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A Feasibility Study Evaluating the Efficiency of Fine Coal Washing Using Gravity Separation Methods

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Abstract

Coal mining and washing activities in South Africa often lead to the generation of fine and ultra-fine coal which is in most cases discarded due to high handling and transportation costs. Studies conducted revealed that a large quantity of these fines have market acceptable calorific values and lower ash contents. In order to reduce fines discarded, processes have been developed to re-mine and process the fine coal discards with the aim of improving the calorific value, adding them to coarse washed coal to increase the yield as well as pelletizing the fines so as to meet the market specifications in terms of size.

The goal of this study was to evaluate the efficiency of fine coal washing using gravity separation methods and comparing the products thereof to the market specifications with regards to the calorific value and the ash content. Coal fines from the No.4 lower seam of the Witbank coalfield in South Africa resulting from a dry coal sorting plant were subjected to a double-stage spiral test work, heavy liquid separation and reflux classifier test work respectively.

The reflux classifier achieved products with low ash content and an increased calorific value, at high mass yields. At higher fluidization water flowrate, the reflux classifier performance was superior to that of the spirals with products of lower ash content and higher calorific value. At low cut point densities, heavy liquid separation yielded the cleanest products with very low ash content but at much lower mass yields. As the density increased, the mass yields increased with the ash content while the calorific value decreased. Most of the products from the different processes met most of the local industries' specifications but none of them met the export market as well as the gold and uranium industry specifications due to the high ash content.

Keywords

Fine coal processing; beneficiation; gravity separation; spirals; reflux classifier

1. Introduction

Coal, just like other minerals is mined and processed in order to meet different market specifications. Due to the fact that it is relatively friable, generation of fine and ultrafine fractions during these value chain processes is expected. In most cases these fractions are not favoured by the user, consequently they are discarded. Their moisture content is in most cases high, resulting in low calorific values and difficulty to handle. Moreover most collieries find it unprofitable to process and handle these fines and ultra-fine slurries due to the high handling and transportation costs as well as environmental concerns subsequently leading to the majority having to discard them (Coaltech, 2014).

The South African Department of Energy (DOE) assessed the generation of coal discards to be 60 million tons per annum, which is estimated to have already accumulated to more than 1 billion tons (DOE, 2016). Technologies have been evolving to process these fines effectively and efficiently to a saleable product. Their recovery not only would increase the overall yield, and hence the mine revenue, but would also lessen the environmental concerns and the diminishing vacant land for mine waste disposal. Moreover, such treatment would lead to better utilization of wastes. This paper serves to report on test work conducted on the -6mm coal sample that was sourced from a flagship project at a South African mine where dry coal from the No.4 lower seam of the Witbank coalfield is sorted and the fines generated are discarded. Different gravity separation processes were compared to see which one will produce a cleaner product at high mass yields.

1.1. Characteristics of coal discards

Run-of-mine (ROM) coal contains varying amounts of fine and ultra-fine coal, which seems to increase with an increase of mechanised mining usage. Fine coal is generally less than 0.5 mm and greater than 150 microns, whereas ultra-fine coal is less than 150 microns, normally in the form of a slurry, (Hand, 2000). Around 21-24% of the 312 Mtpa of the ROM coal in South Africa in 2007 was reported as coal discards of which 4-6% was in the form of ultra-fine slurry (Coaltech, 2011). Typical characteristics of ROM coal, coal discards and ultra-fine slurry (Coaltech, 2011; DMR, 2001) are presented in Table 1 below.

Table 1. Table 1.Typical characteristics of ROM coal, coal discards andultra-fine slurry (Source: (a) Coaltech, 2011; (b) & (c) DMR, 2001)

	ROM coal (a)	Discards (b)	Ultra-fine slurry (c)
Calorific value (MJ/kg)	16-21	11 - 20	20 - 27
Ash %	20-40	30 - 60	10 - 50

The characteristics of the major discard dumps were in the ranges of of 11-20 MJ/kg calorific value (CV) and 30-60% ash content respectively. The ultra-fine slurry were found to be of the same quality as the ROM coal and can be beneficiated with effective processes to generate an extra income. Other studies also alluded to the fact that the quality of ultra-fine coal is generally equivalent to that of the ROM coal, and at some mines the quality is even higher, (Reddick et al., 2007).

2. Fine coal processing/ beneficiation

Various methods for fine coal beneficiation have been employed but dense media separation and spirals have been the most commonly used technologies whereas flotation has mostly been used for the ultra-fine coal (Coaltech, 2011).

2.1. Dense media separation

Horsfall et al, 1986 mentioned that dense-medium cyclones were found to be a highly efficient method for the processing of coal between 0.5mm and 150 μm. Even fines down to 75 μm can be treated, but separation from magnetite medium in ultrafine sizes is difficult. However, the process does have a high degree of selectivity and enables low-ash coal to be produced from fines at economic recoveries (Horsfall et al, 1986).

Dense-medium cyclone cleaning of fine coal was used in South Africa at Greenside Colliery to produce a low-ash coal containing 7% ash and a middling fraction containing 16% ash (De Korte, 2002). The process was found to be more expensive compared to spiral separation or other techniques for fine coal beneficiation though it has the possibility of cleaning fine coal from the No. 4 Seam of the Witbank coalfield , which is generally of poor quality due to the higher ash and inertinite contents (Bergh, 2011).

2.2. Spirals

Coal fines in the ranges of <1mm and 0.1 mm in South Africa are normally treated in spiral concentrators (Coaltech, 2011). At these ranges, spirals are said to offer a simple, cost efficient and reasonably efficient separation, and the lower size at which beneficiation can be conducted is about 100 μm (Coaltech,2011; Horsfall et al, 1986). Though spirals are normally capable of yielding products of export grade quality, especially with fine coal fraction from the No. 2 seam of the Witbank coalfield which contains some of the best quality coal, they were found to be incapable of yielding a fine coal product of a sufficiently high quality from the No. 4 seam of the same coalfield which is of lower quality having predominantly dull to dull lustrous coal (De Korte, 2002; Jeffrey, 2005).

2.3. Froth flotation

Coal flotability and surface properties strongly depend on the coal rank. Very hydrophobic bituminous coals float well using only a simple frother such as methyl isobutyl carbinol (MIBC) or different frothers. In their paper, Horsfall et al, 1986 mentioned that coals with a high percentage of near density material (material of a relative density within 0.1 unit of the separation density) proved difficult to treat since the flotation process finds the near density material difficult to accept or reject precisely as float products.

Original flotation testwork around the 1980s revealed the imense difficulty to float Witbank coal fines because of the type of the surface properties. MIBC was utilized as a frother and power paraffin as a collector at the time and the testwork was unsuccessful commonly yielding low products. Consequently ultra-fine coal by flotation process was deemed not economically reasonable (N. Opperman et al, 2002).

Later studies proved that changing of the reagents improved the process by increasing the recoveries. In their study Opperman et al indicated that testwork at Goedehoop Colliery showed that froth flotation can be successfully employed to wash –150 microns fine coal. The process is the viable beneficiation process for ultra-fine coal though it is expensive since the product market value is negatively affected by its relatively high moisture content.

2.4. Reflux classifier

Production of the higher grade coal required processing of poor quality coal fines (-0.5+0.15 mm) at finer cuts of 1.30-1.50 relative density (RD). This was not easily attainable with spiral concentrators but was accomplished with a reflux classifier (Bergh et al, 2013). Two product streams ($-210 + 100$ μm), coking coal with vitrinite concentration between 28–84% and 20–75% for the thermal coal were attained by changing the fluidizing water flow rate. Light products high in the vitrinite and lower in the ash contents were achieved (Tran et al, 2016).

Water-only density fractionation of South African coal fines could also be achieved with the reflux classifier and the results were similar to the results from the $ZnCl_2$ float-sink data for narrow size ranges between -850+500 μm, (K.E Rakgase, 2012). In other studies, it was confirmed that higher density cuts could be achieved, and any number of density intervals could be prepared. It was also confirmed that separation in the reflux classifier was partially independent of particle size but it operated well for narrow size distributions above 355 μm, (Campbell et al, 2015) .

3. Experimental procedures

3.1. Material

The -6mm coal sample was crushed and screened to produce the -1.7mm+212μm which was then blended and split into various subsamples for head chemical analysis, washability test or heavy liquid separation (HLS), spiral concentration and reflux classifier testwork. The testwork on the fines was undertaken according to the diagrams given in Figure 1 below.

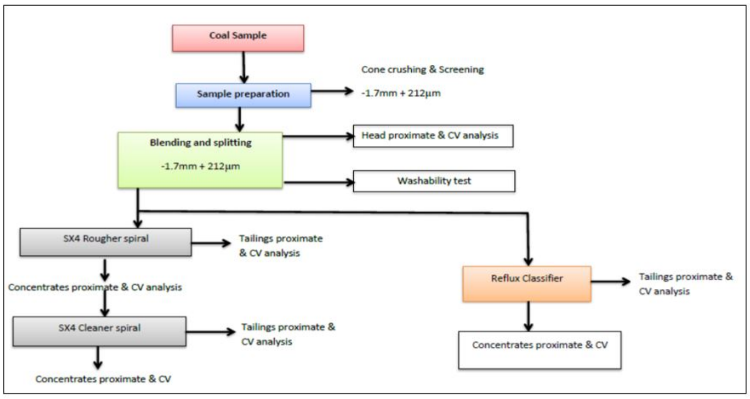

Figure 1. Flowsheetfor work conducted

A head sample was analyzed for proximate and CV analysis. The CV was found to be 22.18 MJ/kg and an ash content of 25.93%. These were in the ranges stated in Table 1 for ultra-fine slurry. The relative density of the sample was found to be 1.60 as measured using a pycnometer.

3.2. Rougher spiral testwork on -1.7mm+212μm material

The screened -1.7mm+212μm material was subjected to spiral testwork with the aim of reducing the ash content and increasing the calorific value. Separation in this instance is based on the specific gravity of the particles. Heavier particles progress to the inner profile while the lighter ones progress to the outer profile of the channel along with most of the water and the slimes. Different product streams are collected at the bottom of the spiral through their set outlets. Table 2 shows the conditions for the test work.

Table 2. Rougherspiral test conditions

Specific gravity of the solids	1.60
Mass of the sample (kg)	30.00
% solids	30.00
Solids feedrate (t/h)	1.50
Slurry feedrate (t/h)	5.00

As soon as the steady state was reached, timed samples of seven streams which comprised of three concentrate streams, a middling stream and three tailing streams were collected. The timed samples were weighed wet, sun-dried and then sub-sampled for chemical analysis for proximate analysis as well as calorific value.

3.3. Cleaner spiral test work on rougher spiral concentrates

Upon review of the analysis results of the rougher spiral products, it was decided that the three concentrate streams be subjected on a cleaner spiral to upgrade the product further. The aim of the cleaner spiral was to check if a product of a better quality can be achieved at high recoveries. Table 3 shows the conditions for the test work.

Table 3. Cleanerspiral test conditions

Specific gravity of the solids	1.60
Mass of the sample (kg)	17.70
% solids	20.00
Solids feedrate (t/h)	1.90
Slurry feedrate (t/h)	9.70

As soon as the steady state was reached, same process as in the rougher spiral for collection, preparation and sub-sampling for analysis was conducted.

3.4. Heavy Liquid Separation (HLS) Testwork on the -1.7mm+212μm material

A representative 2kg subsample of -1.7mm+212μm was subjected to heavy liquid separation testwork to obtain a washability curve and to also assess presence of any near density material. HLS is a laboratory scale density fractionation method, using heavy liquid to separate heavies (sinks) from lights (floats) in order to determine the cutpoint density at which effective separation can occur. Tests were done sequentially at densities of 1.30 g/cm^3 to 2.10 g/cm^3 and increments of 0.10 to characterize the coal sample at different densities. Proximate and calorific value analysis was conducted on nine product streams.

3.5. Reflux classifier testwork on -1.7mm+212μm material

A 75kg screened sample of -1.7mm+212μm was subjected to five reflux classifier testworks at varying conditions. Separation of particles in the reflux classifier is based on their size and density. The REFLUX^{TM} Classifier (RC) is an innovative device offering advantages in both gravity separation and particle size classification (Amarieri et al., 2014; Nguyentranlum and Galvin, 2004). According to Amarieri et al (2014), the device combines a conventional fluidized bed with sets of parallel inclined plates, as shown in Figure 2. Feed slurry enters below the plates while fluidization water is introduced through a distribution plate in the base. The slurry feed moves downwards into the vessel, forming a bed of particles that is fluidized from below. High density particles settle into the lower portion of the bed, and light and fine particles are transported upward, with the majority flow towards the lamellae. The high hydraulic load carries the suspension up into the parallel inclined lamella plates. Here slower settling particles, which are unable to settle against the fluidization water, emerge through the plates and report to the overflow. Faster settling particles drop out of suspension and onto the plates before sliding back to the zone below. When the density of the fluidized bed exceeds the set-point value, a valve opens near the base of the unit and discharges some of the denser particles as an underflow stream.

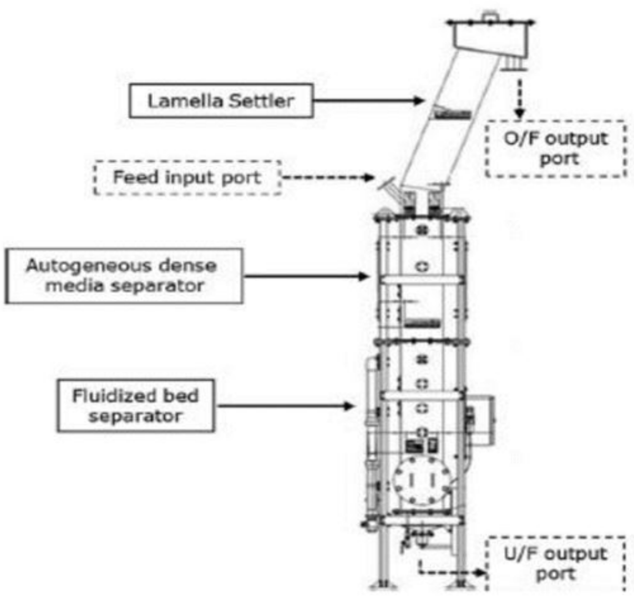

Figure 2. Schematic diagram of a Reflux Classifier (Amarieri et al., 2014).

To understand the effect fluidising water flowrate on the final product, four tests were conducted at 30% solids slurry, dry solids feedrate of 61 kg/hr and a bed density of 1350 kg/m^3. The fluidising water flowrate was varied between 250 l/hr and 300 l/hr at increaments of 50 l/hr. A separate test was conducted at bed density of 1200 kg/m^3

and fluidization water of 400l/hr. The objective of the test was to assess whether lower bed density and increased fluidization water can improve product grade.

4. Results and discussions

Three cleaner product streams with a 77% cumulative mass yield, 20.25% cumulative ash content and an average calorific value of 25.52 MJ/kg were achieved on a rougher spiral (Table 4).

Table 4. Rougher spiral test results

Stream names	Cumm mass %	Cumm Ash grade %	CV (MJ/kg)
Conc 1	45.70	19.40	25.34
Conc 2	64.21	19.23	25.11
Conc 3	77.00	20.25	24.52
Midds	84.23	21.41	23.84
Tails 1	96.61	24.17	22.70
Tails 2	100.00	24.17	22.26

They were then further upgraded on the cleaner spiral to yield three cleaner product streams with 75.2% cumulative mass yield, 19.77% cumulative ash content and a calorific value of 24.22 MJ/kg (Table 5). In both the rougher and the cleaner spiral, the ash content increased as the cumulative mass increased. However the cleaner spiral had low ash and high CV streams as compared to the rougher spiral.

Table 5. Cleaner spiral test results

Stream names	Cumm mass %	Cumm Ash grade %	CV (MJ/kg)
Conc 1	18.05	17.40	25.90
Conc 2	52.95	18.78	24.52
Conc 3	75.21	19.77	24.22
Midds	85.88	20.23	24.04
Tails 1	96.77	21.03	23.71
Tails 2	100.00	21.33	23.60

Coal is a low density mineral, consequently when it is subjected to gravity separation,the cleaner product is collected as the lighter fraction at low cutpoint densities. HLS showed to be capable of achieving low ash content products though at very low mass yields. A product with a 3.10% mass yield, an ash content and a calorific value of 2.90% and 30.59 MJ/kg respectively was obtained at a cutpoint density of -1.2+1.3 g/cm^3 where more than 99% ash was rejected. As the cutpoint densities increased due to the increased separating liquid density, the product mass yield increased along with the ash content (Table 6). A 57.61% cumulative mass yield was achieved at cutpoint density of -1.5+1.6 g/cm^3 with a product having an 11.84% ash content and a CV of 26.11 MJ/kg. More than 70% of the ash was rejected in this density range.

The reflux classifier seemed to be the best option as compared to the rougher and cleaner spiral . At a maximum mass yield of 73%, the ash content of the product was 15.86% at a calorific value of 24.63 MJ/kg (Table 7). Most ash was rejected at a 250L/hr flowrate, though the product yield was very low at 39.70% but the CV was at a maximum 24.88 MJ/kg with a 15.15% ash content.

Table 6. HLS test results

Cut point density	Cumm mass %	Cumm Ash grade %	CV (MJ/kg)
-1.2+1.3	3.10	2.90	30.59
-1.3+1.4	13.69	5.75	29.19

Continued on next page

Table 6 continued

-1.4+1.5	29.34	8.23	27.79
-1.5+1.6	57.61	11.84	26.11
-1.6+1.7	72.91	14.37	24.95
-1.7+1.8	77.79	15.44	24.53
-1.8+1.9	85.76	17.62	23.65
-1.9+2.0	89.37	18.91	23.14
-2.0+2.1	99.96	23.80	21.34

As the water flow rates increased, the ash content increased while the CV decreased. This is attributed to the fact that high water flow rates resulted in the undesired high density material rising together with the low density coal as overflow material to be collected as the desired product.

Table 7. Reflux classiffier test results

Bed density	Fluidising water flowrate (L/h)	Cumm mass %	Cumm Ash grade %	CV (MJ/kg)
1350 kg/m3	250	39.70	15.15	24.88
	300	47.00	15.47	24.73
	350	73.00	15.86	24.63
	400	80.00	17.86	23.88
1200 kg/m3	300	21.90	12.96	26.36

The product quality is also affected by the bed density. When the density is set in the reflux classifier, any material that is lighter than the set density will be carried over as the overflow stream, while the heavy material will report in the underflow stream. In terms of coal, the lower the density, the cleaner the coal product. Proving the afore-mentioned statement to be true, reducing the bed density to 1200 kg/m^3 resulted into the cleanest product of the reflux classifier, with a 12.96% ash content, 26.36 MJ/kg CV at 88.65% ash rejections and a 21.90% mass yield (Table 7).

Comparing all the processes employed (Figure 3), very clean coal can be achieved by HLS, though the mass yields are very low. Factors like mass yield, the cost of the separating media, other process running costs and the customer coal specifications are the ones that give guidance on whether to employ HLS to clean the coal. However, the reflux classifier which uses water as the separating media, achieved the cleaner coal than the two spirals and at mass yields between 70 - 80%, it achieved coal of almost the same ash content with the HLS ranging between 15-18%.

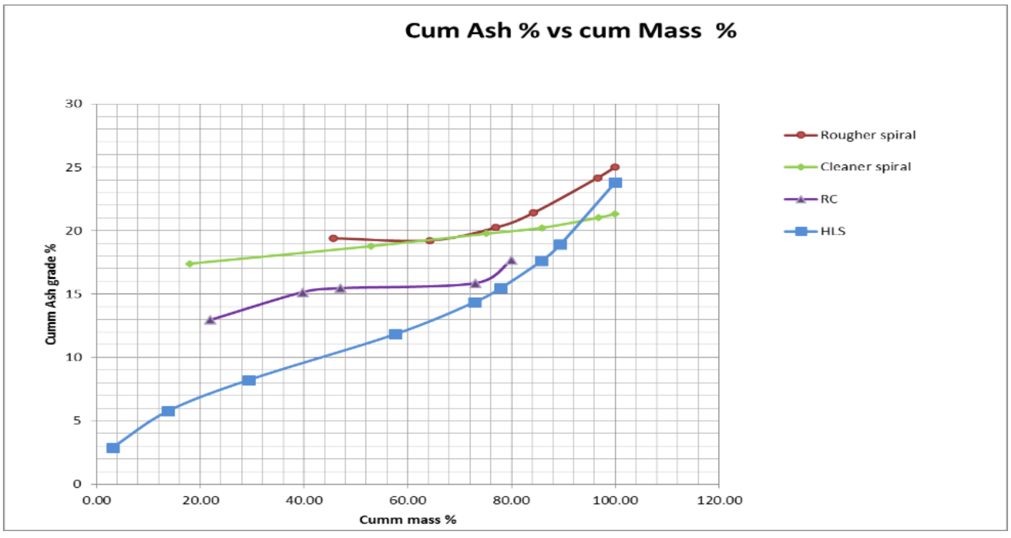

Figure 3. Cumulative ash % vs Cumulative mass % curve for the methods used

5. Comparability of products to the market specifications

Appendix A.1.1 shows the comparability of the product streams from different processes to the market specifications. None of the product streams met the export as well as gold and uranium industry's specifications. With regards to Eskom's and the transport industry's specifications, all the product streams from all the processes, had higher CV's and lower ash contents than the specified requirements. The -1.7+1mm feed sample employed in the project was already at 25% ash and 21 MJ/kg CV which is a coal specification required by Eskom. However the amount of fines in the fraction may not be feasible for Eskom power stations. Product streams from cutpoint densities, -1.5+1.6 to -1.6+1.7 of the HLS were the only product streams meeting the mining industry specifications. Conc 1 stream of the cleaner spiral was also within the range of specifications required by the cement and lime industry.

6. Conclusions

From the gravitational separation methods tested, the reflux classifier proved to achieve products with low ash contents, at high mass yields. Still at higher fluidization water flowrate, reflux classifier performance was superior to that of the spirals in terms of the ash rejections achieved. At low cut point densities, the HLS yielded cleanest products with very low ash content but at much lower mass yields. As the density increased, the mass yield increased with the ash content while the CV decreased. This is attributed to the fact that coal being the low density material will be suitable to be processed through low density methods, unwanted material will be recovered with the coal as soon as the density is increased. The products streams from the different processes met more than 60% of the local industries specifications, though none of them met the export market specifications due to the high ash content.

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Appendix A.

A.1.1. *Comparability of products to the market specifications*

Industry	Size	% Ash	CV (MJ/Kg)	Rougher spiral	Cleaner spiral	HLS	RC
Eskom	0 x 40mm	25 - 33 (AR)	21 (NAR)	All	All	All	X
Sasol	Not specified	20 - 29.7 (AR)	20 - 22.64 (NAR)	Tail 2	Midds - tails 2	-2+2.1	X
Agriculture	Peas	12.8 - 24.3	23.44 - 27.36	Conc 1 - 2	All	-1.5+1.6 & -1.8+1.9	All
Brick and tile	Duff	14.4 - 21.7	24.56 - 27.72	Conc 1 - 2	Conc 1	X	1350kg/m³ at 250l/hr
Cement and lime	Duff	12.4 - 18.8	25.18 - 29.23	X	Conc 1	X	X
Chemical Industries	Small nuts	13.7 - 26.4	18.91 - 25.98	All	All	-1.6+2.1	All 350 kg/m³
Gold and uranium mines	Small nuts	12.5 - 14.7	26.53 - 28.72	X	X	X	X
Industries	Peas, small nuts	10.8 - 24.2	23.44 - 33.19	Conc 1 - Midds	All	-1.5+1.9	All
Iron and steel	Small nuts	7.4 - 18.8	25.18 - 33.19	X	Conc 1	-1.4+1.6	1200 kg/m³ at 300l/hr
Merchants and domestic	All	8.1 - 23.9	23.44 - 30.36	Conc 1 - Midds	All	-1.4+1.6	All
Metallurgical	Peas, small nuts	8.1 - 18.8	25.18 - 30.36	X	Conc 1	-1.3+1.9	1200 kg/m³ at 300l/hr
Mining	Peas, small nuts	11.2 - 16.2	25.80 - 31.62	X	X	-1.5+1.7	X
Transport	Not specified	25.6	21.64	All	All	All	All
RB1	50mm	15	24.50 - 25.12 (NCV)	X	X	X	X
RB2	50mm	15	24.50 - 25.12 (NCV)	X	X	X	X
RB3	50mm	23	22.20 - 23.30 (NCV)	X	X	X	X
X > Do not meet the market specifications							