The potential of electrostatic separation in the upgrading of South African fine coal prior to utilization—a review

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Journal Paper

Synopsis

Coal is a complex mixture of organic and mineral constituents and is the most abundant resource of fossil energy in the world. In recent years, significant research into dry coal beneficiation has gained much attention, primarily due to the need to improve grades and reduce the environmental contaminants in coal without the use of water, and to achieve this in as cost-effective manner as possible, relative to wet beneficiation processes. This paper seeks to review the application of various electrostatic separators with their process principles, to draw comparisons between different dry beneficiation techniques with specific emphasis on the triboelectrostatic separation method, and finally to report the results of triboelectrostatic separation conducted on various South African coals. Previous research conducted on Indian, European and American coals has indicated that this technique is likely to lead to significant economic benefit through the reduction of ash content, NO_X and more specifically SO_X by separating out the liberated Fe-S-bearing minerals prior to utilization. The removal of the latter suite of minerals is also likely to significantly reduce or eliminate the emissions of associated trace elements, including mercury and arsenic. The research results reported in this paper indicate that the rotary triboelectrostatic process has the potential for significant upgrading of high ash pulverized South African coal. The impact of various operational parameters was investigated and key factors established for the optimum recovery of low ash and low sulphur fine coal.

Keywords

Coal, dry beneficiation, electrostatic technique, rotary triboelectrostatic separator, high-gradient magnetic separation.

Introduction

Coal represents the single most abundant source of fossil-based energy available in most countries around the world. The Republic of South Africa (RSA) is the fourth largest coal-producing country and the third largest exporter of coal, behind USA and Australia (Budge, 2000). The South African coals deposits were formed during the Permian period in Gondwanaland, the super-continent that included Africa, Australia, India and South American. Now found predominantly in continents in the southern hemisphere, these coals are known as the Gondwana coals. They are characterized by possessing lower proportions of vitrinite and liptinite, and considerably higher ash contents than those formed during the Carboniferous period in the northern hemisphere.

Coal is highly heterogeneous, with a wide variety of minerals and organic components, all occurring in widely varying proportions from one seam to another and between different coalfields. The minerals exhibit different degrees of intergrowth in the organic matrices, resulting in various levels of liberation and therefore potentials for separation and beneficiation of the host coal. This partially explains the difficulty in adopting a particular washing technique from the numerous techniques available in the market (Dieudonne, 2001).

The total estimated reserves of coal in South Africa are approximately 34 billion tons, and at the present consumption rate, it has been estimated that a mere 7 billion tons might remain by 2040 (Mbedi, 2004). Furthermore, most of the high grade cleaner coals have already been, or are fast being, mined out primarily for export purposes, thereby leaving the lower grade, high ash coals for extraction and use in the future. In addition, more stringent environmental controls in terms of particulate, gaseous and trace element emissions are being imposed on the users of coal, with specific emphasis on SO_X from sulphur-related minerals, NO_X and CO_2. For these reasons, and in order to ensure the continued use of coal for power generation, hydrocarbon production and industrial heat and power, there is an urgent need to conduct detailed research into the upgrading of South African coal leading to cleaner and more efficient use in the future.

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This paper was first presented at the, Indaba Coal, Carbon and Energy Conference, *11–12 March 2009, Glen Hove Conferencing Centre, Melrose, Johannesburg.*

The principle of using dry beneficiation techniques rather than the conventional wet techniques for the beneficiation of South African coals arises for several reasons, First, South Africa is a water-poor country and this situation imposes a severe limitation on all processes requiring water as a medium to succeed. Secondly, the beneficiation of ultra fine fractions of coal (-600 μm) using water-based techniques such as froth flotation is costly and difficult in terms of de-watering the final product, and handling and storage. In terms of the bigger sized fractions, the large quantities of water used and lost during conventional coal preparation, as well as the high cost of managing and treating the large quantities of aqueous slurries generated during the wet processing techniques, serve as further motivations for the introduction of dry beneficiation techniques. Furthermore, most coal beneficiation processes currently employed in South Africa are based on wet techniques and these produce large quantities of potentially polluted water. The estimated cost of handling and treating these pollutants constitutes a major disadvantage to this technique, not only in South Africa but also worldwide (Lockhart, 1984). It has been stated that the treatment of slurries, contaminated water and recovery problems in wet beneficiation techniques are more expensive compared to the dust control and the disposal of dry tailings, which are easier and less expensive in the case of dry beneficiation processes (Lockhart, 1984).

The fact that water demands will be a major problem for present and future developments in mining, beneficiation and in the construction of new power plants in SA, irrespective of the technical and economic feasibility of the wet techniques, gives rise to further motivation for the development of an alternative approach to wet-based beneficiation of coal.

The dry beneficiation of coal has inspired interest not only because of the limitations of wet beneficiation techniques listed above, but also due to the process benefits in downstream utilization where energy is saved through not being required to dry the coal product before being sold as a source of fuel. Furthermore, it is envisaged that the potential to reduce or eliminate Fe and S-bearing minerals (pyrite) to a relatively high degree prior to use may also lead, in turn, to the elimination of SO_X and prevent the need for flue gas desulphurization plants (FGD) at the back end of power plant.

In recent years, extensive research has been conducted on a variety of dry coal beneficiation processes, all for the purpose of producing high particle separation efficiencies, optimum cost-effectiveness and minimal moving-parts engineering leading to reduced maintenance issues. These techniques are based on differences in the characteristics of the coal constituents, including such properties as specific gravity, grindability, friability, shape, size, magnetic susceptibility, electrical resistivity and frictional coefficient. On the basis of these differences in properties, equipment such as the fluidized bed, air/dense medium fluidized bed separator, triboelectrostatic separator, octagonal rotary triboelectrostatic separator, pneumatic jig, pneumatic table and Sortex systems which are applicable to different particle sizes, have been used to beneficiate coal (Cheng and Yang, 2003; Weitkämper and Wotruba, 2004; Biswal *et al.* 2005; Choung *et al.*, 2006; Dwari and Rao, 2007; Dwari and Rao, 2008).

The first attempts at the dry beneficiation of fine pulverized coal (-170 microns) in South Africa were undertaken by Bada *et al.* (2010) using the triboelectrostatic separator.

In this review, a number of dry beneficiating techniques and their feasibilities are reviewed, followed by the presentation of results obtained when testing selected high ash South African coals on a rotary triboelectric separator (RTS). Comments regarding the removal of Fe- and S-bearing minerals such as pyrite, sulphur and ash from the coals under investigation using different operating conditions are also included.

Dry beneficiation as a coal beneficiation process

Dry beneficiation could be regarded as a partial replacement for wet beneficiation techniques or an alternative approach for recovering rejected fine coal that is created in conventional coal preparation plants in the form of underflow thickeners and slurries. The dry beneficiation of coal can be economically competitive and environmentally safe, and it may eliminate the need for flue gas desulphurization (FGD) in future power plants in South Africa. In addition, it could serve as a potential technique for exploiting coals that would have otherwise have been classified as unrecoverable because of environmental or economical constraints. Dry coal beneficiation has also emerged as an alternative approach to solving the problem of the scarcity of water in coal-producing countries and as a great benefit in downstream utilization. Energy is not expended in drying wet coal under dry beneficiation, thereby allowing full use of coal for marketing purposes (Lockhart, 1984). The dry process is also less capital intensive than wet techniques; it does not require thickeners to settle fines and it retains the high calorific value and quality as coal being beneficiated in a wet-processing technology (Dwari and Rao, 2007). This process was also found to be environmentally advantageous due to the effective removal of the now well-liberated ash (mineral-rich) particles, Fe-S pyritic minerals and their attendant harmful trace elements, mercury and arsenic (Higashiyama *et al.*, 1998).

The dry beneficiation technique relies on the differences in physical and chemical properties of the mineral (inorganic) and maceral (organic) components in coal and is also affected by such factors as particle size, magnetic susceptibility, electrical conductivity, shape, and density. Such properties control the effective separation of the organic components (macerals) from the inorganic components (minerals) which, in turn, affect the washability potential, separation efficiencies and yields for certain qualities (initially determined by ash content).

Notable advances in dry coal preparation with specific reference to fluidized bed triboelectrostatic separation of ultra fine or pulverized coal have been made by several authors including Dwari and Rao (2008). Whereas good reductions in ash and sulphur contents with consequent increases in grade of product have been found, emphasis in these research approaches was laid more on reviewing the principles of electrostatic separation as compared to the other techniques which are also discussed below. Having proved to some extent the efficacy of this technique, research is now required to increase the yields and further separation efficiencies of this process in order to match the higher efficiencies and yields encountered when testing the same coal qualities and size ranges under conventional wet beneficiation techniques obtained.

Given the importance of dry coal beneficiation in South Africa, the present status of this technique is herein reviewed. This is followed by a report on results obtained when testing selected samples of high ash South African fine coal in a scale triboelectrostatic separator.

The theory and mechanisms of dry electrostatic beneficiation techniques

Theory of electrostatic beneficiation techniques

The application of electrical conductivity of particles under the influence of a high potential difference has received significant attention in recent years. This separation technique depends on the difference in the electrical resistivities and conductivity, and also differences in the electronic surface structure of the mineral from the organic phases in coal (Kelly and Spottiswood, 1989a). These differences in properties enable the particles to develop two different charged phases which contribute to the separation of these particles. Hence, with the application of various operation parameters on the separator, the separation efficiency of various coal particles from one another can be improved. The simplicity of this technique and ease of operation, as well as the now proven potential for different coal particles to exhibit different electrical properties, has led to increased research in this direction in order to seek alternative approaches to existing wet technologies for the upgrading and beneficiation of South African coal.

Electrostatic separation is based on electrophoresis, which involves charged particles, and dielectrophoresis, which involves uncharged particles. Electrophoresis separation of coal particles in an electric field requires a high-intensity field, following the precharging of the coal through the field. The two electrical separation methods that have been used for the cleaning of coal are the corona electrostatic and the triboelectrostatic processes. These have now been incorporated into various configurational systems with a fluidized bed and cylindrical and octagonal rotary charging chambers (Butcher and Rowson, 1995; Dwari and Rao, 2008; Tao, *et al*. 2009; Bada *et al*. 2010). The particles' electro-physical properties determine the way in which the particles can be endowed with charges. This is achieved either by conductive induction or triboelectrification or corona-electro-static charging mechanisms. The three main mechanisms for charging particles are ion or corona bombardment, contact or triboelectrification and conductive induction (Knoll and Taylor, 1984; Kelly and Spottiswood, 1989a).

Charging mechanisms

Tribocharging occurs through contact charging and friction charging mechanisms and by utilizing the differences in the electronic surface structure of the particles involved. In both cases, the mechanical processes that produce the charging of materials are sliding, rolling or milling, impact, vibration of the surface at contact, separation of solid–solid, solid–liquid, and liquid–liquid surfaces and deformation leading to charge distribution at stress points (Mazumder *et al*., 2006). The quantity of triboelectric charge exchanged between two contacting surfaces depends upon their contacting speed, the relative work function and on the pressure between the surfaces in contact. In addition, as the pressure increases, there is the possibility for an increase in the surface charge density due to the high surface area or number of contact points between particles. This mechanism had been found to be most effective for charging materials with little differences in conductivities such as coal. This assists the separation of minerals and high ash coal particles from clean maceral-rich coal particles.

Ion bombardment is one of the most efficient charging processes and can be applied in a consistent manner to charge both insulating and conducting particles and droplets, either positively or negatively, within a relatively short period of time (usually less than 1 second). The particles are bombarded through atmospheric gases generated from a high-intensity electric field between the roll and one of several electrodes connected to a high-voltage supply. Once the ion bombardment ceases, the insulating particles are held or pinned to the surface of the rotating roll electrode by the electric image force, while the conducting particle loses its acquired charge to ground very rapidly as there is no electro-static force holding it to the conducting surface (Samuila *et al*., 2005). Through this action, both particles can be separated. This approach is very efficient during the separation of two materials with significant differences in conductivities.

Induction charging is the process by which a static field is used in charging particles. The uncharged particle comes into contact with a charged surface such as a plate or screen in an electric field. There it assumes the same polarity and potential of the contacted surface. This particle is then considered to have become polarized, whether it be conductive or dielectric (Dyrenforth, 1978). Under this influence, a conductive particle will become an equipotential surface by redistributing the charge almost instantaneously via the grounded rotor. The particle will acquire a charge opposite to that of the high-voltage electrode generating the electric field (Inculet, 1984a). However, a dielectric particle will become polarized so that the side of the particle away from the charged surface develops the same polarity as the surface. In addition the particle will remain polarized due to its inability to effectively redistribute electrons (Dyrenforth, 1978). For this reason, non-conducting particles have no net charge and so are neither attracted nor repelled by the field. Knoll and Taylor (1984) reported that the forces generated by induction separation are generally weaker than that of ion bombardment due to less particle charging, thereby reducing process efficiency. Hence, effective separation of the particles can be achieved only under the ion bombardment process and subject to significant differences in the various particles' conductive properties. This is the reason why triboelectro-static separation is preferred in the case of coal separation.

Dry electrostatic separation methods

Corona electrostatic method

The utilization of electrostatic separation techniques has been largely developed and employed in various field for mineral beneficiation, removal of the unburned carbon in fly ash and for agricultural application (Trigwell *et al*., 2003; Butcher and Rowson, 1995; Dwari and Rao, 2007; Dwari and Rao, 2009; Tao *et al*., 2009). The rotor-type techniques, using induction by corona charging, has been employed in separating raw materials based on their conductivity into conductive and non-conductive materials. The corona is applied in cases where there is a large difference in the work function of the material involved. However, due to the similarity in the properties and the closeness in the work functions of the minerals or ash contents found in coal fines, the rotor-type technique has not been found to be effective for the separation of particles of coal with varying quantities of minerals (ash) in them. Triboelectrification, on the other hand, has been found to be far more effective as an alternative technique for the separation of particles with little differences in conductivity properties (Higashiyama and Asano, 1998; Soong *et al*., 2001; Chen and Wei, 2003; Dwari and Rao, 2008).

The corona electrical separator technique using ion bombardment for charging and separating minerals is the most common and strongest method of charging particles for electrostatic separation (Butcher and Rowson, 1995; Dwari and Rao, 2007). It has been employed in recovering copper and plastic materials from power cable, removal of stalks from tea leaves, separation of metals from glass, ceramics, plastics, and polymers, and also for removing contaminants from grains and processed foods (Moore, 1973; Hayakawa *et al*., 1985; Taylor, 1988; Higashiyama and Asano, 1998). In the mineral processing industry, the commercial applications of corona separation are in the concentration of heavy minerals (rutile, zircon, ilmenite, monazite) from beach sands and alluvial sediments, and for the separation of zircon and TiO_2 phases during the processing of heavy mineral concentrates derived from heavy mineral sands (Yongzhi, 1992 and Worobiec *et al*., 2007).

The earliest application of the corona technique for the beneficiation of coal used the particle size range 1700–400 Microns (Mukai *et al*., 1967). A coal product of 2.5–3 per cent ash content enriched in vitrinite was obtained, with recoveries of 96–98 per cent. A further example of the reduction in ash content and maceral separation in coal was shown experimentally by Olofinskii *et al.* (1959). Here a corona-chamber, tribo-adhesive-drum and fluidized-bed electric separators were used for beneficiation, size classification, and dust recovery. The results revealed that particle size and coal density were responsible for the separation of the coal particles, with coarse and fine fractions having different mineral and maceral contents.

The Advanced Energy Dynamics (AED) as reported by Lockhart (1984) conducted an extensive test in beneficiating coal particles down to 37 micron size levels. The result indicated that significantly higher quantities of ash (mineral-rich particles) and total sulphur contents could be removed using electrostatic methods than could be achieved using any conventional wet beneficiation method. Recoveries were higher, with the removal of 65 to 89 per cent of ash particles and all at appreciably lower operating costs.

The electrostatic separation of pyrite from coal using the corona roll separator was conducted by Butcher and Rowson (1995) on Moira Pottery coal, using various atmospheres, feed pre-treatments, particle distribution sizes and relative humidities. The authors established that an ash reduction of 50.64 per cent could be achieved under a compressed air atmosphere using -500 + 300 micron particle size fractions relative to only 19.07 per cent ash reduction under ambient condition on the same size range. Results obtained under the nitrogen and carbon dioxide atmospheric condition were found to be comparable to results achieved under standard air atmospheric conditions.

However, certain limitations in efficient separation of varying mineral-rich coal particles were noted when using the corona electrostatic separation for coal beneficiation. Thus further investigations were undertaken by other authors and it was established that triboelectrification was able to increase the effectiveness of particle separation due to its ability to separate coal particles with close work functions little difference in conductivities.

A further limitation was noted by early researchers, namely, that there was a limitation in the separation of particles below several hundred microns using the corona technique (Higashiyama and Asano, 1998). This was further investigated using the triboelectrostatic technique as well.

Triboelectrostatic method

The electrical separation using the tribocharging method has been shown to have considerable potential for coal preparation in the finer size ranges. The triboelectric separation of coal and its tribocharging characteristics have been investigated by many researchers and all have reported successful separation of mineral matter (high ash forming particles) from coal (Mukherjee *et al*., 1987; Nifiku *et al*., 1989; Ban *et al*., 1993a, 1993b; Higashiyama *et al*., 1998; Trigwell *et al.* 2003b; Dwari and Rao, 2008; Dwari and Rao, 2009). This method, however, has not reached commercial status in the coal industry as yet, as reported by Hower *et al.* (1997), Dwari and Rao (2007) and Dwari and Rao (2008).

This electrostatic method takes place in a separator using a cyclone, fluidized bed, octagonal rotary chamber, a rotating cone or a charging pipe. The tribocharging occurs through the impact of particles with other particles either by contact or friction or with a third material, usually the walls of a container or pipe. This is followed by the downward freefall of the particles through an electric field that deflects the particles according to the magnitude and sign of their charges (Gidaspow *et al*., 1987; Masuda *et al*., 1984; Finseth *et al*., 1993; Higashiyama *et al*., 1998).

The test conducted by Masuda *et al.* (1984) using a cyclone charger (Figure 1) illustrated that positively charged coal particles are deflected towards a negative electrode and the negatively charged particles (usually mineral-rich (ash-forming) particles) are deflected towards a positive electrode. The result obtained indicated that the coal ash content was reduced from 15.2 per cent to 7.1 per cent with a clean coal recovery of 90 per cent. This finding is supported by the investigations conducted by Lockhart (1984) and Alfano *et al.* (1988) where they found that clean coal particles are generally charged positively and mineral-rich or high-ash coal particles are charge negatively.

Based on these results and observations, further research was undertaken to establish the impact of varying operating parameters on efficiency of electrostatic separation potentials of coal. A copper tribocharger pipe operating under different conditions such as varying velocity, different concentrations (or loads) of coal feed in air and different separator voltages were investigated by Finseth *et al.* (1993). The authors found that the triboelectrostatic beneficiation method using a tribocharging pipe (Figure 2), had efficiently removed high ash particles thereby producing a clean coal with 2.1 per cent ash (relative to the 24.4 percent ash in the feed coal) and 0.6 per cent sulphur (with 1.4 per cent in the feed coal) and achieved a carbon recovery rate of 38.8 per cent.

Dwari and Rao (2006) also investigated the effect of different tribochargers on high ash non-coking Indian thermal coal using particle size ranges of -300 + 210 μm at a constant voltage of 15 kV and a tribocharge period of 5 minutes. Copper was found to have the best separation efficiency among the tribochargers tested and it was concluded that this was due to copper's higher electrical conductivity. The results obtained by these authors on the high ash Indian coal shows a clean coal product collected in the negative bin with 18 per cent ash relative to 43 per cent ash content in the feed coal. The parallel heavy media washability test conducted on the same high ash coal was able to reduce the ash content only to 25 per cent ash, with a carbon recovery yield of 65 per cent.

The removal of pyritic sulphur from finely ground coal was conducted by Gidaspow *et al.* (1987) in an electrostatic sieve conveyor. The result obtained showed that the pyritic sulphur content of 2.4 per cent in the feed coal was reduced to 0.86 per cent after a five stage sieve conveyor. The relatively high rate of efficiency was attributed to the grinding of the coal to -40 μm size which resulted in good liberation of the pyrite minerals from the organic coal matrix and hence ease in separation (Figure 3).

The precombustion cleaning of coal by triboelectric separation of minerals was also examined by Trigwell *et al.* (2003b). These results indicated that the triboelectric separation of minerals from coal is a viable beneficiation method with significant potential commercial application. Clear reduction of both sulphur and ash contents for Pittsburgh No. 8 and Illinois No. 6 coal samples was illustrated by petrographic and XRD analyses undertaken on the feed and separated coal samples. Finer grinding of the coal samples yielded even cleaner coal, with the Pittsburgh samples showing a greater reduction for both sulphur and ash as compared to the Illinois feed and cleaned coal due to better mineral liberation. Similarly, Lewowski (1993) studied the electrostatic desulphurization of polish steam coals and his results confirmed those of Trigwell *et al.* (2003b), i.e. that the triboelectrostatic method of dry beneficiation can clearly separate minerals and mineral-rich particles of coal from clean coal particles (Figure 4).

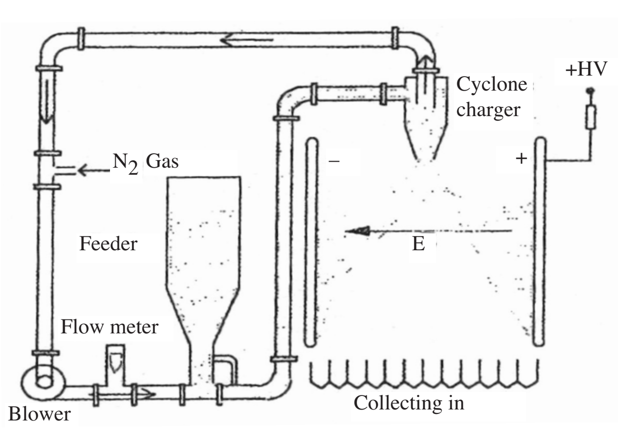

Figure 1—Schematic representation of electrostatic cyclone charger for coal cleaning

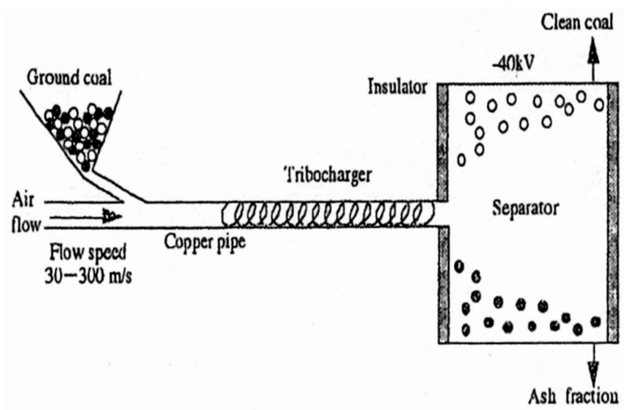

Figure 2—Schematic representation of electrostatic separation with tribo-charging pipe

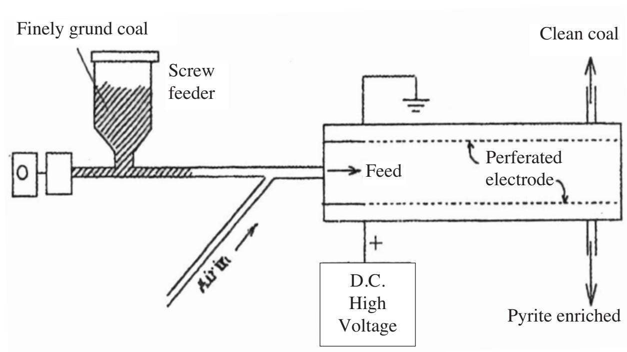

Figure 3—Schematic representation of electrostatic sieve conveyor (Gidaspow *et al.* 1987)

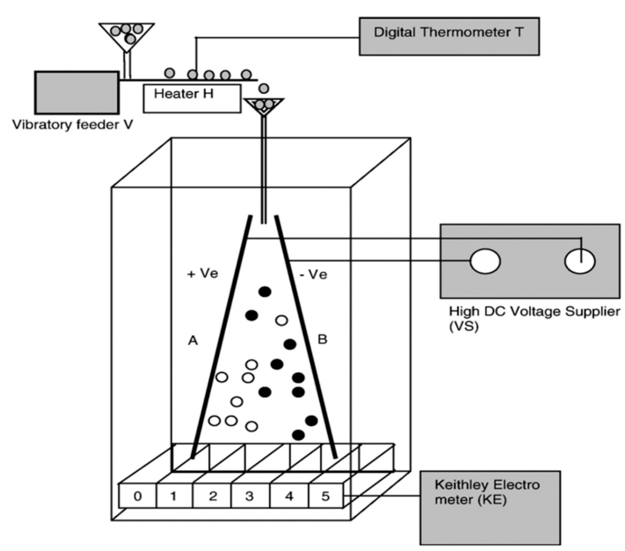

Figure 4—Triboelectrostatic (Dwari and Rao, 2006)

Inculet *et al.* (1980) used a fluidized bed tribocharger for beneficiation tests on coal. Their report indicated that ash was successfully reduced in the product relative to the feed coal while still retaining the same calorific value as in the original feed coal. In addition, the ash content obtained on the electrostatically recovered product was comparable to that obtained when beneficiating the coal sample using wet processes.

Dwari and Rao (2008) also investigated the potential of a fluidized bed tribocharger with internal baffle system (FTB), this time for the beneficiation of non-coking coal from Hingula block of Talcher coal field. The effect of particle size on the separation potential was determined for two size fractions, -75 mm and -1 mm. The result showed a reduction in ash from 39.39 per cent in the feed coal to 25 per cent ash for the -75 mm size fraction, and to 17 per cent ash for the -1 mm size fraction, the latter with 85 per cent yield. It was concluded that non-liberation of minerals from coal in the -75 mm size range was responsible for the higher ash content. Experimental result obtained at 15 kV and at 30 second tribocharging times revealed that it was possible to achieve 15.6 per cent ash clean coal from 25 per cent feed coal with 69 per cent yield.

A cylindrical fluidized bed tribcharger with internal baffles made of copper metal was recently designed and used by Dwari and Rao (2009). This was used for testing the beneficiation potential of Indian thermal coals from the Ramagundam mines. The authors established that coal particle size distribution, tribocharging time, voltage, gas flow rate and residence time of fluidization all played a role in the separation of clean coal from its associated minerals. These authors reported a reduction in ash content from 43 per cent in the feed coal to 18 per cent in the separated product using -300 micron particle sized material with a 30 per cent yield, at 10 Kv and 60 second tribocharging times. At a higher yield of 67 per cent, an ash content of 33 per cent was obtained. Conventional wet washability studies conducted on this sample resulted in the production of a clean coal product with 25 per cent ash and a yield of 65 per cent.

The separation efficiency for both the triboelectrostatic method and a bench scale fuel oil agglomeration technique was investigated by Hower *et al.* (1997) and the results were compared with each other. The bench scale triboelectrostatic separator was found to provide a more efficient separation in comparison to the bench scale fuel oil agglomeration technique when testing the three eastern Kentucky and two Illinois coals. Petrographic analyses indicated that the clean coal fraction was enriched in vitrinite and vitrinite-enriched microlithotypes while the tailings were dominated by inertinites, liptinite and minerals. Further work indicated that similar coals evaluated by this technique have different separation efficiencies due to varying moisture contents. The authors then proposed that moisture reduces the degree of charging and lowers the separation efficiency but it is not clear whether the driest materials had the best charging properties (Mazumder *et al.*, 1995; Kwetus, 1994). Subsequent research reported by Mazumder *et al.* (1995) has shown that the resistivity of coal particles will depend greatly on the moisture and ash content of the feed coal and therefore different types of coal are likely to have different resistivity.

Based on the observations above, further studies were undertaken on how to modify or alter the surface energetic structure of fine coal in order to improve its separation efficiency. The increase in coal separation efficiency after chemical pretreatment was first investigated by Zhou and

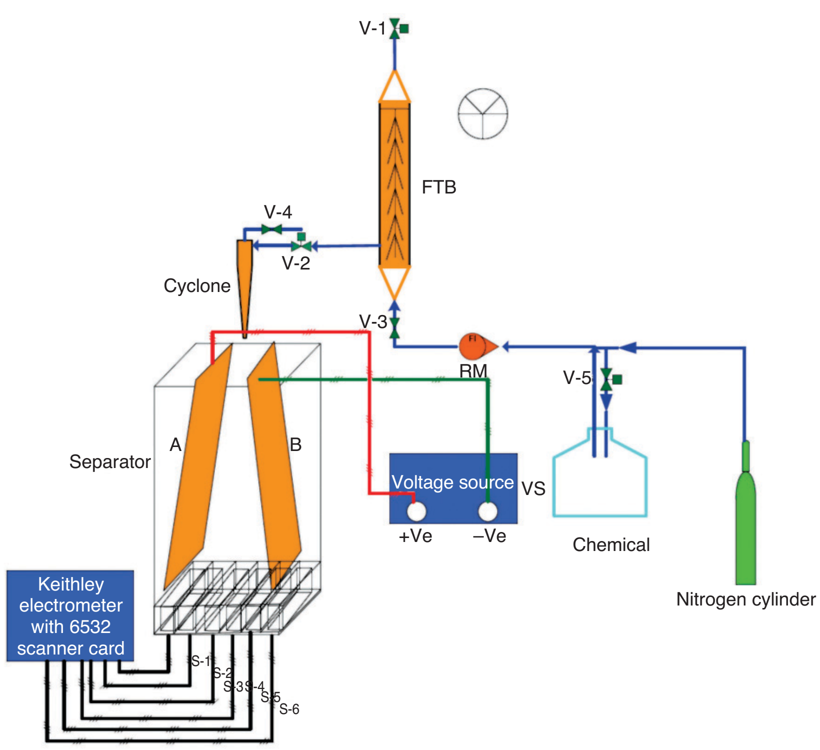

Figure 5 Schematic representation of fluidized bed triboelectrostatic separator (Dwari and Rao, 2006)

Brown (1988). They utilized the vapours of different organic chemicals such as methyl acetate, acetone, and acetic acid under dry nitrogen atmosphere in the fluidized-bed tribo-charging medium in order to improve the charging capability of the coal. The surface treatment performed on the coal samples with particle sizes between 75 and 150 microns showed an improvement of separation to some degree. Trigwell *et al.* (2003) studied the influence of acetone, ammonia, and sulphur dioxide vapours on the charge properties of coal exposed to these chemical. They found beneficiation to be slightly enhanced when using acetone whereas ammonia was found to be detrimental to benefi-ciation. SO_2 was found to be ineffective as a conditioning agent. Dwari and Rao (2009) recently reported ongoing research in which fine coal is being treated in the vapour of acidic and /or basic organic solvents in the fluidized bed tribo-charger. The results, however, will be presented only in future publications.

Mazumder *et al.* (1995) suggested that there are several fundamental factors associated with tribocharging and separation processes which have been hindering commercial implementation to date. This included (1) the effect of the coal surface composition on work function and (2) the composition of different tribochargers such as copper, stainless steel, aluminium and nylon. These aspects were evaluated by Trigwell and Mazumder (2001) using X-ray photoelectron spectroscopy and UV photoelectron spectroscopy. The investigation showed that the work functions for samples varied considerably as a function of the samples' surface composition, which in turn can differ due to alteration in their surface composition as a result of exposure to different environments. This has led to the understanding that electron transfer during frictional charging is surface-properties dependent rather than bulk-properties and that the magnitude of charge and polarity transferred between two dissimilar materials was controlled partly by the surface chemistry (Ruckdeschel and Hunter, 1975; Trigwell, 2003; Trigwell *et al.*, 2003a; Sharma *et al.*, 2004; Mazumder *et al.*, 2006).

Preliminary results of triboelectrostatic separation of South African coal

On the basis of the enhanced understanding gleaned from previous researchers, preliminary tests using the triboelectric separator were undertaken by Bada (2010 and in press) on a variety of South African coals.

Figure 6 shows the rotary triboelectrostatic separator (RTS) used for the beneficiation of South African fine coal, with the characteristic features discussed by Bada *et al.* (2010). The RTS tests conducted by Bada *et al.* (2010) reduced the ash content of the -177 micron coal fractions from 36 and 31 per cent in two high ash power station feed samples to 14.9 per cent and 12.2 per cent respectively, with corresponding combustible recovery values of 10.7 per cent and 8.9 per cent. Total sulphur contents were reduced from 2.1 per cent to 0.9 per cent and from 2.8 per cent to 0.4 per cent, with corresponding combustible recovery values of 5.7 per cent and 8.9 per cent, respectively.

Bada reported a further investigation using a two-stage separation process on the -177 μm size fraction. This indicated that the RTS reduced a feed coal with 30 per cent ash to a clean product of 10.76 per cent and 19.46 per cent ash respectively, at a combustible recovery of 9.83 per cent and 53.02 per cent. The calorific value for the feed coal was increased from 20.149 MJ/Kg to 27.479 MJ/Kg with a combustible recovery of about 10 per cent after the second stage of separation. The single stage separation also produced a clean coal product with 25.7 MJ/Kg, 14.67 per cent ash and 25.22 per cent combustible recovery.

A similar separation performance with another high ash power station feed coal achieved a coal product of approxi-mately 17 per cent ash with a combustible recovery of 50 per cent when the separation voltage was at 20 KV.

Bada *et al.* (2010) then examined the effect of Co-flow on two seam coals, the Number 2 and 4 Seams in the Witbank Coalfield. The effect was evaluated on the basis of grade (ash content) and recovery of the coal products generated. The effect of co-flow rate was assessed in order to maximize coal cleaning.

Co-flow, also known as the flow straightening process, is provided for sweeping away the particles drawn to the surface of electrodes and for reducing the turbulent flow by forming smooth co-flow of gas parallel to the feed stream upon entering the separation zone. The airflow within the separation zone is expected to be laminar so that the charged particles are only deflected by the action of the electric field which is of comparable strength to the drag force.

The test on No. 2 and No. 4 seam coals were performed at a constant injection velocity of 1.9 m/s and a varied outlet velocity of 1100 ft/min, 1300 ft/min and 1500 ft/min. The effect of co-flow speeds of 2.5 m/s, 3.0 m/s and 3.5 m/s for No. 2 seam coal are presented in Figure 7.

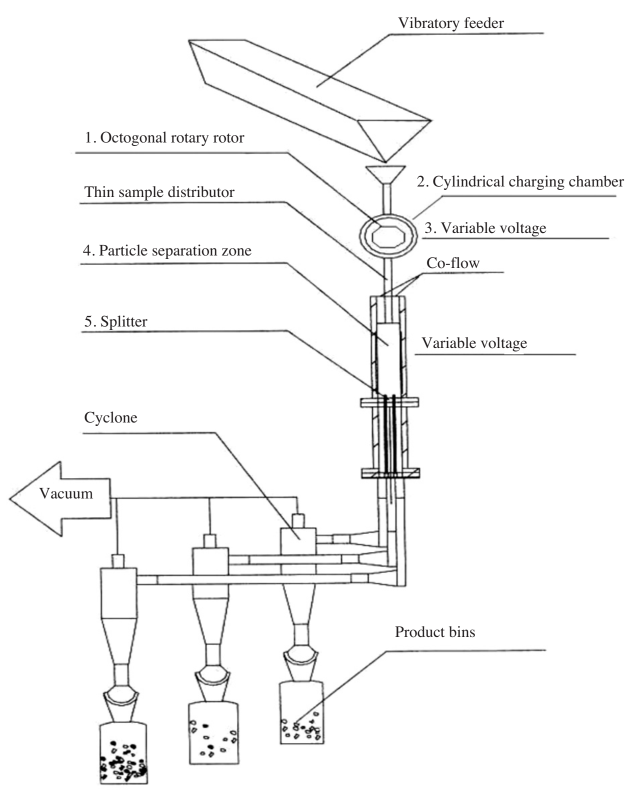

Figure 6—Schematic representation of an octagonal rotary tribo-electrostatic separator (Bada *et al.* 2010)

The highest grade product from No. 2 Seam was obtained at the lowest co-flow velocity of 2.5 m/s, with a product ash of 8.9 per cent and 9.6 per cent yield from a feed coal of 30.4 per cent ash. At 3.5 m/s co-flow velocity, a coal product with 9.41 per cent ash was obtained under the same two stage test. The same trend was also observed for No. 4 seam coal as illustrated in Figure 8 where the highest grade coal product was obtained at 2.5 m/s co-flow velocity.

At 2.5 m/s co-flow velocity for the two coals presented, the results show that the highest quality coal products were obtained at 1100 ft/min outlet velocity. This was assumed to be the result of a decrease in turbulent flow caused by the smooth stream of air within the separation zone as the outlet velocity decreases. A similar result was observed by Tao *et al.* (2009), where an increase in co-flow velocity unfavourably affected the separation capacity of the cylindrical rotary separator.

In terms of qualitative differences between feed coals and final product after triboelectric beneficiation, Bada *et al.* (2010, in press) undertook XRD analyses on the samples under investigation. The diffractograms in Figure 9 to 12 illustrate the X-ray diffraction patterns for five South African coals and their products. Analysis reveals that the South African feed coals consist mostly of crystalline minerals such as quartz and kaolinite with a smooth hump representing the organic fraction. The peak intensities of quartz and kaolinite in the feed coals are very strong relative to the considerably lower peaks in the clean products from the single pass and second pass. This reduction in peak intensities is characteristic of the reduction in mineral matter content after beneficiation, which is typical in processing technology of high ash coals of the southern hemisphere. In contrast, a lower organic hump adjacent to the high mineral matter peaks in the feed coals followed by a much larger hump in the cleaned product corresponds to the higher proportion of organic matter and lower mineral matter contents in the products coal, as may be seen in all the coals tested.

The impact of triboelectrostatic separation on commercial parameters such as calorific value, total sulphur and ash content is illustrated in Tables I and II. From these it is

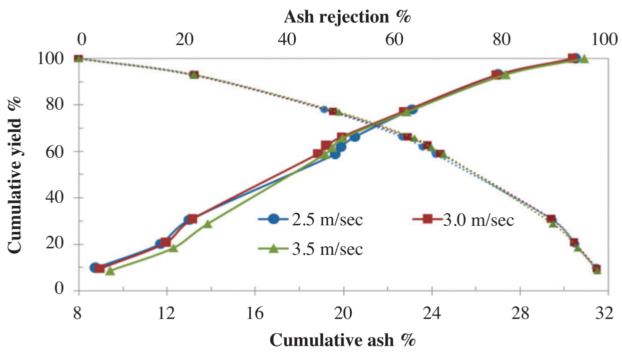

Figure 7—Effect of Co-flow on No. 2 seam coal at constant air velocity: 1.9 m/s; charging and separating voltage: 0 KV and 12.5 KV; and different outlet velocity of 1100 ft/min, 1300 ft/min and 1500 ft/min

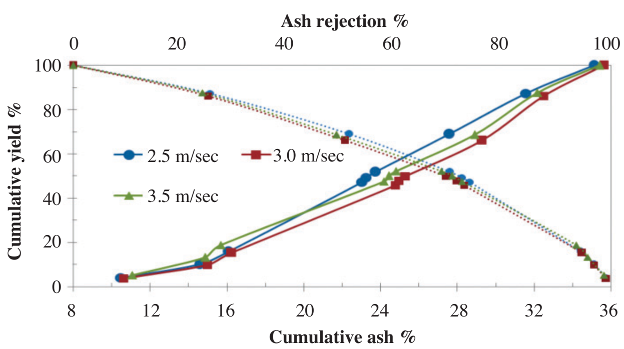

Figure 8—Effect of Co-flow on No. 4 seam coal at constant air velocity: 1.9 m/s; charging and separating voltage: 0 KV and 12.5 KV; and different outlet velocity of 1100 ft/min, 1300 ft/min and 1500 ft/min

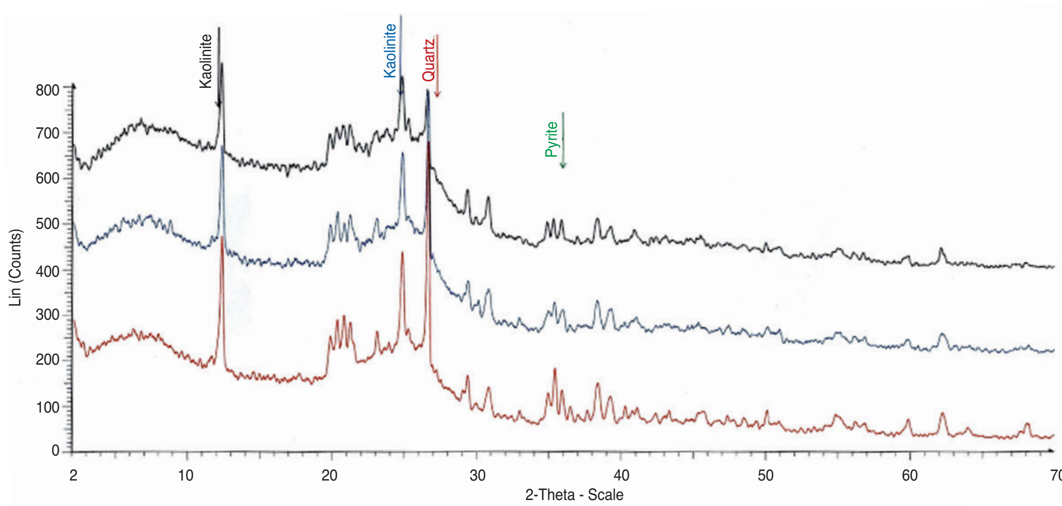

Figure 9—X ray diffraction pattern K feed (below), cleaned single pass product (middle) and cleaned second pass coal product (above) after triboseparation

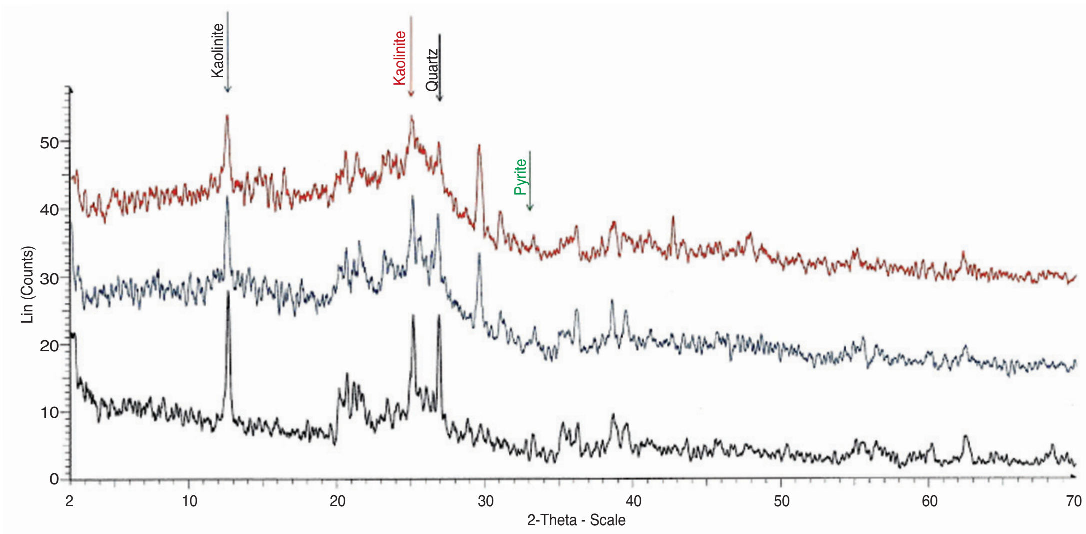

Figure 10—X ray diffraction pattern M feed (below), cleaned single pass product (middle) and cleaned second pass coal product (above) after triboseparation

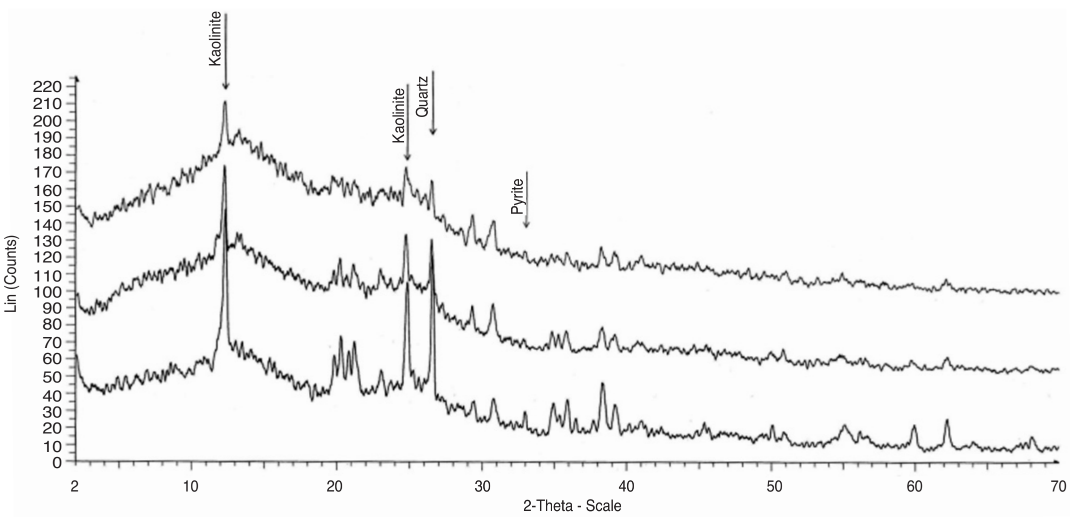

Figure 11—X ray diffraction pattern of No. 2 seam feed coal (below), cleaned single pass product (middle) and cleaned second pass product (above) after triboseparation

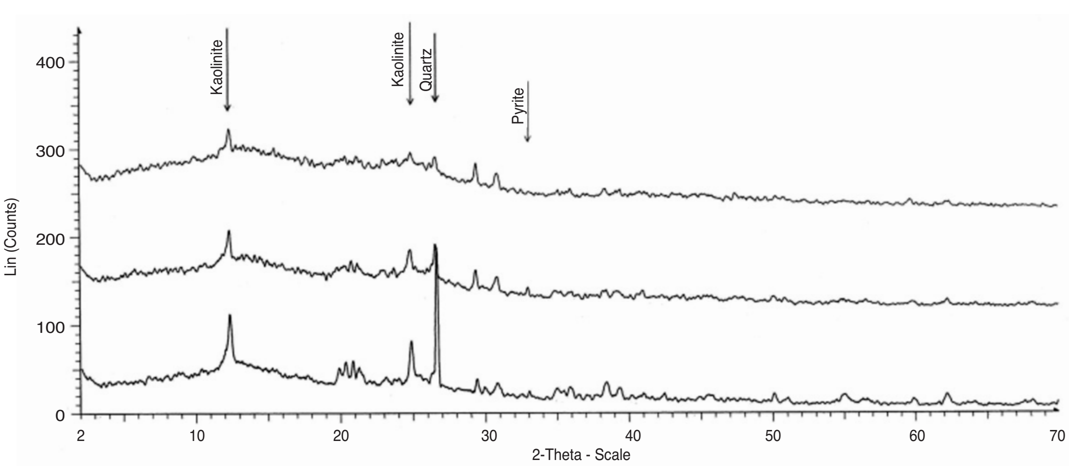

Figure 12—X ray diffraction pattern of No. 4 seam feed coal (below), cleaned single pass product (middle), and cleaned second pass product (above) after triboseparation

Table I

Second stage triboelectrostatic test results

Coal (-177 μm)	Feed ash content (%)	Calorific value (MJ/Kg)	Total sulphur	Second pass (cum. ash) %	Cum. Wt %	Calorific value (MJ/Kg)	Total sulphur
L	31.30	21.313	1.740	12.20	8.90	27.730	0.351
No. 2 seam	30.40	20.872	1.610	8.90	9.60	29.438	0.718
No. 4 seam	36.00	18.126	1.590	10.94	6.01	28.183	0.873
M	30.00	20.149	2.35	10.76	9.83	27.497	0.725
K1	36.00	21.735	1.90	14.52	8.49	27.023	0.565
K2	22.00	24.530	0.884	9.98	3.06	28.350	0.510

Table II

Single stage triboelectrostatic test results

Coal (-177 μm)	Feed ash content (%)	Calorific value (MJ/Kg)	Total sulphur	Second pass (cum. ash) %	Cum. Wt %	Calorific value (MJ/Kg)	Total sulphur
L	31.30	21.313	1.740	14.64	17.11	26.853	0.513
No. 2 seam	30.40	20.872	1.610	14.64	25.66	26.952	0.809
No. 4 seam	36.00	18.126	1.590	18.18	17.36	25.160	1.02
M	30.00	20.149	2.35	14.67	25.22	25.669	0.924
K1	36.00	21.735	1.90	17.42	19.58	25.955	0.896
K2	22.00	24.530	0.884	13.12	11.30	27.233	0.685

possible to observe the process optimum conditions yielding maximum ash reduction and product recovery, and the factors responsible for effective separation using data from both single and two stage pass results. For example, in Table II, coal L feed has an ash content of 31.3% which is reduced to 14.6% after a single stage pass. The effectively increases the caloric value from 21.3 MJ/Kg to 26.8 MJ/Kg and reduces the sulphur content from 1.7% to 0.5%. The preliminary data obtained for both separation stages indicate that single stage triboelectric separation is effective in producing cleaned coals, but cleaner, higher grade with lower total sulphur content products are obtainable under two stages of separation but at the expense of coal carbon recovery.

Conclusions

It is evident from this review that coal, and more specifically South African coal, can be beneficiated through the application of dry cleaning processes. The application of triboelectrostatic separation as an alternative approach to wet beneficiation processes has been shown to be a promising step in realizing this goal, and more specifically for the upgrading of fine coal. Furthermore, it does not have the drawbacks of wet cleaning, subsequent drying, and the processing of associated aqueous waste.

The importance of this research, in terms of its future application, is that it could be of potential benefit to a number of industries. Providing lower ash coal could increase the efficiency of all pulverized fuel fed kilns in the cement industry and certain operations in the pyrometallurgical field, such as iron and steelmaking.

It could lead to higher efficiencies in coal utilization by reducing the unburned carbon content obtained in fly ash. This in turn would lead to low carbon ash products which have high value as mineral admixtures for cement in the manufacturing of concrete. More so, the application of RTS to beneficiate phosphate from its host rock concentrate could be of benefit to the South African phosphate industry.

Such process developments are likely to become increasingly important in a country such as South Africa due to the fact that water is an extremely limited commodity especially in locations where future mining will take place and because millions of tons of ultra fine coal are being produced and stored in slurry ponds or discarded in abandoned mines.

Given that such fine coal material is comprised of minerals that are largely liberated from their host coal particles and that a significant proportion of clean coal particles in this fine size range is therefore available (subject only to successful separation), beneficiation of this material could lead to the production of high grade, low ash products with potentially high value. Markets for such materials could range from feed to power stations, cement kilns and blast furnaces using pulverized coal injection and for the reduction of chromite or manganese ore in the ferroalloy industry. Current research is also underway to utilize ultra clean fine coal as a source for nanotechnology. Perhaps the greatest application of this dry fine coal beneficiation process would be the significant reduction of Fe-S pyritic minerals and the associated trace elements including mercury and arsenic. If successful, this could lead to the potential reduction in the need for flue gas desulphurization plants and associated technologies in utilization of coal in future.

For these reasons, further research is required to upgrade the rotary triboelectrostatic technique for specific application to South (and southern) African coal. In order to achieve this, a variety of parametric studies is required in order to optimize the conditions suitable for these coals and to obtain data for validating this process for scaling-up purposes and for evaluating it relative to conventional wet fine coal beneficiation processes. In addition, the surface electrodes used in this research would be replaced with grid electrodes to mitigate the effect of particle build-up within the separating zone and increase the separation efficiency and recovery at higher separation voltage.

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