Dry beneficiation of +0.5mm-5.6mm South African coal using an air dense medium fluidization bed

Elmarie Sunette Diedericks (elmariepeters@gmail.com)
North-West University Potchefstroom Campus: North-West University https://orcid.org/0000-0001-9597-0621
Marco Le Roux
North-West University Faculty of Engineering
Quentin Peter Campbell
North-West University Faculty of Engineering

Research

Keywords: ADMFB, coal beneficiation, dense medium, magnetite, air dense medium fluidization, minimum fluidization velocity, ash yield

Posted Date: July 8th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-678819/v1

Dry beneficiation of +0.5mm-5.6mm South African coal using an air dense medium fluidization bed

ES Peters, M le Roux, QP Campbell*

School of Chemical and Minerals Engineering, North-West University, Potchefstroom, South Africa.

***marco.leroux@nwu.ac.za**

Abstract

The separation performance of solid phase bed material, at various particle size ranges, in an air dense medium fluidized bed (ADMFB), were evaluated during this study. The coal particles were separated into +0.5mm-1mm, +1mm-2mm, +2mm-2.8mm, +2.8mm-4mm, +4mm-4.75mm and +4.75mm-5.6mm particle size ranges and fed to the fluidized bed in these fractions. Along with the six coal particle size ranges, three dense media to coal ratios and the addition of vibration was tested to identify the best operating conditions. Adequate results were obtained for larger particle size ranges down to and including +2.0mm-2.8mm coal particles, after which the separation performance decreased significantly. Density stratification was irregular and not obvious for coal particles below 2.0mm and maintaining a consistent fluidization state also proved to be challenging, especially when dense medium was added.

The coal particles separated vertically along the bed height because of differences in particle and bed density, while particle size proved to have a notable influence on the degree of separation. An air fluidization velocity of between 1.1 to 1.4U_{mf} was shown as the best performing velocity, which yielded the maximum ash differential between the top and bottom layers of the bed for all the particle size ranges tested.

For +2.0mm-5.6mm coal particles, low cumulative ash yields were obtained at high mass yields, however the ash yields increased for -2mm coal. Vibration and dense medium have, in some cases, enhanced the separation efficiency of the ADMFB. The -2.0mm particles experienced stronger particle-particle interactions as well as elevated levels of bubbling and back mixing than that of the +2.0mm particles, which explains the poor performance of the small particle sizes.

Keywords: ADMFB, coal beneficiation, dense medium, magnetite, air dense medium fluidization, minimum fluidization velocity, ash yield.

Introduction

Coal preparation plants most commonly employ wet separation processes to clean coal (Luo *et al.*, 2006). However, water reserves are unevenly distributed worldwide, with approximately two-thirds of the coal reserves located in the arid regions (Luo *et al.*, 2006). South Africa is an established coal-producing country that is subjected to periods of draught and it is therefore challenging to source reliable process water. Companies that supply coal need to ensure that the coal meets the specification for the thermal-, metallurgical- or export markets. To ensure that feedstocks adhere to these specifications, coal are washed using mainly wet dense medium processes. These processes are known to produce low ash products at high yields; however, it is water intensive and ends up with a wet product that is costly and difficult to dewater (Strydom *et al.*, 2016).

South Africa is a water-scarce country and as a result, government enforced water regulations have become more stringent. Slurry and coal fines associated with coal processing plants, are both difficult and expensive to dispose of and manage (De Korte, 2013). As a result, research has shifted to developing dry-based coal beneficiation processes that operate at high separations efficiencies (Luo *et al.*, 2006). Air dense medium fluidized beds (ADMFB) have grown popular in recent years and are known for producing comparatively high separation efficiencies with the added benefit of eliminating the use of water. An ADMFB is a dense gas-solid system that is characterized by a high bed density and micro-bubbles percolating from the bottom of the bed to the top (Wang *et al.*, 2015). The feed material is stratified according to density along the height of the bed resulting in the less dense material (clean coal) reporting to the top and more dense material (gangue) sinking to the bottom (Zhao *et al.*, 2010).

Background

Coal deposits in South Africa have been mined commercially since the late 1800's (Falcon & Ham, 1988; Peatfield, 2003). Over the past 15 years, the coal production in South African has hovered between 250 to 260 Mt/annum, peaking at 261 Mt in 2014 (CoM, 2016). Collectively, the Witbank, Highveld and Waterberg coalfields holds more than 70% of South Africa's coal reserves (Jeffrey, 2005). Typically, the ash yield of run-of-mine coal from these fields in South Africa ranges between 20-30$\%_{wt}$; which is expected to increase with the depletion of high quality seams (Dikgwatlhe, 2018). To negate the impurities, beneficiation of high ash coals is required. Both dry and wet beneficiation methods separate particles based on the difference in density between the high value particles and the impurities. This is achieved by developing a stable bed of specific density, using a medium like magnetite that will stratify all particles fed to the bed and hence separate it at a controlled density cut point.

The movement of particles inside the fluidized bed is based on its response to gravity and the resistance to buoyance caused by the upwards movement of an induced fluid (Wills & Napier-Munn, 2006). The particles with a relative density lower than that of the pseudo fluid will float and those that are heavier will sink (Wills & Napier-Munn, 2006). During recent years, an extensive number of research studies for developing and industrializing high separation efficiency dry beneficiation technology with minimal engineering and economic limitations have been ongoing. Substantial progress has been made with the implementation of an air dense medium fluidizing bed (ADMFB). During ADMFB operation, a steady, uniform air-solid suspension is established as separation medium (pseudo fluid). The density and volume fraction of the solids suspended in the air is used to control the density of this pseudo fluid. Results from various investigations on ADMFB are provided in Table 1 and it is apparent that the separation efficiency decreased according to a reduction in particle size. In particular, the study conducted by Luo *et al*. (2003) shows a significant increase in Ep value when the particle size is decreased, indicating the ADMFB separation performance suffers with particle size reduction.

Table 1: Summary of experimental investigations on ADMFB, adapted from Mohanta *et al.* (2011)

Investigators	Bed type and geometry (cm)	Gas velocity (cm/s)	Medium size (μm)	ρ_{medium} (g/cm^3)	H_{bed} (cm)	Coal particle size (mm)	Separation time (s)	Ep
Mak *et al*. (2008)	Cylindrical (20)	5.3-6.8	208	5.1	-	22.6-5.66	480	-
Luo *et al*. (2003)	Rectangular vibrated (200x8x20)	1.65	58.2	-	7.5	6-0.5	-	0.07
Choung *et al*. (2006)	Cylindrical (4)	23.5	300-150	5.2	2.6	5.66-3.35	120	0.03
Luo *et al*. (2008)	Rectangular vibrated (10x10x22)	1	74-43	4.35	7.5	6-0.5	20	0.07
Beeckmans *et al*.(1982)	Counter current cascade, rectangular (548x19x60.9)	21.4	170		18.5	3-1	-	0.21
Luo *et al*. (2003)	Magnetically stabilized Cylindrical (10)	-	74-43	4.2	-	6-3 3-1 1-0.5 0.5-0.3	-	0.05 0.06 0.09 0.22
Kozanoglu *et al*. (1993)	Cylindrical (15.2)	4.14	150-124	-	7	0.29-0.17	60	

Mohanta *et al*., (2011) conducted a comprehensive experimental study on the applicability of ADMFB for cleaning high-ash Indian thermal coal and it was concluded that the performance of the ADMFB separator was poor for the -13mm feed coal. This is because the upward drag force that is required by a coal particle is reduced as the particle size is decreased; therefore, the probability of a low-density, coarse particle to pass through the dense medium and reporting the gangue fraction is smaller than that of a finer particle of similar ash content (Mohanta *et al*., 2011).

Diedericks *et al.* (2020) studied the beneficiation of +5.6mm-13.2mm South African coal and was able to separate the coal successfully according to density using a verticle ADMFB. By discarding the bottom bed layer (cut point height of 50mm from the top of the bed), the best cumulative product was obtained and are provided in *Table 2*. These results were obtained for runs that had no dense medium (DM 0:1) and no added vibration (VD).

Table 2: Best cumulative results obtained from study

PSD (mm)	Ash yield ($\%_{wt}$)	CV (MJ/kg)	Density (g/cm^3)	Mass yield ($\%_{wt}$)
+11.2-13.2	14.2	24.1	1.56	31.9
+9.5-11.2	13.0	25.0	1.54	27.6
+8.0-9.5	14.9	23.7	1.56	34.2
+6.7-8.0	13.7	24.0	1.57	27.9
+5.6-6.7	17.6	22.7	1.64	28.9

It was found that particle size range affected the stratification achieved in the ADMFB, as larger particles produced a higher ash rejection compared to the smaller particle size ranges. A reduction in particle size range had a significant effect on the minimum fluidization velocity required by the bed, in that a lower minimum fluidization velocity was experienced. The lower velocity was because of the reduced buoyant force required for particle suspension (Diedericks *et al.,* 2020).

Experimental

Coal used

Coal from the number four seam in the Witbank coal fields in Mpumalanga, South Africa, was used during this investigation. The structure of the Witbank coalfield is uncomplicated, making it one of the most significant coal-mining regions in South Africa (Jeffrey *et al*., 2015). However, conventional collieries in this and related areas are expected to reach exhaustion in the near future. Bituminous thermal grade coal for both the local and export market is mined from seam four and therefore need to adhere to set specifications (Jeffrey, 2005).

The feed coal was used as received and prepared by air drying, crushing and screening it. According to a study conducted by Terblanche (2013), the particle surface moisture of coal required for effective fluidization should be about $5\%_{wt}$. The dried coal was spilt into the six particle size ranges listed in *Table 2* to obtain a representative sample for each particle size range. The proximate analysis and calorific value for each size interval were determined and the results are provided in *Table 2*.

Table 2: Average initial proximate and calorific values for each coal particle size range

Description	*PSD-01* (+0.5mm -1.0mm)	*PSD-02* (+1.0mm -2.0mm)	*PSD-03* (+2.0mm -2.8mm)	*PSD-04* (+2.8mm-4.0mm)	*PSD-05* (+4.0mm-4.75mm)	*PSD-06* (+4.75mm-5.6mm)	*Standards*
Moisture ($\%_{wt}$)	2.35	1.93	2.13	2.46	2.30	1.67	ACT-TPM-010 based on SANS 5925: 2007
Volatiles ($\%_{wt}$)	24.17	23.62	23.13	23.91	23.04	21.60	ACT-TPM-012 based on ISO 562: 2010
Ash yield ($\%_{wt}$)	27.46	29.16	30.72	30.79	29.99	32.59	ACT-TPM-011 based on ISO 1171: 2010
Fixed carbon ($\%_{wt}$)	46.02	45.29	44.02	42.85	43.66	44.14	By difference

CV (MJ/kg)	25.17	25.15	24.60	25.45	22.08	24.28	ACT-TPM-014 based on ISO 1928: 2009

A density profile of each particle size range was obtained by using the traditional method of densimetric analyses. During the process, zinc chloride was prepared at different densities and a sample was moved between these liquids to establish a density profile of that sample (SANS 7936:2010). For this study, the densities ranged from 1.3 to 1.8 g/cm^3 for the +1.0mm-5.6mm coal. In addition to the zinc chloride densimetric analyses, an organic solution was used to complete the densimetric analyses on the +0.5mm-1.0mm coal. White spirits and tetrachloroethylene were prepared at densities ranging from 1.30 to 1.60 g/cm^3 and solutions of tetrachloroethylene and tetrabromoethane ranging from 1.70 and 1.80 g/cm^3 were prepared. Figure 1 shows the cumulative float curves at the various prepared densities for each coal size interval.

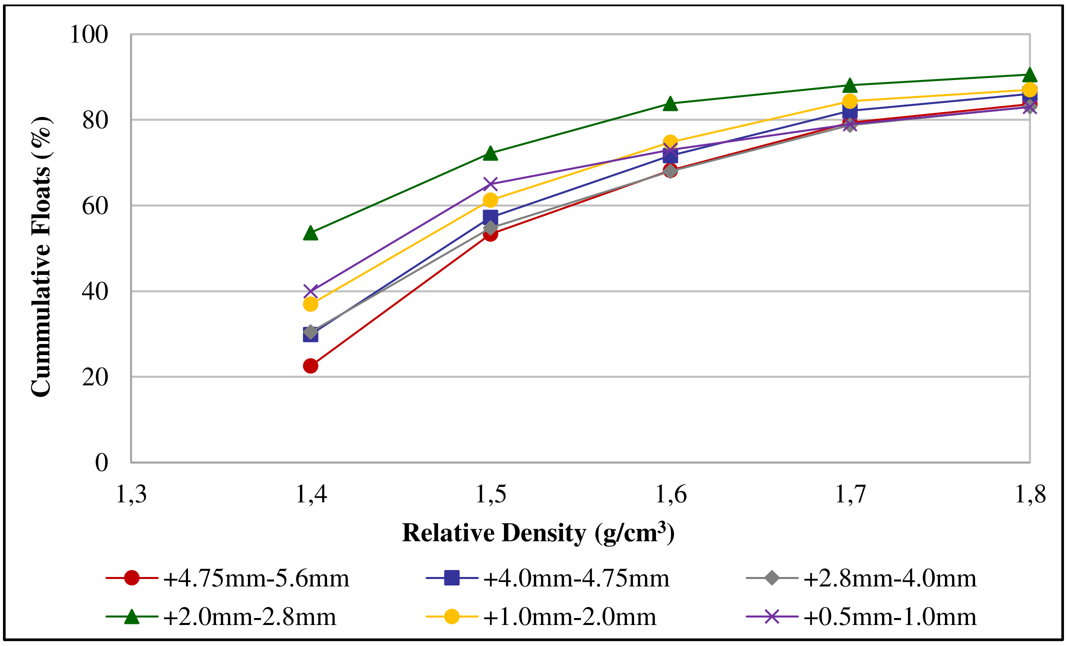

Figure 1: Density profiles for +0.5mm-5.6mm coal

Dense medium

Fine magnetite was selected as a dense medium for this study. The magnetite was prepared by air-drying it for 24-48 hours to obtain a moisture content below 5%$_{wt}$ and then screened to >300µm (d_{50} of 490µm). The true density of the magnetite was found by helium pycnometry

(SANS 1014:1985) to be 4.8 g/cm^3. The particle shape of the magnetite, as determined by SEM photography, was pyramidal.

Experimental setup

An inhouse constructed air dense medium fluidized bed was operated in batch mode for the experimental runs. A three-dimensional rendering of the setup is shown in *Figure 2*. Three conjoined sections can be identified from the unit and will hereafter be referred to as *(1)* an *airflow system, (2) fluidized bed and (3) dust control* section. The airflow *system* was composed of an air blower, airflow sensor and an air-distribution compartment. Air from the blower was distributed evenly across the bed by a distribution device placed at the bottom, consisting of a packed bed of ceramic balls inserted between two distribution plates and a 100µm wire mesh. Eight rectangular frames (0.3m x 0.3m x 0.05m), constructed from clear blue PVC, was stacked on top of each other to form the 0.4m high *fluidized bed section*. A ninth fluidized bed layer (0.3m x0.3m PVC layer), was added to the top of the preceding layers to allow enough space for the particles to fluidize. The bed was designed for the layers to be removable, allowing for variability in the cut-point along the height of the bed. At the top, a tapered trapezoidal extension (20° hopper angle) was added for *dust control* purposes. The trapezoidal extension was covered by a 100µm stainless steel wire mesh to keep the particles inside the bed during operation. A 0.18kW oscillating vibration motor was affixed against the external structure of the ADMFB unit, which was used to induce vibration to the bed.

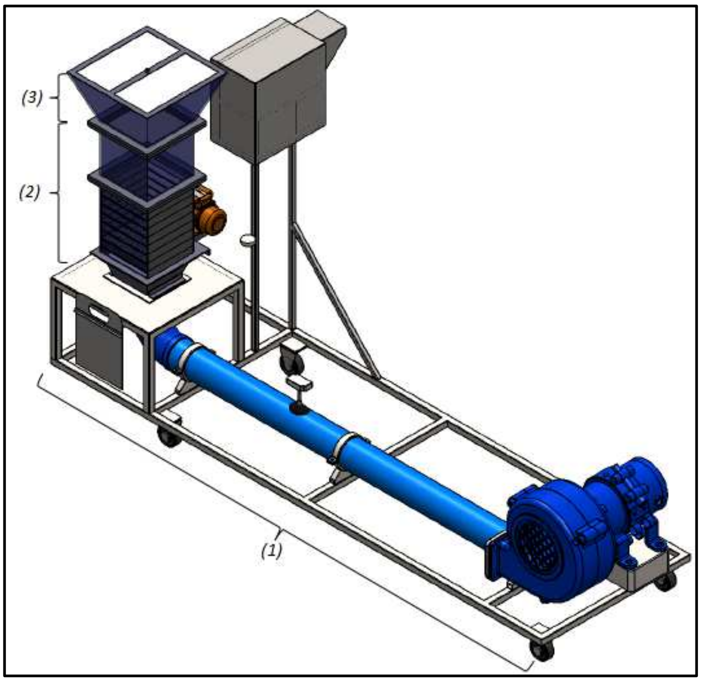

Figure 2: Three-dimensional illustration of the ADMFB with (1) airflow system, (2) fluidized bed system and (3) dust control section

The frequency and amplitude range of the vibration motor was 15Hz and 0.7-1.0mm, respectively. The fluidized bed section was loaded with a predefined amount of magnetite to coal. The load was then fluidized at 1.1 times the predetermined minimum fluidization velocity (U_{mf}), known as the operating velocity (U*). After 10 minutes of fluidization, the air flow was switched off, allowing the bed to settle. Samples were taken from the bed by isolating each layer and removing all the particles inside it. The content of each layer was coned and quartered until a representative sample for ash yield, calorific value and density analysis was obtained.

Results and discussion

Stratification of coal was quantified by analyzing the ash yield and calorific value (CV) for each sampled layer of the bed and comparing that with the feed coal. The change in these values along the bed height as compared to the feed, is an indication of the bed's ability to upgrade coal.

1. Influence of variables

Particle size

The effect of particle size on the performance of the ADMFB is shown by the performance curves of the bed depicted in *Figure 3.* The curves show the cumulative ash yield for the three different size ranges of +4.75mm-5.6mm, +2.8mm-4.0mm and +1.0mm-2.0mm, operating the bed with (VA) or without (VD) the vibration motor running. This was done in the absence of a dense medium to determine the behaviour of the pure coal particles in relation to one another. The solid line in *Figure 3* represents the general float-sink performance curve, which will serve as a benchmark for the best possible performance obtainable for the coal used in this study.

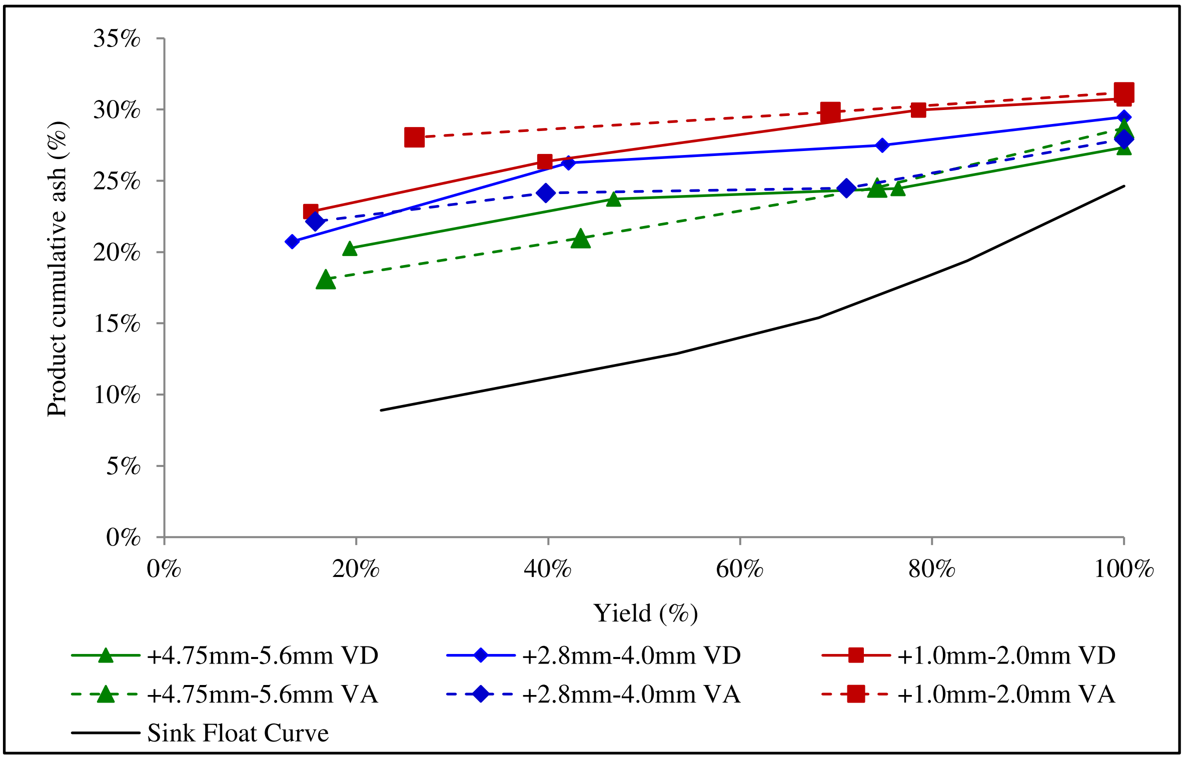

Figure 3: Comparison of bed performance curves for various PSD's (DM 0:1; VD and VA)

The results obtained for PSD-06 (+4.75mm-5.6mm), PSD-04 (+2.8mm-4.0mm) and PSD-02 (+1.0mm-2.0mm) followed the same general trend of the float-sink curve; however it is evident that the separation performance of the bed becomes poor when the particle size range decreases. Although the product cumulative ash of PSD-06 and PSD-04 varied considerably from the float-sink performance curve, a cumulative ash differential of 24% to 18.1% and 24% to 22.1% was obtained at a yield of 55%. At the same yield, the trend of PSD-02 varied considerably from the float-sink curve and evidently, no ash yield reduction was observed. The separation performance mechanism of the ADMFB is density related, but the influence of particle size range is such that in some cases it competes with the extent of segregation based on density to the point that it overpower the former. For larger sized particles, segregation occurs more vigilantly whereas the extent of segregation decreases for the smaller particles, typically those less than 2.8mm. This observation was confirmed by Yang *et al (*2015), who also found a low degree of segregation for -3mm sized particles in an ADMFB using Chinese coal.

Dense medium

The influence of addition of various feed mass ratios of dense medium to coal on the separation performance of the bed was investigated by comparing the coal ash yield values of the top and bottom bed layers to that of the feed coal after fluidization. The experimental runs without dense medium comprised of coal only and are referred to as DM 0:1. For a DM 1:1, 7.5kg magnetite and 7.5kg coal was mixed and fed to the bed, whereas for DM 2:1, 10kg magnetite and 5kg coal was mixed. The coal and magnetite sample were mixed thoroughly and fed to the bed. The feed mixture was fluidized at hundred and ten per cent of the predetermined minimum fluidization velocity for a period of 10 minutes, where after the airflow was switched off and the bed allowed to settle prior to sampling the different layers. The results for performance curves of +1.0mm-2.0mm (PSD-02) and +4.0mm-4.75mm (PSD-05), was compared to the theoretical float-sink performance curve (solid line) as shown in *Figure 4.*

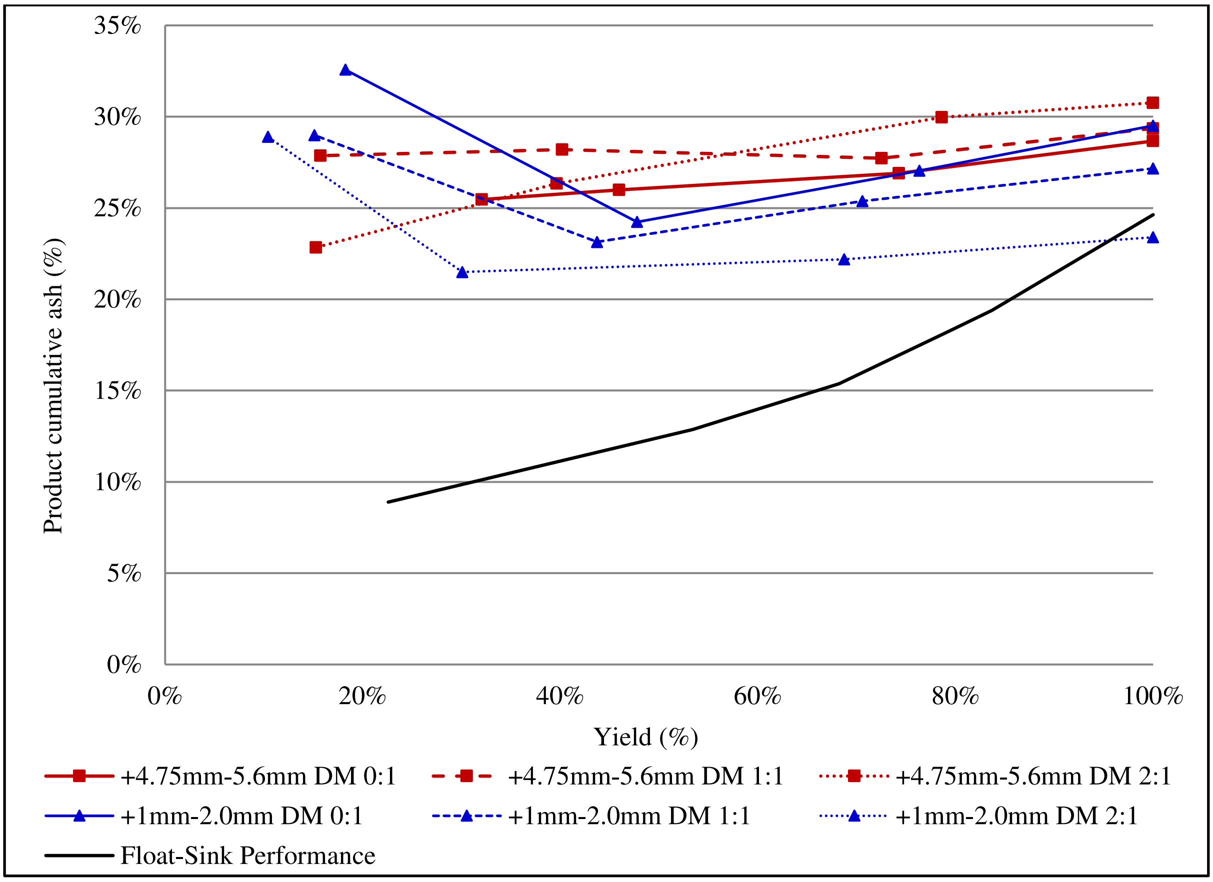

Figure 4: Comparison of bed performance for +1.0mm-2.0mm and +4.0mm-4.75mm without vibration

From *Figure 4* it is evident that the addition of dense medium yielded no significant improvement in the performance of the bed. The previously observed size influence was again clear by comparing the extreme sizes for each of the setups. Theoretically, the small dense medium particles should behave as a lubricant that, by moving in-between the coal particles, it assists the coal in moving around more freely in the bed. In actual practice, the movement of dense medium particles in the ADMFB occurs due to a disturbance created by the air penetrating the bed (Mohanta *et al*., 2015) and hence transporting the dense medium particles to form the pseudo fluid.

The curves displayed in *Figure 4* does not follow or fall within range of the float-sink performance curve, which is indicative of poor separation. By running the bed in batch mode whereby both the coal and dense medium is fed to the bed prior to fluidization, the dense media is not allowed to form a uniform suspension and therefore cannot direct coal to move through the bed based on its density. This results in the mixing of particles which hinders the segregation thereof.

Operating velocity

The operating air velocity of the ADMFB in relation to the minimum fluidization velocity was investigated by analysing the level of segregation of the coal particles subjected to various fluidization factors. These variable factors included the coal PSDs, coal to dense medium ratios, the addition and absence of vibration to the bed as well as the velocity of the fluidizing air. *Table 3* provides the ash yield results obtained for the feed coal, the top and bottom sampled layers as well as the ash difference between the feed coal and top layer and that of the top and bottom layer against the Fluidization factor. This factor is defined as the fraction of the minimum fluidization velocity (U_{mf}) at which the bed is operated. The results for PSD-03 (+2.0mm-2.8mm) are shown in Table 3.

Table 3: Influence fluidization factor on ADMFB performance

	Bed Layer	**Fluidization Factor (U*)**				
		1.05	**1.1**	**1.2**	**1.3**	**1.4**
Ash Yield (%$_{wt}$) DM 0:1	*Feed*	28.87	27.55	27.22	27.47	27.88
	Top	23.97	22.89	22.19	24.86	25.38
	Bottom	32.38	34.55	35.97	35.73	32.20
	Feed – Top	4.9	4.66	5.03	2.61	2.5
	Bottom - Top	8.41	11.66	13.78	10.87	6.82

For all the PSD's investigated, it was established that the velocity of the fluidization air has a definite effect on the stratification of coal within the bed. The results in *Table 3*, showed that an increase in the fluidization factor prompted an increase in the ash yield values of the bottom layer and led to an increased ash differential across the bed (*Bottom-Top*). Increasing the fluidization factor beyond this ideal point resulted in vigorous fluidization/back mixing of particles within the bed, which affected the ash yields of the layers.

He *et al.* (2016(a)) marked that a point of maximal segregation can be identified at the moment when the performance of the ADMFB would produce the best segregation depending on the coal particle size, dense medium, and vibration as well as other fluidization factors. Maximal segregation efficiency was obtained, for all the PSDs investigated by He *et al.* (2016(a)), at a fluidization factor of 1.6. It was decided to investigate the maximal segregation for the finer coal fractions of +1.0mm-2.0mm (PSD-02) and +2.0mm-2.8mm (PSD-03). *Figure 6* contains the results from the experimental runs compared to the results reported by He *et al.* (2016(a)), including the maximal point of segregation.

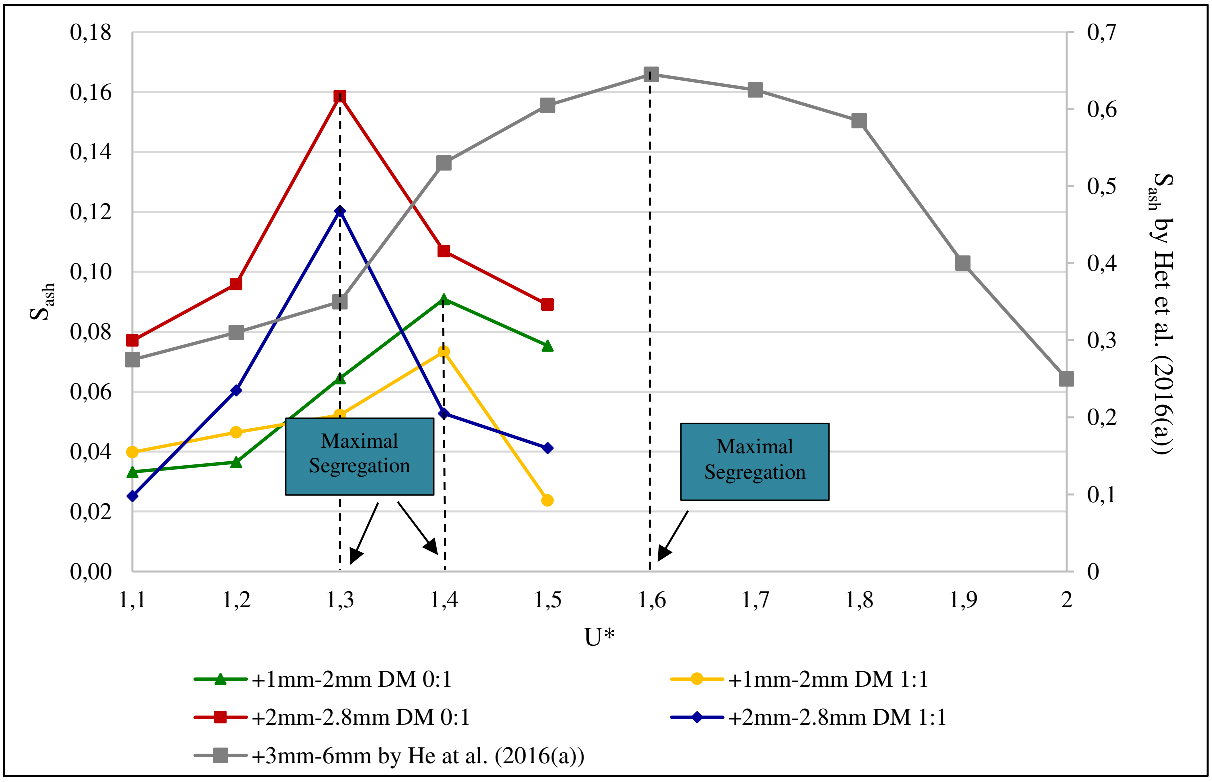

Figure 6: Degree of segregation for PSD-02 and PSD-03 compared to the segregation degree adapted from He *et al.* (2016(a)).

The maximal segregation point indicated in *Figure 6* represents the best ADMFB operating air velocity. The best operating velocity for the coal tested by He *et al.* (2016(a)) was found to be 1.6 U_{mf}. He *et al.* (2016(a)) showed that segregation occurred, with maximal segregation efficiency (S_{ash}) increasing from 0.65 to 0.75 for +3mm-6mm and +20mm-25mm, respectively. A similar trend was observed for the results obtained by this study, with the maximum segregation efficiency increasing from 0.09 to 0.15 for +1.0mm-2.0mm (PSD-02) and +2.0mm-2.8mm (PSD-03), respectively. Compared to the results of He *et al.* (2016(a)), the airflow velocity required for maximal segregation is significantly lower. This indicated that the segregation efficiency is reduced with a reduction in particle size.

At 1.1U_{mf} in *Figure 6*, more-dense and less-dense coals were slightly mixed, and therefore the density segregation of the coal particles was minimal. Initially, the air velocity was not sufficient to overcome the packed bed resistance caused by the coal and magnetite; however, the resistance was overcome when the air velocity was increased to 1.2U_{mf} and particle segregation started. When the airflow was increased, the segregation efficiency of the coal particles was improved as small bubble formation was enhanced, allowing additional space for coal particles to float or sink. Maximal segregation was obtained around at 1.3U_{mf} and 1.4U_{mf} for +2.0mm-2.8mm (PSD-03) and +1.0mm-2.0mm (PSD-02), respectively. However, when the airflow was increased beyond the point of maximal segregation, back mixing was initiated resulting in small bubbles joining to produce larger, undesirable bubbles. The increased velocity leads to bubbles bursting, resulting in back mixing of particles. This back mixing causes the finer particles to percolate to the bottom of the bed creating mixed bed density, hindering the stratification along the bed height. Upon further increasing the air velocity, back mixing in the bed was intensified.

Vibration frequency and amplitude

The separation performance of the ADMFB was expected to improve when vibration was added to the system because the particles are loosened, creating a more stable fluidized bed (Sahu *et al*., 2009). He *et el.* (2015) states that the effect of vibration on an ADMFB depends on the geometry of the bed. In order to select the appropriate frequency and amplitude values for operating of the bed, a study conducted by Yang *et al*. (2013) was consulted. The study states that frequencies ranging from 18 to 33Hz and amplitudes ranging from 2.6 to 3.8mm is ideal for the fluidization of +1mm-6mm coal particles. The upper and lower bounds of the vibration frequency and amplitude was identified by testing the combined influence of the amplitude and frequency.

A 0.18 kW oscillatory vibration motor is affixed to the bottom of the bed. The motor is a 2-pole BM 200/3 model OMB vibration motor that regulates the vibration induced into the system by adjusting the frequency. The maximum capability that can be achieved by the motor is 3000 revolutions per minute (RPM) at 50 Hz and an amplitude 10mm. The amplitudes investigated were 30%, 40% and 50% of the motor`s maximum amplitude. The lower bound frequency was identified as 20 Hz was, while the upper bound was found to be at a frequency of 22 Hz.

Figure 7 displays the results of two experimental runs in which the frequecy is varied and the ash yields are compared.

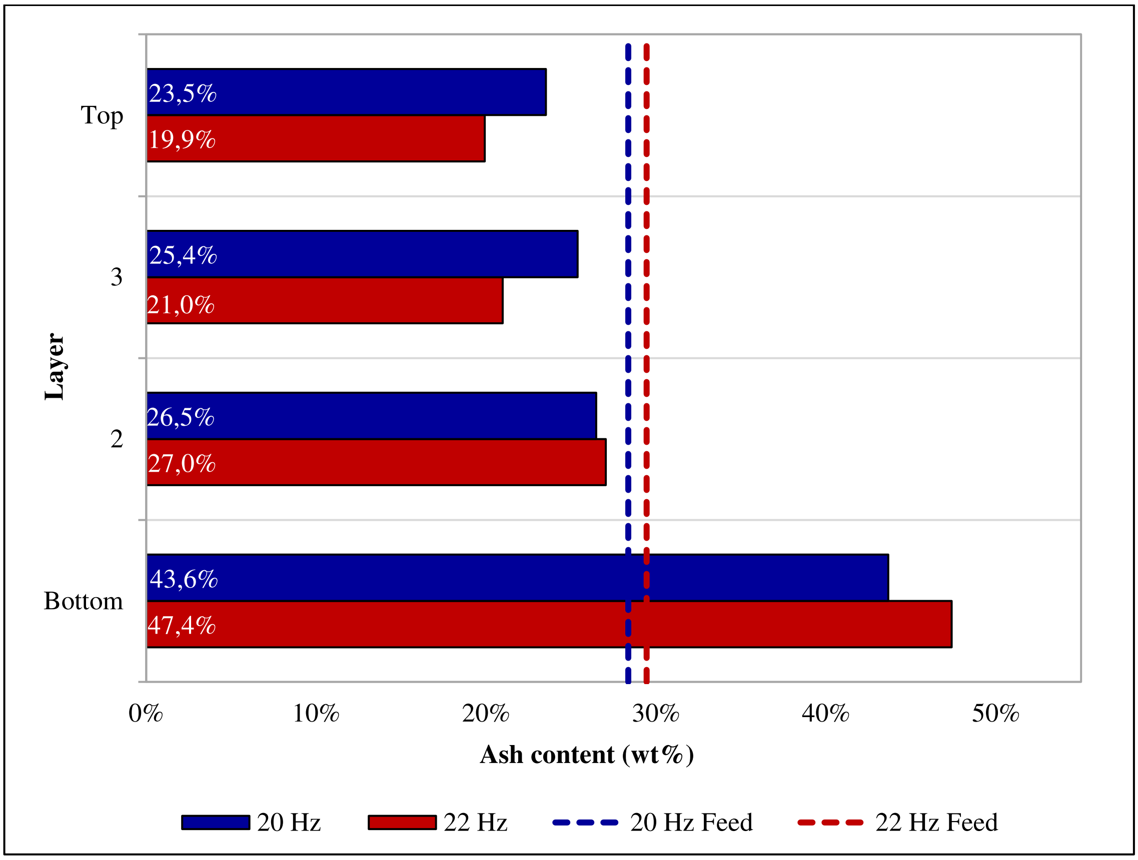

Figure 7: Ash analyses for +4.75-5.6mm particles and 30% amplitude and 20 Hz

The difference in ash values between the feed and top layer of the 22 Hz run, shown in *Figure 7,* is about 10%$_{wt}$, whereas the top and bottom layers yielded a differential of 27.5%$_{wt}$. The difference in ash values between the top and bottom layers of the bed improved when the frequency of the bed is increased, which is verified by the findings of Sahu *et al*. (2009). The two bottom layers for both runs shown in Figure 7 indicates that the stratification and amount of dense material reporting to these layers are dependent on the feed coal values. A study conducted by Diedericks *et al.* (2020) also showed that the separation performance when adding vibration to the ADMFB was dependent on the particle stratification in the two bottom layers of the bed. No major improvement in the results of the various bed layers was seen when vibration was added to the system, with the exception of an increase in the ash values in the bottom bed layer. However, this may be due to the respective feed ash values of the coal (Diedericks *et al*., 2020).

To assess the influence of vibration amplitude added to the system, the vibration frequency was maintained at 21.97 Hz and the amplitude was varied between 30%, 40% and 50% of the motor's maximum capabilities (motor weights). It should be noted that the percentage amplitude refers to the capability of the vibratory motor. The influence of amplitude is shown by the ash yields obtained for +4.75mm-5.6mm coal in *Figure 8*.

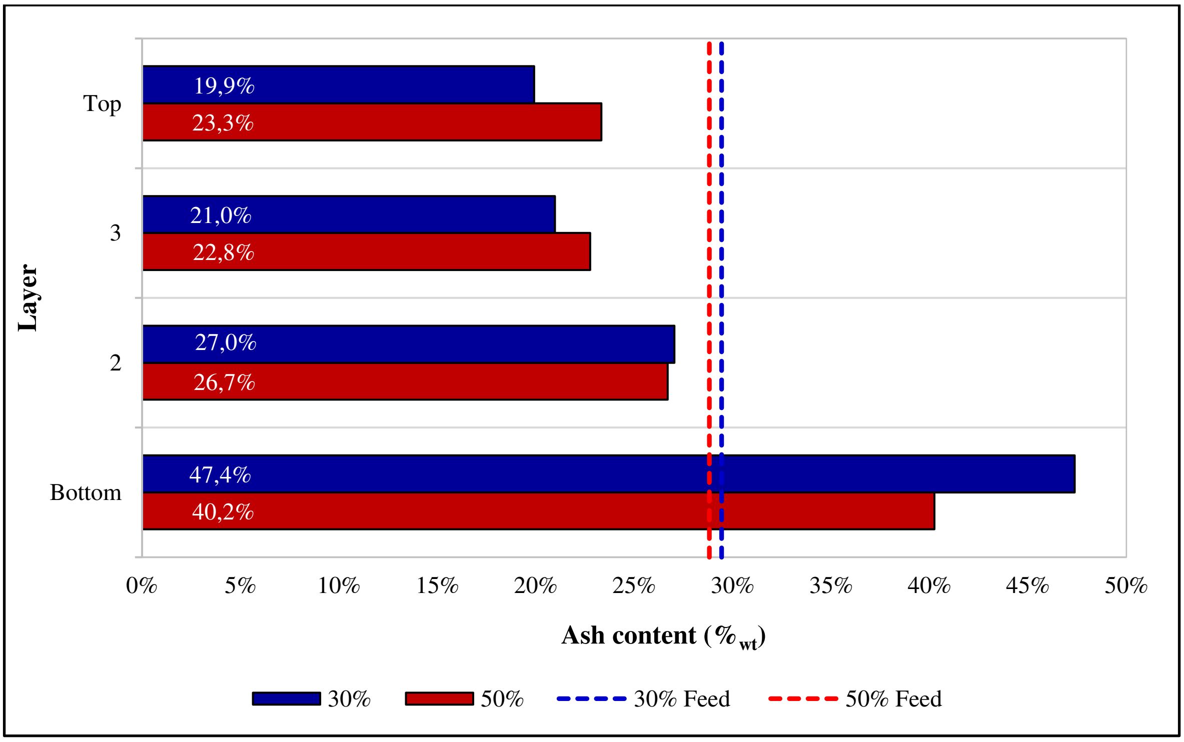

Figure 8: Ash analyses for +4.75-5.6mm particles at 21.97 Hz

The difference is apparent in the differentials of the beds shown in *Figure 8*; where the ash yield at 30% amplitude yields a 27%$_{wt}$ differential and the 50% amplitude yields a 17%$_{wt}$ differential. This trend is observed for all the experimental runs tested and indicates that the separation performance of the bed decreases with an increase in the vibration amplitude. This is in accordance with the results found by He *et al*. (2015), who remarked that the formation of uniform micro-bubbles is hindered by elevated vibration amplitudes, which causes the separation performance to dwindle.

Furthermore, it was concluded from the experimental results that the minimum fluidization velocity (U_{mf}) was lowered when vibration was added to the system for all the particle size ranges. Studies conducted by McLaren *et al*. (2021) and He *et al*. (2015) made a similar conclusion that adding vibration to gas-solid fluidized beds enables fluidization of particles that are cohesive, reduce the minimum fluidization velocity (U_{mf}) of the particles as well as increase the fluidized bed stability.

Conclusion

The separation performance of solid phase bed material, at various particle size ranges (-5.6mm+0.5mm coal particles), in an air dense medium fluidized bed, were evaluated during this study. To obtain the best operating conditions, the experiments were conducted under similar ambient conditions in the presence of varying parameters. Six coal particle size ranges, three dense media to coal ratios and the addition of vibration was tested to identify the best operating conditions. Adequate results were obtained for larger particle size ranges down to and including +2.0mm-2.8mm coal particles, after which the separation performance decreased significantly. Density stratification was irregular and not obvious for coal particles below 2.0mm and maintaining a consistent fluidization state also proved to be challenging, especially when dense medium was added.

The coal particles separated vertically along the bed height because of differences in particle and bed density, while particle size proved to have a notable influence on the degree of separation. An air fluidization velocity of between 1.1 to 1.4U_{mf} was shown as the best performing velocity, which yielded the maximum ash differential between the top and bottom layers of the bed for all the particle size ranges tested. A summary of the lowest ash yield and highest mass yields obtained for +0.5mm-5.6mm is presented in *Table 4*.

Table 4: Cumulative ash yield and mass yield at a 50mm cut-point height (discarding only the bottom layer)

Particle size	Dense medium	Vibration	U_{mf} (m/s)	Feed Ash ($\%_{wt}$)	Cumulative Ash yield ($\%_{wt}$)	Cumulative Mass yield ($\%_{wt}$)
+4.75mm-5.6mm	0:1	Yes		34.8	18.1	74.3
+4.0mm-4.75mm	2:1	No		28.9	21.5	68.7
+2.8mm-4.0mm	1:1	No		31.8	20.7	74.8
+2.0mm-2.8mm	2:1	No		30.9	20.9	77.2
+1.0mm-2.0mm	0:1	No		29.9	25.5	74.3
+0.5mm-1mm	0:1	No		27.5	27.3	75.1

For +2.0mm-5.6mm coal particle sizes shown in *Table 4*, low cumulative ash yields were obtained at high mass yields, however the ash yields increased for coal smaller than 2mm. Vibration and dense medium have, in some cases, enhanced the separation efficiency of the ADMFB. The -2.0mm particles experienced stronger particle-particle interactions as well as elevated levels of bubbling and back mixing than that of the +2.0mm particles, which explains the poor performance of the small particle sizes.

References

Beeckmans, J. M., M. Goransson, and S. G. Buthce. 1982. Coal cleaning by counter-current fluidized cascade. *Canadian Mining and Metallurgical Bulletin,* 75: 184–191

Choung, J., C. Mak, and Z. Xu. 2006. Fine coal beneficiation using an air dense medium fluidized bed. *Coal Preparation*, 26: 1–15.

De Korte, G. J. 2013. Dry processing versus dense medium processing for preparing thermal coal. *CSIR Report, p.* 1-10.

Diedericks, E.S., Le Roux, M., Campbell, Q.P., and Hughes, N. 2020. Beneficiation of small South African coal using an air dense medium fluidized bed. *International Journal of Coal Preparation and Utilization,* 40: 1-14.

Dikgwatlhe, P. 2018. Coal as a strategic resource in South Africa. *Society of Mining Professors (SOMP) in collaboration with the Mining Engineering Education South Africa (MEESA) and The South African Institute of Mining and Metallurgy (SAIMM), p.* 1-7.

Eberhard, A. 2012. Overview of South African coal sector. *Coal International.*

Falcon, R. & Ham, A.J. 1988. The characteristics of South African coals. *Journal of the South African Institute of Mining and Metallurgy*, 88(5): 145–161

He, J., Tan, M., Zhao, Y., Zhu, R. & Duan, C. 2016 (a). Density-based segregation/separation performances of dense medium gas–solid fluidized bed separator (DMFBS) for coal cleaning and upgrading. *Journal of the Taiwan Institute of Chemical Engineers,* 59: 252–261.

International Energy Agency (IEA). 2011. Power generation from coal. https://www.iea.org/publications/freepublications/publication/Power_Generation_from_Coal 2011.pdf (Date of access: 15 March 2019).

Jeffrey, L. S. 2005. Characterization of coal resources of South Africa. *The Journal of the Southern African Institute of Mining and Metallurgy, 105*: 95–102.

Jeffrey, L. S., Henry, G. & McGill, J. 2015. Introduction into South African coal mining and exploration. *CSIR. http://hdl.handle.net/10204/8153*. (Date of access: 17 June 2019).

Kozanoglu, B., E. K. Levy, T. Ulge, R. Sahan, and T. Schmitt. 1993. Prediction of rates of coal cleaning in a fluidized bed of magnetite. *AIChE Symposium Series*, 89: 150–161.

Luo, Z., Y. Zhao, Q. Chen, X. Tao, and M. Fan. 2003. Separation lower limit in a magnetically gas-solid two-phase fluidized bed. *Fuel Processing Technology,* 85: 173–178.

Luo, Z., Zhao, Y., Fan, M., Tao, X., & Chen, Q. 2006. Density calculation of compound medium solids fluidized bed for coal separation. *The Journal of the Southern African Institute of Mining and Metallurgy, 106*: 749–752.

Luo, Z., M. Fan, Y. Zhao, X. Tao, Q. Chen, and Z. Chen. 2008. Density-dependent separation of dry fine coal in a vibrated fluidized bed. *Powder Technology,* 187: 119–123.

Mak, C., J. Choung, R. Beauchamp, D. J. A. Kelly, and Z. Xu. 2008. Potential of air dense medium fluidized bed separation of mineral matter for mercury rejection from Alberta subbituminous coal. *Industrial and Engineering Chemistry Fundamentals,* pp.115–132.

McLaren, C.P., Metzger, J., Boyce, C. M., and Müller, C.R. 2021. Reduction in minimum fluidization velocity and minimum bubbling velocity in gas-solid fluidized beds due to vibration. *Powder Technology,* pp.1–24.

Mohanta, S., Daram, A.B., Chakraborty, S., & Meikap, B.C. 2011. Applicability of the air dense medium fluidized bed separator for cleaning high-ash Indian thermal coals: An experimental study. *South African Journal of Chemical Engineering, Volume 16, Issue 1:* 50–62.

Mohanta, S., Daram, A.B., Chakraborty, S., & Meikap, B.C. 2013. Air dense medium fluidized bed for dry beneficiation of coal: Technological Challenges for future. *Particulate Science and Technology, Volume 31, Issue 1:* 16–27.

Mohanta, S. & Meikap, B.C. 2015. Influence of medium particle size on the separation performance of an air dense medium fluidized bed separator for coal cleaning. *The Journal of the Southern African Institute of Mining and Metallurgy, Volume 115, Issue 8:* 761–766.

Peatfield, D. 2003. Coal and coal preparation in South Africa - A 2002 review. *The Journal of the Southern African Institute of Mining and Metallurgy, Volume 103, Issue 6:* 355–372.

Sahu, A. K., Biswal, S. K. & Parida, A., 2009. Development of Air DenseMedium Fluidized Bed Technology for Dry Beneficiation of Coal – A Review. *International Journal of Coal Preparation and Utilization*, 29(4), pp. 216-241.

SANEDI. 2011. South African Coal Roadmap. Retrieved from http://www.fossilfuel.co.za/initiatives2013/SACRMroadmap.pdf (Date of access: 20 March 19.)

Strydom, C.A., Campbell, Q. P., Le Roux, M., & Du Preez, S.M. (2016). Validation of Using a Modified BET Model to Predict the Moisture Adsorption Behavior of Bituminous Coal, *International Journal of Coal Preparation and Utilization*, 36:1, 28-43

Terblanche, A., 2013. Dry beneficiation of fine coal using a fluidized dense medium bed, Potchefstroom: North West University, School of Chemical and Minerals Engineering .

Van der Walt. 1984. Lecture notes on coal washability.

Wills, B. A. & Napier-Munn, T., 2006. Mineral Processing Technology. Seventh ed. Burlington: Elsevier Science Ltd.

Wang, Q. et al., 2015. Numerical study of particle segregation in a coal beneficiation fluidized bed by a TFM–DEM hybrid model: Influence of coal particle size and density. Chemical Engineering Journal, Volume 110, pp. 219-224

Yang, X., Zhao, Y., Zhou, E., Luo, Z., Fu, Z., Dong, L. & Jiang, H. 2015. Kinematic properties and beneficiation performance of fine coal in a continuous vibrated gas-fluidized bed separator. Fuel, 162: 281–287.

Zhao, Y. et al., 2010a. The effect of feed-coal particle size on the separating characteristics of a gas-solid fluidized bed. *The Journal of the Southern African Institute of Mining and Metallurgy*, Volume 260, pp. 240-257.

Availability of data and materials

All materials and data is available upon request subject to the North West University policies.

Competing interests

No competing interests.

Funding

SACPS - South African Coal Processing Society

NWU - North West University of Potchefstroom

Authors' contributions

M le Roux for assistance, guidance as promotor in my PhD studies.

QP Campbell for assistance, guidance as co- promotor in my PhD studies.

Acknowledgements

- SACPS – South African Coal Processing Society for funding to further the research.
- M le Roux for assistance, guidance as promotor in my PhD studies.
- QP Campbell for assistance, guidance as co- promotor in my PhD studies.
- North West University of Potchefstroom Laboratory personnel for assistance in analysis of samples.
- North West University of Potchefstroom Workshop personnel for assistance with building, modifying and repairing the ADMFB.