Dry processing for coal preparation: a review

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Utilizing dry coal beneficiation as opposed to the conventional wet methods arises for numerous reasons including the scarcity of water in some regions, the associated costs of product and fine material de-watering and handling and erecting plants that are economically feasible for small or remote reserves. Dry coal processing benefits downstream utilizations through possible cost and energy savings along with a reduction in water pollution. As a result, dry processing has inspired interest in the coal preparation industry and research into many methods has commenced.

Addendum A:

Performance report on the applicable dry coal processing techniques

Herein, the performance of each applicable dry coal processing method is compiled into a tabular comparison. The table includes data pertaining to the particle size range, capacity, efficiency, moisture restrictions and finally, the characteristics and application of the selected processes. The table is divided by mechanism of separation viz. sensor-based sorting (SBS), elutriation or gravity separation, magnetic separation (MS), electrostatic separation (ES) and microwave treatment (MWT). The performance of the applicable methods available under each of these mechanisms is summarized under the headings as already listed.

From literature, it was determined that the dual-energy X-ray transmission (DE-XRT) and electromagnetic (EM) sorters are most applicable for dry coal processing. The processes considered under elutriation are pneumatic jigs such as the *All Air jig*; the standard, *KAT*, *AKAflow* and *FGX* air tables; fluidized bed separators such as the *ADMFB*; pneumatic vortex fluidization such as the *SEP-AIR* and some processes that are still in the developmental stages of research such as the reflux classifier and coal winnower. The rare earth roll magnetic separator (*RERMS*) is considered best for dry coal processing under magnetic separation and the most suitable electric concentration method is the tribo-electrostatic technique. Some coal treatment is possible by adding heat or microwave energy which may improve certain moisture, grinding, magnetic and electro-physical properties; making the coal more susceptible to say, magnetic or electric separation.

Sensor-based sorting (SBS)				
Process	PSD (mm)	Capacity (tph)	Efficiency	Characteristics & Application
(P1) Dual-energy X-ray transmission (*DE-XRT*) sorter	+10 mm – 120 mm [1]	70 - 240 tph [1]	The following data pertains to the possible separation efficiency of the DE-XRT: EPM of 0.04 - 0.29 [2,3] Product yield of 47.5% - 84.5% [2,3] Cut-point density of 2.062 SG(D_{50}) [2] Ash reduction from 26.2% in the feed to 16.56% in the product [4] Sulphur reduction from 1.34% in the feed to 0.58% in the product [4] Product CV of 28 MJ/kg in the product from 22 MJ/kg in the feed [5]	In terms of coal preparation, sorting is primarily used for de-stoning and pre-concentration of coarse ore feed prior to the preparation plant and is applicable in dry, wet and freezing conditions. Sorting can be utilized for concentration to a final product in the cases of: • A good quality, easy to separate feed with little near dense material present or a feed that does not require extensive upgrading to reach product specification • Separating coal from torbanite and also pyritic sulphides • Coal beneficiation in extremely arid or arctic regions • Small, short term operations; remote or underground coal mines and also scavenging and recovery of coarse ore discard Sorters are compact and modular with multi-stage and multi-technology applications. They are low in investment and operating costs and allow significant energy savings but maintenance may be tricky and costly. During processing, narrow PSD's are essential. Smaller sizes and sensitive threshold settings may affect throughput. Feed de-dusting may not be necessary for the *DE-XRT* but feed presentation in a monolayer and at the correct speed is required. Competing water-based methods: Dense medium drum

(P2) Electromagnetic (EM) sorter	+20 mm - 50 mm [6]	10 - 20 tph [6]	The following data pertains to the possible separation efficiency of the EM sorter: EPM of 0.1 - 0.15 [6] Product yield *N/A* Cut-point density of 1.5 - 2.3 SG(D_{50}) [6] Ash reduction *N/A* Sulphur reduction *N/A* Product CV *N/A*	In terms of coal preparation, sorting is primarily used for de-stoning and pre-concentration of coarse ore feed prior to the preparation plant and is applicable in dry, wet and freezing conditions. EM sorting is still in the developmental stages of research but can be potentially utilized for concentration to a final product in the cases of: • A good quality, easy to separate feed with little near dense material present or a feed that does not require extensive upgrading to reach product specification • Separating coal from pyritic sulphides such as pyrite (FeS) • Coal beneficiation in extremely arid or arctic regions • Small, short term operations; remote or underground coal mines and also scavenging and recovery of coarse ore discard • In combination with heat or microwave pre-treatment to enhance the magnetic susceptibly or electro-physical properties of the coal and in so improve the detection and separation Very little literature is available on the EM sorter and further investigation into this technology is required. It is a multi-technology unit, utilizing more than one sensor and is also designed as compact and modular. Most of the characteristics of DE-XRT sorter above applies to the EM sorter. Competing water-based methods: Dense medium drum

Elutriation or gravity separation				
Process	PSD (mm)	Capacity (tph)	Efficiency	Characteristics & Application
(P3) *All Air Jig*	+ 0.5 mm - 50 mm [7]	50 - 120 tph [7]	The following data pertains to the possible separation efficiency of the *All-Air Jig*: EPM of 0.16 - 0.27 [7] Product yield of 70% [8] Cut-point density of 1.95 - 2.20 SG(D_{50}) [7] Ash reduction of 15 - 25% in the feed to 10 - 18% in the product [7] Sulphur reduction from 1.8% in the feed to 0.7% in the product [9] Product CV is improved by 25% from the feed [7]	In terms of coal preparation, the *All Air Jig* is primarily used for beneficiation of a coarse feed and is applicable for coal that is dry free-flowing. This unit can be utilized for concentration in case of: • A good quality, easy to separate feed with little near dense material present or a feed that does not require extensive upgrading to reach product specification • Separating coal from pyritic sulphides or beneficiating young lignite coals that degrade in the presence of moisture • Coal beneficiation in extremely arid or arctic regions • Small, short term operations; remote or underground coal mines and also scavenging and recovery of a coarse discard • De-stoning and pre-concentration of ROM feed The *All Air Jig* is containerized and modular with dust control mitigations. It is low in investment and operating costs and allows for significant energy savings. It is robust and automated making it easy to operate and maintain. During processing, narrow PSD's are not required and feed preparation and presentation is also not essential. Smaller sizes ranges and fine material may affect unit throughput. Competing water-based methods: DM drum, DM cyclone, spiral

(P4) *FGX*	6 mm - 80 mm [2,10]	10 - 350 tph [2,11]	The following data pertains to the possible separation efficiency of the *FGX*: EPM of 0.12 - 0.23 [12] Product yield of 70 - 84% [2] Cut-point density of 1.9 - 2.03 SG(D_{50}) [12] Ash reduction to 10.8 - 19.4% in the product from 30% in the feed [12] Sulphur reduction from 4.17 - 5.13% in the feed to 3.05 - 4.08% in the product [12] Product CV of 20.12 MJ/kg in the product from 16.18 MJ/kg in the feed [13]	In terms of coal preparation, the *FGX* is primarily used for beneficiation of a coarse feed and is applicable for coal that is dry free-flowing but separates effectively regardless of moisture present. The *FGX* can be utilized for concentration in the cases of: • A good quality, easy to separate feed with little near dense material present or a feed that does not require extensive upgrading to reach product specification • Separating coal from pyritic sulphides or beneficiating young lignite coals that degrade in the presence of moisture • Coal beneficiation in extremely arid or arctic regions • Small, short term operations; remote or underground coal mines and also scavenging and recovery of a coarse discard • De-stoning and pre-concentration of ROM feed The *FGX* is containerized and modular with dust control mitigations. It is low in investment and operating costs and allows for significant energy savings. It is robust and automated making it easy to operate and maintain. During processing, narrow PSD's are not required and feed preparation and presentation is also not essential. Airflow and distribution, vibration frequency and deck angle are important. Smaller sizes and fines may affect unit throughput and efficiency. Competing water-based methods: DM drum, DM cyclone

(P5) *Air table*	0 mm - 6 mm [14]	5 tph [14]	The following data pertains to the possible separation efficiency of an air table: EPM of 0.18 - 0.2 [15] Product yield of 40 - 60% [15] Cut-point density *N/A* Ash reduction from 48.7 - 54.9% in the feed to 23.7 - 29.9% in the product [14] Sulphur reduction of 33% from the feed [16] Product CV of 29.6 MJ/kg in the product from 23.9 MJ/kg in the feed [16]	In terms of coal preparation, the *air table* is primarily used for concentration of fine feed and is applicable for coal that is dry free-flowing. High moisture may cause clogging of the perforated deck, sticking to the unit walls and particle agglomeration. The *air table* can be utilized for concentration in the cases of: • A good quality, easy to separate feed with little near dense material present or a feed that does not require extensive upgrading to reach product specification • Separating coal from pyritic sulphides or beneficiating young lignite coals that degrade in the presence of moisture • Fine coal beneficiation in extremely arid or arctic regions • Small, short term operations and also scavenging and recovery of fine discard The air table is containerized and modular with dust control mitigations. It is low in investment and operating costs and allows for significant energy savings. It is robust and automated making it easy to operate and maintain. During processing, narrow PSD's are essential and feed preparation is required for the correct size range and moisture contents. Smaller sizes ranges and fine material may affect unit throughput and efficiency. Competing water-based methods: DM cyclone, spiral, floatation

(P6) KAT	1 mm - 10 mm [48]	3.7 -31 tph [48]	The following data pertains to the possible separation efficiency of an air table: EPM *N/A* Product yield of 40.9 - 56.3%[48] Cut-point density 2.0 SG(D_{50})[48] Ash reduction from 35.6 - 48.4% in the feed to 9.4 - 12.0% in the product [48] Sulphur reduction N/A Product CV of 29.2 - 30.3 MJ/kg in the product from 15.8 - 20.6 MJ/kg in the feed [48]	In terms of coal preparation, the *KAT table* is primarily used for concentration of fine feed and is applicable for coal that is dry free-flowing. High moisture may cause clogging of the perforated deck, sticking to the unit walls and particle agglomeration. The *KAT* can be utilized for concentration in the cases of: • A good quality, easy to separate feed with little near dense material present or a feed that does not require extensive upgrading to reach product specification • Separating coal from pyritic sulphides or beneficiating young lignite coals that degrade in the presence of moisture • Fine coal beneficiation in extremely arid or arctic regions • Small, short term operations and also scavenging and recovery of fine discard The KAT is containerized and modular with dust control mitigations. It is low in investment and operating costs and allows for significant energy savings. It is robust and automated making it easy to operate and maintain. During processing, narrow PSD's are essential and feed preparation is required for the correct size range and moisture contents. Smaller sizes ranges and fine material may affect unit throughput and efficiency. Competing water-based methods: DM cyclone, spiral, floatation

(P7) *AKAflow*	45 µm - 3 mm [17,18]	5 - 25 tph [17]	The following data pertains to the possible separation efficiency of the *AKAflow*: EPM *N/A* Product yield of 73.5% [17] Cut-point density *N/A* Ash reduction from 29.5% in the feed to 18% in the product [17] Sulphur reduction *N/A* Product CV *N/A*	In terms of coal preparation, the *AKAFlow* is primarily used for concentration of fine feed and is applicable for coal that is dry free-flowing. High moisture may cause clogging of the perforated deck, sticking to the unit walls and particle agglomeration. The *AKAFlow* can be utilized for concentration to a final product in the cases of: • A good quality, easy to separate feed with little near dense material present or a feed that does not require extensive upgrading to reach product specification • Separating coal from pyritic sulphides or beneficiating young lignite coals that degrade in the presence of moisture • Fine coal beneficiation in extremely arid or arctic regions • Small, short term operations and also scavenging and recovery of fine discard The *AKAFlow* is containerized and modular with dust control mitigations. It is low in investment and operating costs and allows for significant energy savings. It is robust and automated making it easy to operate and maintain. The air flow and distribution and also vibration are of importance for efficiency. During processing, narrow PSD's are required and feed preparation is essential. Smaller sizes and ultra-fine material may affect unit throughput and efficiency. Competing water-based methods: Spiral, floatation

(P8) Air dense medium fluidized bed (ADMFB) separator	Coal of 0 mm - 300 mm [10] Dense medium magnetite of 74 µm - 300 µm [35]	0.15 - 150 tph [19,20,21]	The following data pertains to the possible separation efficiency of the ADMFB: EPM of 0.05 - 0.07 (for +6-50mm)[22] and 0.06 - 0.225 (for +1-6mm) [44,45,46] Product yield of 41 - 56% for (+6-50mm) [22] and 38 - 61.3% (for+1-6mm) [45,46] Cut-point density of 1.3 - 2.2 SG(D_{50}) (for +6-50mm) [10] and 1.5 - 1.9 SG(D_{50}) (for +1-6mm) [44,45,46] Ash reduction from 39 - 46% in the feed to 16.4 - 18.2% in the product (for +6-50mm) [22] and from 31 - 40% in the feed to 12 - 16% in the product (for+1-6mm) [45,47] Sulphur reduction *N/A* Product CV *N/A*	In terms of coal preparation, the *ADMFB* is primarily used for concentration of a coarse feed and is applicable for coal with a moisture content below 3%$_{wt}$. The *ADMFB* utilizes magnetite as dense medium and is used for concentration in the cases of: • A good quality, easy to separate feed with little near dense material present or a feed that does not require extensive upgrading to reach product specification • Coarse coal beneficiation in extremely arid or arctic regions • Small, short term operations; remote or underground coal mines and also scavenging and recovery of a coarse discard • Investigations into the use of ADMFB for the <6mm with the aid of vibration or a magnetically stabilized bed is underway with good results and so a concentration of a fine fraction is also possible with ADMFB The ADMFB is containerized, modular and low in investment. The use of dense medium may be expensive and recovery thereof proves difficult. The ADMFB is robust and automated making it easy to operate and maintain. During processing, narrow PSD's may be required and feed preparation is essential. Smaller size ranges, fine material and moisture may affect unit throughput and efficiency. Competing water-based methods: DM drum, DM cyclone, spiral

(P9) SEP-AIR	1 mm - 100 mm [23]	45 - 220 tph [23]	The following data pertains to the possible separation efficiency of the *SEP-AIR*: EPM of 0.1 - 0.17 [24] Product yield of 85 - 93% [24] Cut-point density of 1.78 - 1.90 SG(D_{50}) [24] Ash reduction from 13.1 - 19.0% in the feed to 7.0 - 14.8% in the product [24] Sulphur reduction *N/A* Product CV *N/A*	In terms of coal preparation, the *SEP-AIR* is primarily used for concentration of fine and coarse feed and is applicable for coal that is dry free-flowing but also in wet and freezing conditions. The *SEP-AIR* can be utilized for concentration to a final product in the cases of: • A good quality, easy to separate feed with little near dense material present or a feed that does not require extensive upgrading to reach product specification • Coarse and fine coal beneficiation in arid or arctic regions • Small, short term operations; remote or underground coal mines and also scavenging and recovery of a coarse and fine discard • De-stoning and pre-concentration of ROM feed The *SEP-AIR* is attractive because of the very wide particle size range that it can process and the fact that it combines air vortex with the basic pneumatic separators. It allows the treatment of ore by grain and not as a body with one air flow. It is modular with dust control mitigations and is low in investment and operating costs. It is robust and automated making it easy to operate and maintain. During processing, narrow PSD's are not required and feed preparation is also not essential; feed presentation may however be. Smaller size ranges and fines may affect unit throughput but not unit efficiency. Competing water-based methods: DM drum, DM cyclone, spiral

(P10) Dry reflux classification	Tracers or coal of 0.25 mm - 8 mm [25] Dense medium sand of <355µm [25]	50 - 200 tracer particles (laboratory scale) [25]	The following data pertains to the possible separation efficiency of the dry reflux classifier: EPM of 0.06 - 0.46 [25] Product yield of 77% [26] Cut-point density of 1.42 - 2.13 SG(D_{50}) [25] Ash reduction from 24 - 30% in the feed to 10 - 11% in the product [26] Sulphur reduction *N/A* Product CV *N/A*	In terms of coal preparation, the *dry reflux classifier* is still on an experimental scale and requires some further investigation and upscaling for pilot and commercial testing. The *dry reflux classifier* proves capable of density separation of coal from the associated gangue minerals and could potentially be utilized for concentration to a final product in the cases of: • Separation of small and fine coal such as those screened from the coarse feed to other separation units • A good quality, easy to separate coal with little near dense material present in the feed • A feed that does not require extensive upgrading to reach product specification • Scavenging and recovery of fine coal discard The *dry reflux classifier* separation efficiency may be improved by the addition of fine sand as a dense medium material and also vibration. The effects of air and coal and dense medium feed moisture on the operation are not yet documented. It is expected that narrow PSD's are required and feed preparation (size, moisture, etc.) may be essential. Smaller sizes ranges and ultra-fine material may affect unit throughput and efficiency. Competing water-based methods: DM cyclone, spiral

(P11) Coal winnower	2 mm - 100 mm [27,49]	6 kg - 10 kg (laboratory scale) [27]	The following data pertains to the possible separation efficiency of the coal winnower: EPM of 0.065 - 0.25 [27] Product yield of 30 - 80% [27] Cut-point density of 1.76 - 1.97 SG(D_{50}) [27] Ash reduction to 22 - 39.4% in the product from 28.7 - 46.1% in the feed [27] Sulphur reduction *N/A* Product CV *N/A*	The coal winnower requires some further investigation and upscaling for pilot and commercial testing coal preparation as itis still on an experimental scale. The *winnower* proves capable of density separation of coal from the associated gangue minerals in feed moisture ranges of 3%$_{wt}$ and could potentially be utilized for concentration to a final product in the cases of: • A good quality, easy to separate coal with little near dense material present in the feed that does not require extensive upgrading to reach product specification • Coarse and fine coal beneficiation in arid or arctic regions • Small, short term operations; remote or underground coal mines and also scavenging and recovery of a coarse and fine discard • De-stoning and pre-concentration of ROM feed The *winnower* separation efficiency has been proven on an experimental scale and operation thereof seems simple and robust. Some consideration of the proper air flow requirements is essential for effective utilization. It is expected that narrow PSD's are required and feed preparation (size, moisture, etc.) may be essential. Smaller sizes ranges and ultra-fine material may affect unit throughput and efficiency. Investigations into <6mm particles are underway. Competing water-based methods: DM drum, DM cyclone, spiral

Magnetic separation (MS)				
Process	PSD (mm)	Capacity (tph)	Efficiency	Characteristics & Application
(P12) Rare earth roll magnetic separator (RERMS)	+ 75 µm - 25 mm [28]	2 - 10 tph [29]	The following data pertains to the possible separation efficiency of the RERMS: EPM *N/A* Product yield *N/A* Ash reduction of 40%[30] typically from 39.49% in the feed to 14.2% in the product[31] Sulphur reduction of 10%[30] typically from 2.09% in the feed to 0.41% in the product[31] Product CV *N/A*	In terms of coal preparation, MS is primarily used for concentration of small, fine and ultra-fine feed that is dry free-flowing. MS can be utilized for concentration to a final product in the cases of: • Coal associated with mostly paramagnetic mineral matter and small amounts of diamagnetic mineral matter • Removal of pyritic sulphides and in so, desulphurization • In combination with pyrolysis or microwave heating which can enhance the mineral magnetic properties • In combination with sorting, gravity or electrostatic separation to enhance efficiency and recovery • In the treatment of dry fine and ultra-fine tailings MS are containerized and modular but have high belt wear and tear with intricate maintenance procedures. This process too requires narrow size fractions and the production rate is readily affected by particle size, density and amount of magnetics. Monolayer presentation at the correct velocity and feed de-dusting is essential but this may affect the throughput. Multiple stages of MS may enhance productivity and recovery. Competing water-based methods: DM cyclone, spiral, floatation

Electrostatic separation (ES)				
Process	PSD (mm)	Capacity (tph)	Efficiency	Characteristics & Application
(P13) Tribo-electrostatic separator (TBS)	+ 0 mm - 1 mm [32,33]	Charging unit 5 - 50g for a residence time of 15 - 90s [10,32,33] Separating unit 1.2 kg/h (*Laboratory scale) [10,32,33]	The following data pertains to the possible separation efficiency of the TBS: EPM *N/A* Product yield of 25.22 - 50% in carbon recovery [34] Ash reduction from 30.4 - 36% in the feed to 8.9 - 13.1% in the product [34,47] Sulphur reduction from 1.6 - 2.1% in the feed to 0.7 - 0.9% in the product[34,47] Product CV of 25.2 - 29.4 MJ/kg from a feed of 18.0 - 20.9[34,47]	In terms of coal preparation, triboelectric separation is primarily used for concentration of fine and ultra-fine feed with surface moisture of 1 - 2%$_{wt}$. TBS can be utilized for concentration to a final product in the cases of: • Coal with a prominent difference in the electro-physical properties between clean coal and mineral gangue • Removal of pyritic sulphides from coal and in so, desulphurization • Recovery of unburned carbon from fly-ash post-combustion as well as tailings sites • With the aid of pyrolysis, microwave energy or surfactants that alter the surface characteristics and improve particle charging • Some application possibilities for combination with gravity and magnetic separation or in the burner pipes prior to combustion The TBS technique is still in the developmental stages of research and so only experimental scale units have been investigated. As such upscaling is required. De-dusting of the feed and narrow PSD's are essential. Moisture, temperature and RH affect charging and separation. Recovery may be enhanced by multiple stage processing. Competing water-based methods: Spiral and floatation

Microwave treatment (MWT)				
Process	PSD (mm)	Capacity (tph)	Efficiency	Characteristics & Application
(P14) Microwave irradiation (MI)	+0 mm - 3 mm [36]	15tph [41] Microwave powers of 500 W to 20 kW [38,39] Microwave frequencies of 2.45 GHz to 5 GHz [37] Processing times of 0.1 s - 10 minutes [36,41]	The following data pertains to the possible process efficiency of MI: EPM *N/A* Cut-point density *N/A* Product CV *N/A* Desulphurization with MS: A reduction of 55.11% points in sulphur and 21.54% points in ash yield with a 20.39% increase in calorific value [42] Desulphurization with TBS: More effective liberation with a decrease in ash yield from 49% to 18% [36] For dewatering: Improved drying rates [43] For improved grindability: Larger grindability index [39]	In terms of coal preparation, the *microwave treatment* can be utilized to enhance certain properties of the coal. The treated coal particles can then be concentrated more efficiently in a unit already utilized for separation thereof. MWT is has been proven on an experimental scale for small coal sizes in very high moisture contents and could potentially be utilized for beneficiation in case of: • Improving the magnetic susceptibility or dielectric properties of the pyrite mineral constituent of coal in order to use magnetic or triboelectric separation for desulphurization, respectively. • In order to de-water coal successfully at reduced operating times without affecting the coal matrix or combustion properties • To improve the grindability of coal • In coke-making, liquefaction, liquefaction pre-treatment, enhancing fluid flow in coal beds and characterization of coal. Microwave treatment holds true potential in coal processing and has been proven useful to coal beneficiation in experimental and some commercial scale investigations. MI is relatively simple in the concept of operation but may however be an energy-intensive process and in so prove costly to operate.

Conclusion

From the performance data given in this report, the potential of numerous processes in the dry beneficiation of coarse and fine coal is seen. It is, however, important to consider the process applicability and all performance and operability limitations before implementation. Upon determining the most suitable dry beneficiation processes for a specific application - de-stoning, concentration to a final product, desulphurization, recovery - the coal type, size and moisture needs to be taken into account. It is essential to understand the geology of the coal along with its washability characteristics in order to determine the amount of near dense material and difficulty of separation. Certain processes are only suitable for coarse coal while others are better implemented for the fine coal fractions. In some cases, narrow particle size ranges are essential, along with minimal undersize fractions. Moreover, the presence of moisture in the feed and during operation may have some effect on the separation efficiency especially with regards to the fine and ultra-fine coal particles.

From the performance data summarized in this report, it is clear that the *ADMFB* provides the best separation efficiency for coal of 6 - 50 mm yielding an EPM value range of 0.05 - 0.07. The *SEP-AIR* and *coal winnower* are viable competitors within the same size range having only slightly higher EPM values of 0.1 - 0.15 and 0.065 - 0.25, respectively. The concept of winnowing for coal separation is still in an experimental phase and may require further investigation and upscaling. The *SEP-AIR* provides the advantage of being able to process particle sizes down to 1mm, allowing the previously removed 1 - 6 mm coal to be beneficiated which may lead to a better quality product. The *SEP-AIR* may not yield the same low separation efficiency as the *ADMFB* but does not require the added dense medium material abating the associated consumption, handling and recovery issues. Much research has commenced on techniques for beneficiating the 0 - 6mm PSD, yielding comparably low EPM values. The *AKAflow* and air tables are the only commercialized units in this capacity yielding EPM values ranging in 0.18 - 0.2. Many other processes have been investigated such as some variants in the *ADMFB*, the dry reflux classifier, and coal winnower and could potentially provide good separation efficiencies on an experimental scale but may require further investigation and possible upscaling.

From here it is possible to establish which techniques are best for the project at hand and then the individual process efficiency and capacity limitations can be determined with regards to the product quality and throughput specifications. Utilizing multiple units or different dry separation methods in conjunction with one another may provide solutions to the efficiency and capacity limitations but this has to be weighed against the cost in the long run.

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References

[1] King, I. 2015 (March 3). The importance of ore sorting technologies in the future. Powerpoint presentation at Mintek, South Africa.

[2] De Korte, J.G. 2013. Dry processing versus dense medium processing for preparing thermal coal. CSIR (Council for Scientific and Industrial Research). Pretoria, South Africa.

[3] Robben, C., De Korte, J., Wotruba, H. and Robben, M. 2014. Experiences in dry coarse coal separation using X-ray -transmission-based sorting. *International Journal of Coal Preparation and Utilization, 34:210-219.*

[4] Von Ketelhodt, L. and Bergmann, C. 2010. Dual-energy X-ray transmission sorting of coal. *The Journal of the Southern African Institute of Mining and Metallurgy,* 110:371-378.

[5] Strydom, H. 2010. The application of dual-energy X-ray transmission sorting to the separation of coal from torbanite. University of the Witwatersrand Johannesburg, South Africa.

[6] De Jong, T.P.R., Houwelingen, J.A. and Kuilman, W. 2004. Automatic sorting and control in solid fuel processing: opportunities in European perspective. *Geologica Belgica*, 7(3-4):325-333.

[7] Weinstein, R. and Snoby, R.J. 2007. Advances in dry jigging improve coal quality. *Mining Engineering*, 59(1):29-34.

[8] Boylu, F., Cetinel, T., Guven, O., Karakas, F., Cinku, K., Karaagaclioglu, I.E., Celik, M.S. 2015. Optimum separation route for semi-bituminous coal using semi-pilot pneumatic stratification jig. *Physiochemical Problems of Mineral Processing,* 51(2):559 - 573.

[9] Sampaio, C.H., Aliaga, W., Pacheco, E.T., Petter, E. & Wotruba, H. 2008. Coal beneficiation of Candiota mine by dry jigging. *Fuel Processing Technology*, 89: 198–202.

[10] Dwari, R.K. & Rao, K.H. 2007. Dry beneficiation of coal - A review. *Mineral Processing & Extractive Metallurgy*, 28:177–234.

[11] Zhang, B., Zhao, Y., Zhou, C., 2015. Fine Coal Desulfurization by Magnetic Separation and the behavior of sulfur Component Response in Microwave Energy Pre-treatment. *Energy and Fuels*, 29(2):1243–1248.

[12] Zhang, B., Akbari, H., Yang, F., Mohanty, M.K., Hirschi, J. 2011. Performance optimization of the FGX dry separator for cleaning high-sulfur coal. *International Journal of Coal Preparation and Utilization*, 31(3-4):161-186.

[13] De Korte, J.G. 2014. Dry processing of coal - status update. CoalTech Research Association NPC Ltd. Secunda, South Africa.

[14] Gupta, N. 2016. Evaluation of pneumatic inclined deck separator for high-ash Indian coals. *International Journal of Coal Science Technology*, 3(2):198-205.

[15] Chavaldi, G., Singh, R.K., Das, A. 2016b. Processing of coal fines using air fluidization in an air table. *International Journal of Mineral Processing*, 149:9-17.

[16] Patil, D.P. & Parekh, B.K. n.d. Beneficiation of fine coal using the air table. Centre for applied energy research, University of Kentucky Lexington, USA.

[17] Wotruba, H., Weitksemper, L., Steinberg, M. 2010. Development of a new dry density separator for fine-grained materials. XXV International Mineral Processing Congress (IMPC) Brisbane, Australia 6 - 10 September 2010.

[18] Chavaldi, G., Singh, R.K., Sharma, M., Das, A. 2015. Recovery of combustibles from fine coal through controlled air fluidization over inclined deck. *Separation Science and Technology*, 50:2032-2040.

[19] Sahu, A.K., Bismal, S.K. & Parida, A. 2009. Development of air dense medium fluidized bed technology for dry beneficiation of coal – A review. *International Journal of Coal Preparation and Utilization*, 29: 216–241.

[20] Chen, Q. & Wei, L. 2005. Development of coal dry beneficiation with air-dense medium fluidized bed in China. *China Particuology*, 3:42.

[21] Hughes, N., Le Roux, M., Campbell, Q.P. 2017. The dry beneficiation of South African small coal in a dense medium fluidized bed. North-West University Potchefstroom Campus Potchefstroom, South Africa.

[22] Luo, Z. & Chen, Q. 2001. Dry beneficiation technology of coal with an air dense-medium fluidized bed. *International journal of mineral processing*, 63: 167–175.

[23] Gormash Export. 2016. SEP-AIR pneumatic concentration complex. Gormash Export Novosibirsk, Russian Federation. Accessed from http://www.gmexp.ru. Date of access: 4 June 2018.

[24] De Korte, J.G. 2018. SEP-AIR dry coal separator: efficiency determination carried out in Russia. CoalTech Research Association NPC Ltd. Secunda, South Africa.

[25] Macpherson, S.A., Iveson, S.M., Galvin, K.P. 2011. Density-based separation in a vibrated reflux classifier with air-sand dense medium: tracer studies with simultaneous underflow and overflow removal. *Minerals Engineering*, 24:1046-1052.

[26] Macpherson, S.A. & Galvin, K.P. 2010. The effect of vibration on dry coal beneficiation in the reflux classifier. *International Journal of Coal Preparation and Utilization*, 30:283-294.

[27] Sakhre, D.K., Singh, S.P., Acharya, R.K., Katley, R.L., Prasad, A.L.V., Chayande, P. 2018. Coal winnowing: an innovative technique for dry coal beneficiation. *CPSI Journal*, 10(28):3-13.

[28] Tripathy, S.K., Banerjee, P.K., Suresh, N., Murthy, Y.R., Singh, V. 2017. Dry high-intesnity magnetic separation in mineral industry - a review of present status and future prospects. *Mineral Processing and Extractive Metallurgy Review*, 38(6): 339-365.

[29] Mineral technologies. 2018. Rare earth roll magnetic separator, data sheet - RER. Mineral Technologies a Downer company, Carrara Gold Coast, Queensland.

[30] Saeid, A. M., Butcher, D. A., and Rowson, N. A. 1993. Coal desulphurisation and ash removal in intensified magnetic fields. *Magnetic and Electrical Separation*, 4(2):107–116.

[31] Celik, M. S, and Yildirim, I., 2000. A new physical process for desulfurization of low-rank coals. *Fuel*, 79:1665–1669.

[32] Mohanta, S., Rout, B., Dwari, R.K., Reddy, P.S.R., Mishra, B.K. 2016. Tribo-electrostatic separation of high ash coking coal washery rejects: Effect of moisture on separation efficiency. *Powder Technology*, 294:292-300.

[33] Dwari, R.K., Mohanta, S.K., Rout, B., Soni, R.K., Reddy, P.S.R., Mishra, B.K. 2015. Studies on the effect of electrode plate position and feed temperature on the tribo-electrostatic separation of high ash Indian coking coal. *Advanced Powder Technology*, 26:31-41.

[34] Bada, S.O., Falcon, R.M.S. and Falcon, L.M. 2010. The potential of electrostatic separation in the upgrading of South African fine coal prior to utilization-a review. *The Journal of the Southern African Institute of Mining and Metallurgy, 10:691-702.*

[35] He, J., Tan, M., Zhao, Y., Zhu, R. & Duan, C. 2016a. 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.

[36] Turcaniova L., Soong Y., Lovas M., Mockovciakova A., Orinak A., Justinova M., Znamenackova I., Bezovska M., Marchant, S. 2004 The effect of microwave radiation on the tribo-electrostatic separation of coal. Fuel, 83 (14-15):2075-2079.

[37] Zavitsanos, P. D. 1978. Coal desulfurization using microwave energy. General Electric Company, Environmental Protection Agency: Research Triangle Park, N.C., United States.

[38] Rowson N. A. & Rice N. M. 1990b. Desulfurization of coal using low-power microwave-energy. *Minerals Engineering*, 3 (3-4):363-368.

[39] Toraman O. Y. 2010. The effect of high power microwave energy on the grindability of Turkish Cayirhan lignite. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 32 (19): 1794 - 1800.

[40] Wu T., Lester E., Kingman S., Dodds C. 2005. Quantification of the influence of microwave pre-treatment on coal breakage. 13th International Conference on Coal Science and Technology, October 9- 14th, Okinawa, Japan.

[41] Wilson, A. 2009. Super Coal. Vision Systems Design, 14 (7).

[42] Uslu T. & Atalay U. 2004. Microwave heating of coal for enhanced magnetic removal of pyrite. *Fuel Processing Technology*, 85:21-29.

[43] Standish N., Worner H., Kaul, H. 1988. Microwave drying of brown coal agglomerates. *Journal of microwave power and electromagnetic energy*, 23(3):171-175.

[44] Wei, L., Chen, Q. & Zhao, Y. 2003. Formation of Double-Density Fluidized Bed and Application in Dry Coal Beneficiation. *Coal preparation*, 23: 21–32.

[45] Yang, X., Zhao, Y., Luo, Z., Song, S., Duan, C. & Dong, L. 2013a. Fine coal dry cleaning using a vibrated gas-fluidized bed. *Fuel Processing Technology*, 106: 338–343.

[46] Luo, Z., Zhao, Y., Chen, Z., Fan, M., Tao, X. 2002. Separation characteristics for fine coal of the magnetically fluidized bed. *Fuel Processing Technology*, 79:63-69.

[47] Bada, S. O., Falcon, L. M., Falcom, R. M. S., Du Cann, V. M. 2012. Qualitative analysis of fine coals obtained from triboelectric separation. *The Journal of the Southern African Institute of Mining and Metallurgy,* 112:55-62.

[48] Davaasuren, J., Kim, B. G. Lee, J. H., Davaatseren, G., Bazarragcha, M. 2016. Dry coal preparation of fine particle by KAT process, in (Litvinenko, V.), XVIII International Coal preparation congress Saint-Petersburg, Russia 28 June – 1 July 2016, Springer, Switzerland, 1171-1176.

[49] Morgan, L. 2017. *Winnowing as dry separation method for fine coal*. North-West University Potchefstroom Campus Potchefstroom, South Africa