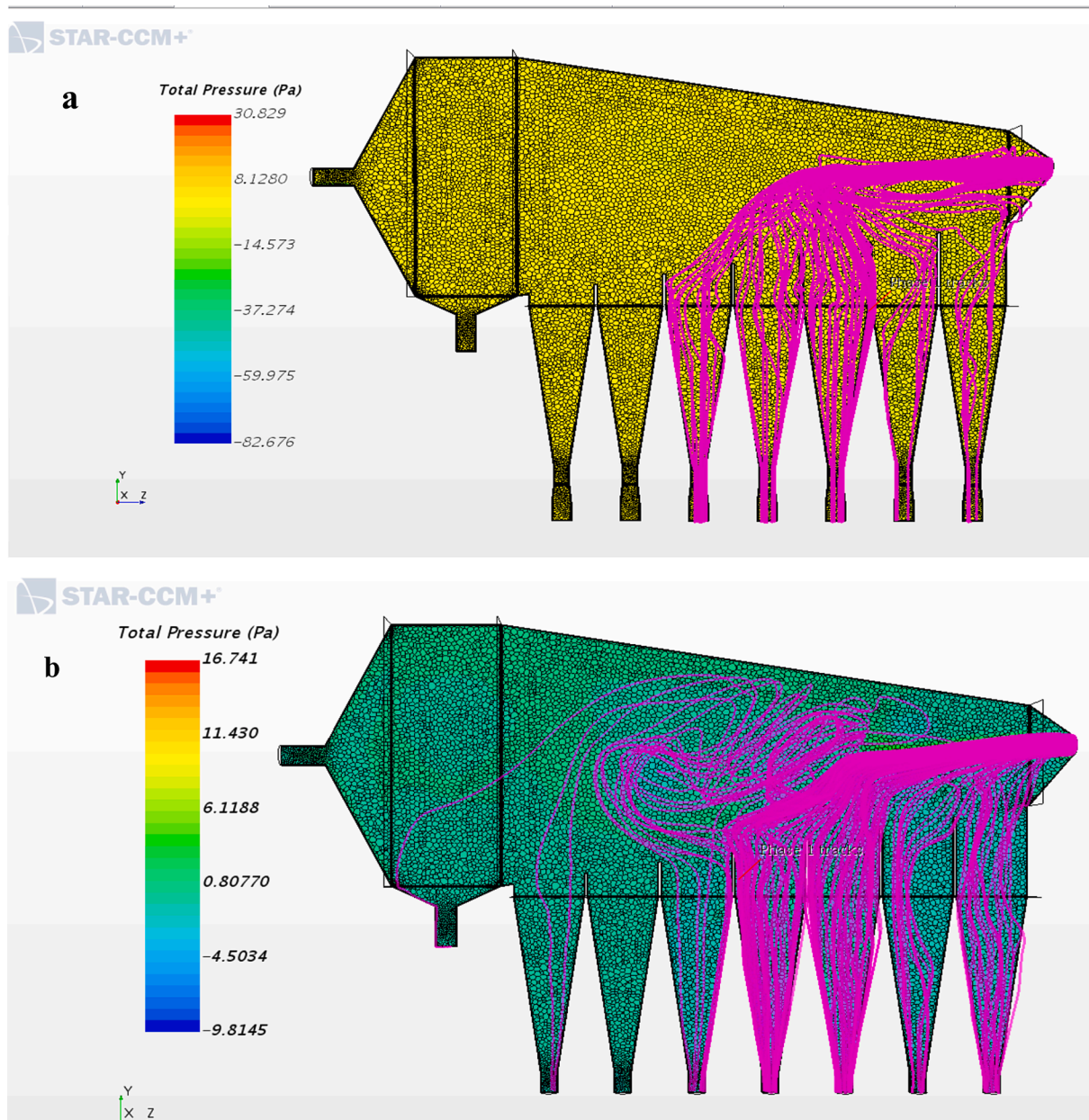


Fig. 18. Test for 0.1 mm particle for (a) closed (b) open bins.

was retained. The inadequate lining of the old separator's wall may have contributed to this inefficiency. Tests were conducted at airstream velocities of 1.7 m/s and 1.0 m/s. Consistent with the coarser size fractions, decreasing airstream velocity reduced the cumulative ash contents and yields of the clean coal products. The beneficiation results for the $(-1.0 + 0.2)$ mm size fraction at different airstream velocities are illustrated in Fig. 23. At 1.7 m/s, chamber 2 of the separator yielded a clean coal product with 26.74 % cumulative ash and 95.76 % cumulative yield from feed coal with 29.30 % ash content, moisture content of 3.02 % and 19.71 MJ/kg calorific value. However, minimal separation was achieved at this velocity, as evidenced by a flat line in the cumulative ash plot. When the airstream velocity was reduced to 1.0 m/s, chamber 2 produced a clean coal product with 25.22 % cumulative ash and 42.13 % cumulative yield. The cleanest coal products at 1.7 m/s was 25.00 % specific ash content and 22.57 MJ/kg, and 21.67 % specific ash content and CV of 24.81 MJ/kg at 1.0 m/s.

4. Conclusion

Reducing the ash content in coal is crucial in reducing environmental pollution and a critical focus area for environmental management strategies. In this study, an optimized wind-sifter separator was designed and fabricated based on the principles of wind-sifting to beneficiate high-ash coal with a feed ash content of 37.38 %. Raw coal samples were screened into three different particle sizes and processed using the optimized separator. The design process involved computer-aided design, simulation, and fabrication to optimize performance.

The results indicate a correlation between simulation and experimental investigations, with parameters such as airstream velocity, particle size, density, and shape having a significant impact on particle separation. The results for both the simulation and experimental investigation showed that decrease in airstream velocity leads to a decrease in mass recoveries and vice versa as shown in Fig. 5 (simulation), and Figs. 21 to 23 (experimental). The simulation results suggest that the separator can effectively operate with and without collecting

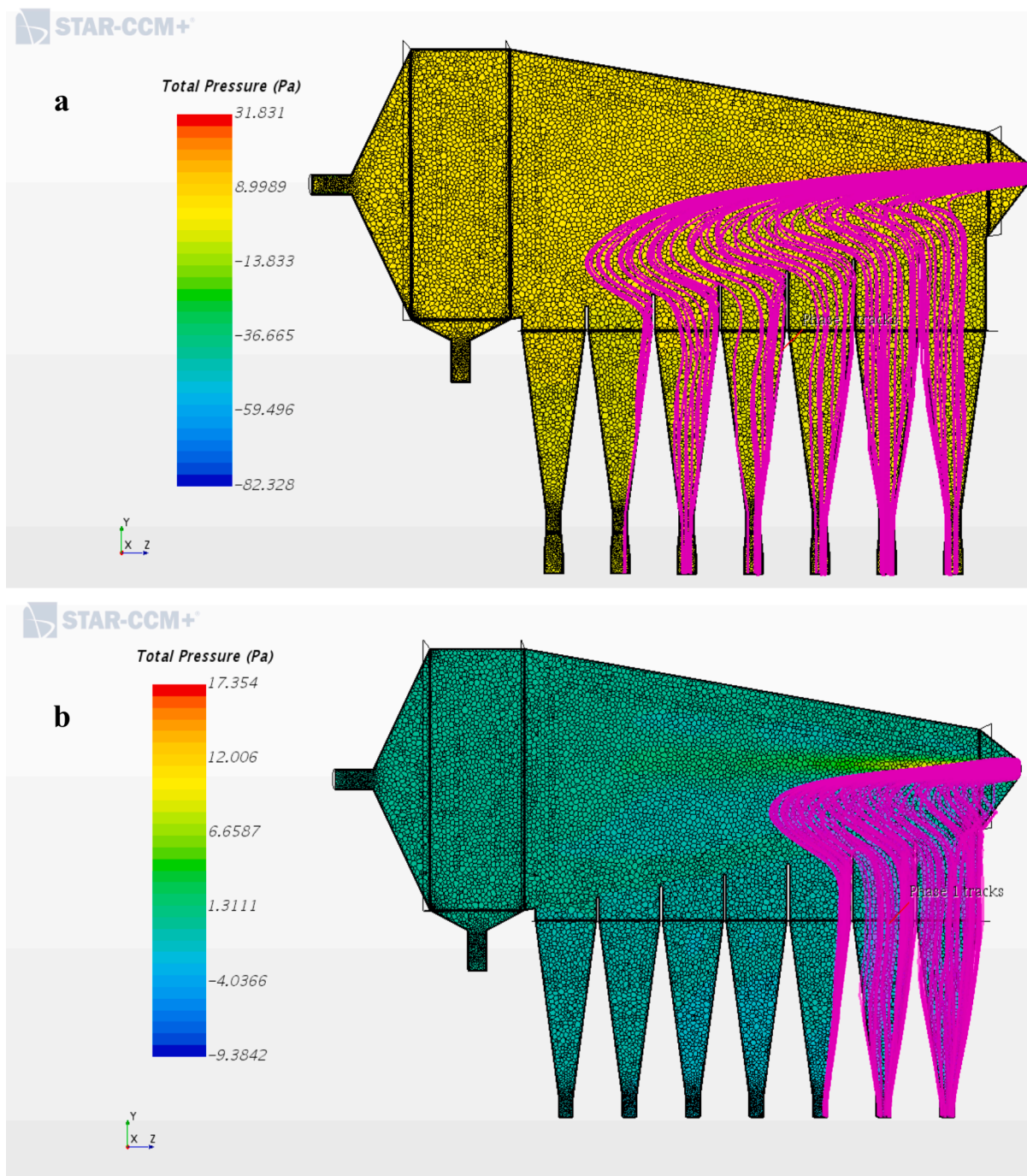


Fig. 19. Test for 0.150 mm (150 μ m) particle for (a) closed and (b) open bins.

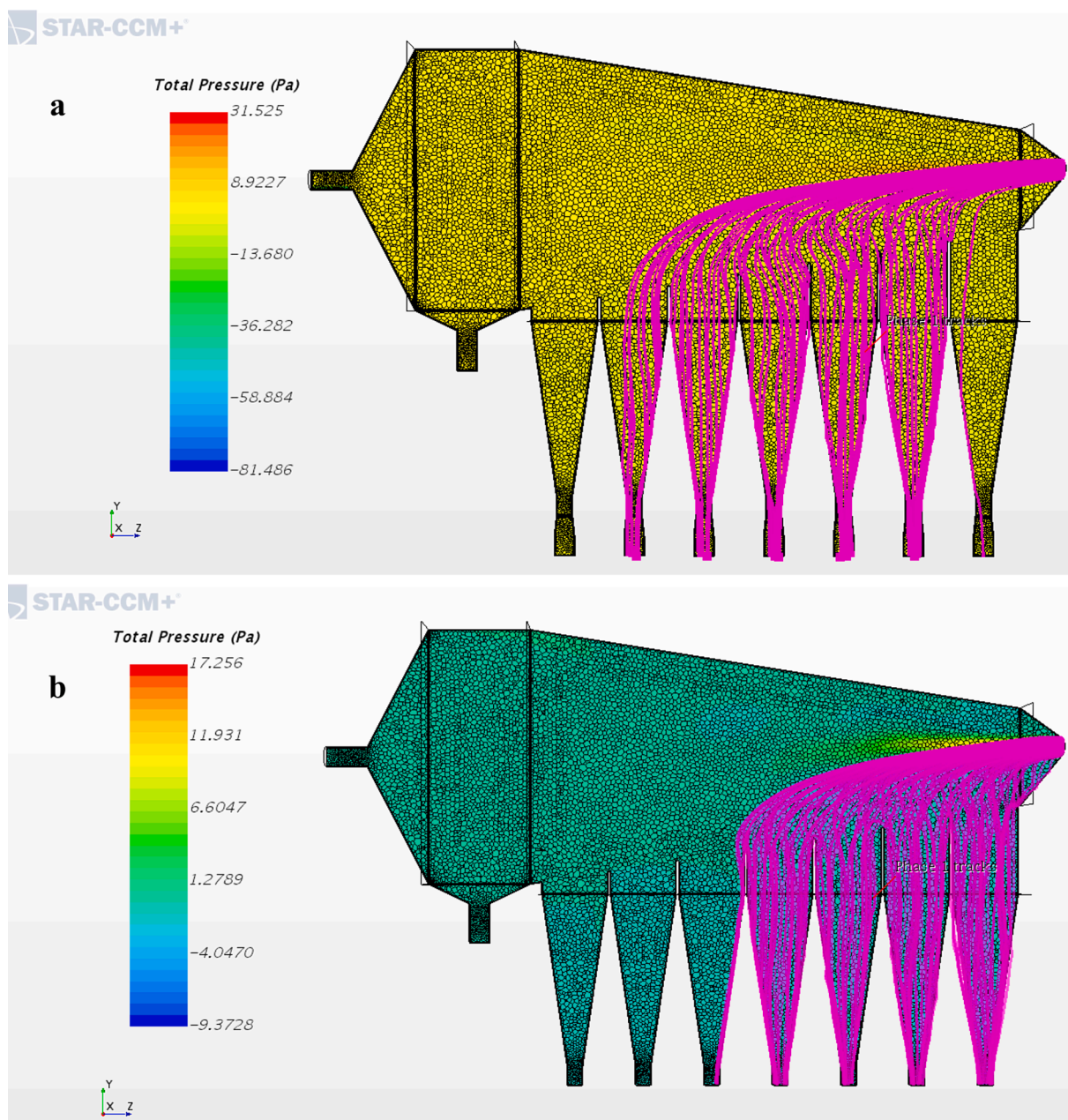


Fig. 20. Test for 0.2 mm (200 μm) particle for (a) closed (b) open bins.

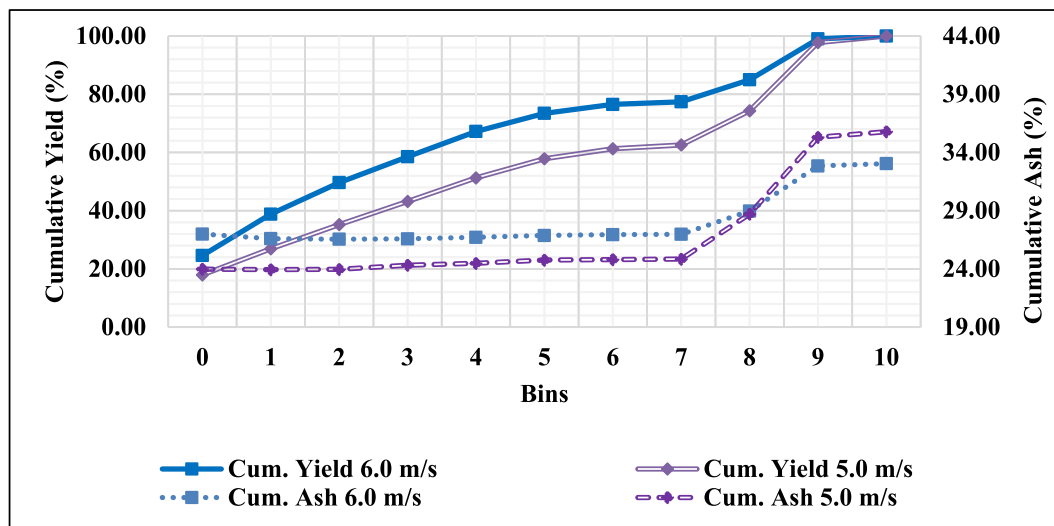


Fig. 21. Cumulative yield and cumulative ash contents for the $(-6.7 + 3.35)$ mm size fraction at different airstream velocities (with bins).

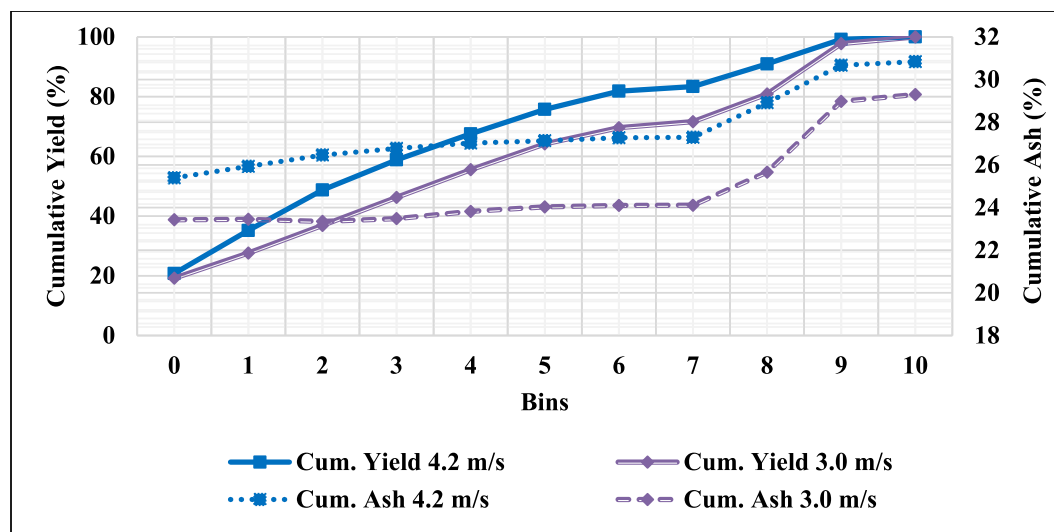


Fig. 22. Cumulative yield and cumulative ash contents for the $(-3.35 + 1.0)$ mm size fraction at different airstream velocities (with bins).

bins to upgrade coal, with particle tracks providing a guide into the separation process. Also, it was observed that particle shape had the greatest impact on the coarsest size fraction, while the least impact on the smallest size fraction.

Reductions in airstream velocity led to decreased product ash content and yield due to lower airstream velocities' inability to effectively transport lighter particles (predominantly coal) but not the heavier mineral-rich particles. Experimental findings demonstrated the superior coal upgrading capability of the optimized wind-sifter separator compared to the previous design, achieving a reduction in cumulative ash content from 37.38 % to as low as 24.11 %. Moreover, the optimized design successfully upgraded the $1.0 + 0.2$ mm coal fractions which the previous design failed to do. Additional experimental research is being conducted to assess the efficiency of the optimized wind-sifter separator, as well as other crucial characteristics of clean coal obtained, such as

petrographic and ultimate analyses.

CRediT authorship contribution statement

Jimmy Alade: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Orevaoghene Eterigho-Ikelegbe:** Writing – review & editing, Visualization. **Samson Bada:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

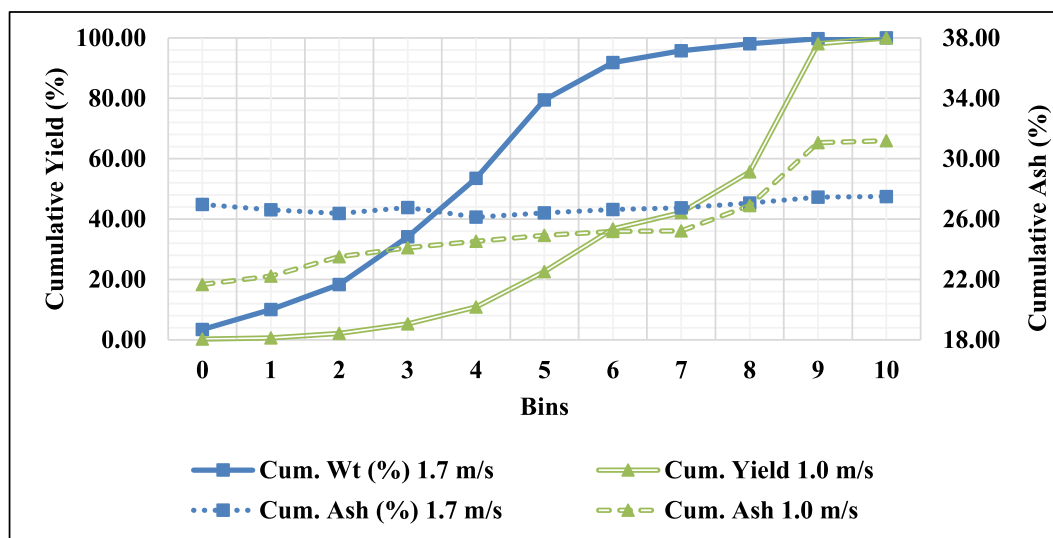


Fig. 23. Cumulative yield and cumulative ash contents for the $(-1.0 + 0.2)$ mm size fraction at different airstream velocities (with bins).

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Data availability

No data was used for the research described in the article.

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