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Triboelectrostatic Separation of Mineral Matter from Slovakian Coals

Soong,Y. [1], Link, T. A. [1], Schoffstall, M. R. [1], Turčániová, Ľ. [2], Baláž, P. [2], Marchant, S. [1] and Schehl, R. R. [1]

Triboelektrostatická separácia minerálnej substancie zo slovenského uhlia

V článku sú diskutované niektoré technické aspekty triboelektrostatickej separácie a výsledky aplikácie tohto postupu pri úprave troch typov uhlia, konkrétne energetického uhlia z Cígľa, Handlovej a Novák. Bolo zistené, že účinnosť separácie veľmi úzko závisí na druhu separovan uhlia. Prvé výsledky preukázali súvislosť medzi účinnosťou separácie obsahom popola v uhlí.

Key words: triboelectrostatic separation, Slovak steam coal, ash content.

Introduction

Slovakian brown coal is a significant resource of the power production section of Slovakia. The coal is mined in five mines (Handlová, Cígeľ, Dolina, Záhorie and Nováky). These coals contain rare organic substances, and elevated levels of ash, sulphur and arsenic. The reduction of emitted oxides of the above components to environmentally acceptable levels, requires the use of dry or wet precombustion cleaning processes.

Precombustion cleaning is very desirable since the cleaning of coal reduces the environmental hazards arising from SOx, NOx, and toxic trace elements such as arsenic, cadmium, mercury, etc., present in the coal. Precombustion beneficiation of coal can reduce fouling in combustors and the need for post combustion flue gas cleanup. Typically, precombustion beneficiation has been achieved by processes which separate coal from its impurities in an aqueous suspension. As the requirements for removal of mineral impurities become more stringent, these processes need to work on finer particle sizes to insure liberation of the mineral matter from the coal. The resultant wet fine coal product poses a number of practical handling problems if it is to be used in conventional combustion systems. Dewatering and drying of fine coal slurries can be expensive. The potential means to avoid the expense of dewatering fine coal products is to use dry beneficiation processes.

Dry beneficiation is used for a wide variety of bulk materials, but has not gained wide popularity in the coal industry (Lockhart et al., 1984). These separations are usually based on differences in density or surface properties between mineral impurities and clean coal, but there are alternative dry separations based on differences in electrostatic behavior (Butcher and Symonds, 1981; Ealston, 1961; Kelly & Spottiswood, 1989). Electrostatic separations have a long history but have not achieved commercial status in the coal beneficiation industry. Electrostatic methods for separation of mineral matter from the organic phase of the coal is based on differences in the ability of these two phases to develop and maintain a static charge in a variety of different types of separators. Previous studies (Gidaspow et al., 1984; Masuda et al., 1984; Link et al., 1990 and Finseth et al., 1992, 1994, 1997) evaluated various aspects of bench scale dry fine coal cleaning using triboelectric charging techniques.

Current work in the FETC Solids Processing and Separations Division has focused on the beneficiation of coal after triboelectric charging. In this process the fine coal powder is entrained in a gas stream and made to impact on a metal surface under turbulent flow conditions. This particle-to-surface contact causes differential charging of the organic and inorganic phases in the coal with the particles of organic matter acquiring a positive static charge and the mineral matter, both silicate and sulfide, acquiring a negative charge. When this gas-entrained charged cloud of particles is directed

[1] *Dr. Y. Soong, Dr. T. A. Link, Dr. M. R. Schoffstall, S. K. Marchant, CPA, MBA, Dr. R. R. Schehl.* U.S. Department of Energy, Federal Energy Technology Center, P.O. Box 10940, Pittsburgh, PA 15236-0940, U.S.A.
[2] *Ing. Ľudmila Turčániová, CSc., RNDr. Peter Baláž, DrSc.* Ústav geotechniky SAV, Watsonova 45, 043 53 Košice
(Received July 18, 1998)

into a high voltage field, the positive and negative particles deposit on oppositely charged plates. Coal samples deposited on the electrodes as well as those passing through the separation chamber were collected and analyzed to determine separation efficiency.

This paper discusses some of the technical aspects of the triboelectrostatic separation and the results of applying this technique to the beneficiation of three types of Slovakian coal, namely Cígeľ, Handlová and Nováky steam coal.

Background

Electrostatic separation of particles from gas streams is a well-developed commercial technology and is practiced on a large scale in electrostatic precipitators used on electric utility boilers. There are a number of other well-documented industrial separations based on related technology for the beneficiation of minerals (Ciccu, 1989), food products, and recycling wastes. Most of these separations utilize induction or corona charging and the separation is based on differences in the charging or discharging characteristics of particles of different composition. Methods utilizing induction or corona charging have also been applied to the separation of coal from its mineral impurities, but for the most part these methods have met with limited success (Inculet, 1980). Recent efforts to use electrostatic methods for cleaning of coal have focused on the use of triboelectric charging of the coal particles followed by separation of the dry charged material in a static high voltage field (Zhou and Brown, 1980; Alfano et al., 1985). These studies have demonstrated that it is feasible to use triboelectric charging to achieve high separation efficiency, but the application of this technique at a commercial scale has yet to be demonstrated.

Triboelectric charging, charge exchange between materials during forceful contact, occurs when any two different surfaces contact one another (Lowell and Rose-Innes, 1985). The resultant static charge is not usually noticeable unless it occurs in a system where the conductivity of the material surface is low, allowing the charge to build up to high levels. This static buildup can be a significant problem in the handling of large amounts of fine dry powders such as flour or powdered chemicals and polymers. It can also be used as the basis of effective separation of particulate mixtures if the components of the mixture charge differently on contact with a surface. It has been demonstrated that triboelectric charging of coal has definite advantages over inductive or corona charging because the mineral and the organic phases assume opposite charges and surface conductivities are low. These factors simplify the rapid separation of the phases when compared with corona or induction charging where all particles are charged with the same charge and the separation of different phases relies on differences in charging or discharging characteristics. This process separates materials based on one or more of their electrical properties of work function or contact potential. When two materials are in contact, electrons move until the energy of electrons in each material at the interface is equalized. The material with a higher affinity for electrons gains electrons and charges negatively, while the material with the lower affinity loses electrons and charges positively. A measure of the relative affinity for electrons is the work function. The values of work function of various compounds in coal such as carbon, Cu, Al_2O_3, MgO, SiO_2, and mineral are 4.0, 4.38, 4.7, 4, 5 and 5.4, respectively (Kim et al., 1997). Figure 1 shows the principle of a triboelectrostatic separation system for recovering the clean coal. Particles of clean coal (carbon; 4.0 eV) and minerals (SiO_2; 5.00, Al_2O_3; 4.7 eV) can be imparted positive and negative surface charges, respectively, with the copper (Cu; 4.38 eV) tribocharger due to differences in the work function values of the particles and the tribocharger, and can be separated by passing them through an external electric field. The differential charging of coal and its mineral impurities, achieved in the triboelectrostatic method, makes it possible to use a static high voltage separator to direct the clean coal and mineral refuse into separate receivers as shown in Figure 1.

Methods

Triboelectrostatic research at FETC has focused on development of a totally pneumatic system without mechanical charging devices (Finseth et al., 1997). A schematic of this separator is shown in Figure 2. The separator used in this work was developed for parametric studies of coal/mineral separations and consists of a venturi feed system driven by nitrogen pressure, an injection nozzle, and a high voltage separation section. The coal particles pass through the venturi feeder and become charged in this turbulent flow zone by contact with the copper tubing and with one another. The contact of the particles with copper surfaces, especially in the turbulent zone of the in line mixer, results in effective charging of both coal and mineral impurities. These charged particles then are forced out the nozzle in a ribbon of entrained particles approximately 7.62x 0.3175 cm. This plume of particles is directed between two parallel charged plates 15.24 cm long and 7.62 cm apart. For coal separations this unit is operated + or - 25,000 volts on the separator plates. The positively charged coal particles are attracted to the negative electrode and the negatively charged mineral particles are moved to the positive electrode. A splitter is placed 15.24 cm downstream from the nozzle to separate the coal rich and ash rich fractions and direct them to two collection cyclones. The entire separator is swept with laboratory air by applying vacuum to the outlets of the collection cyclones. Sweep flow enters the separator through flow straighteners around the nozzle to control the flow in the separator section.

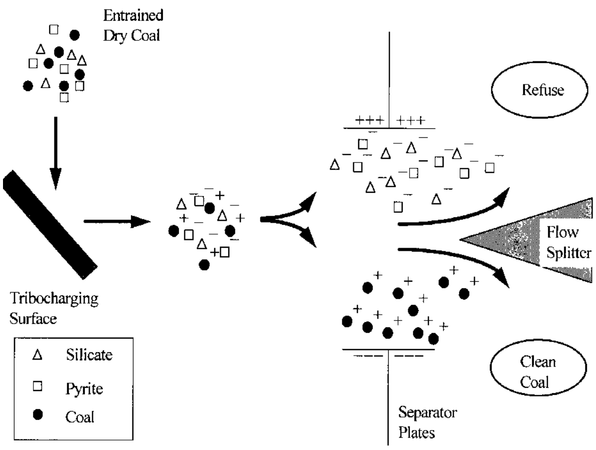

Fig.1. Principles of triboelectrostatic separation.

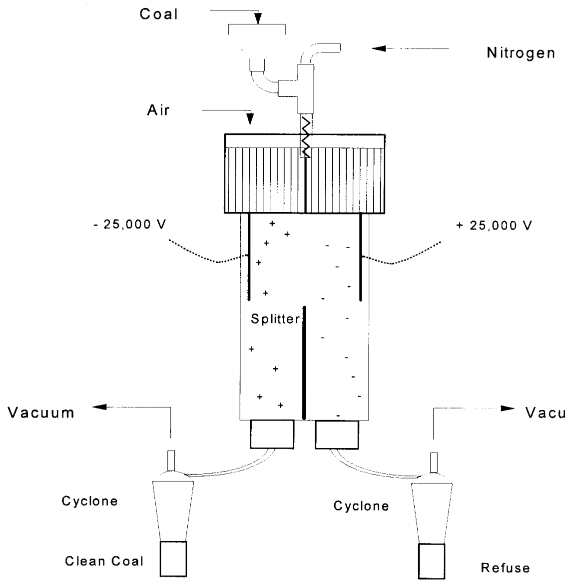

Fig.2. Schematic Diagram od a Triboelectric Separator.

This separator has a capacity of about 8 Kg/hr in continuous operation and can be used in the batch mode using as little as 100g of coal feed. The recovery efficiency of the cyclones is typically greater than 95%.

This simple separator has been used extensively to investigate the dependence of coal separation performance on operation parameters such as feed rate, particle size, voltage, injection velocity and splitter position. In this work we used this apparatus to evaluate a variety of feed coals so that their performance curves could be compared. In this application separations are done with the injector in three positions with respect to the splitter-centered on the splitter, displaced 0.635 cm toward the positive plate and displaced 0.635 cm toward the negative plate. The cleaned coals (attracted to the negative electrode) generated in these three runs, together with the feed, are then analyzed for carbon, ash, and sulfur content to yield a performance curve. These curves can be used to evaluate the potential of coal for separation and to compare the responses of coals from different sources.

This experimental configuration was used to measure the dependence of the separation on three types of Slovakian coals, namely Cígeľ, Handlová and Nováky steam coal. The coals were ground to -200 mesh to approximate the feed to a conventional pulverized coal combustor. Using this configuration the three coals were fed to the separator at feed rates varying from less than 454 grams per hour to more then 4,540 grams per hour. These feed rates correspond to particle-to-gas mass ratios of 0.1 to 1 g coal/g gas. The clean coal and refuse fractions were collected on the negative and positive plates respectively. After collection and homogenization the fractions were analyzed for sulfur and ash content.

Results

The detailed analysis of the Slovakian coals is illustrated in Table 1. Both Handlová and Cígeľ coals have high ash content, of 51.58 and 48.74 wt.%, respectively. The Nováky coal has a relatively high sulfur content of 2.62 wt.%, nearly double to that of Handlová and Cígeľ coals. The moisture content for Nováky coal is the highest at 8.8 wt.% versus that of 7.47 and 5.58 for Cígeľ and Handlová coals.

The quality of this triboelectrostatic separation can be determined by measuring the cumulative recovery of combustible matter, sulfur, and ash as a function of position of the splitter. The results are tabulated in Table 2. The yield of combustible matter and ash on the clean coal and refuse sides is presented as a percentage of the total amount of each component in the feed. Typical performance curves for Handlová, Nováky and Cígeľ clean coals is shown in Figure 3.

Table 1. Ultimate, mineral ash and sulfur form analyses on Slovakian Coals.

Content [wt.%]	Nováky	Cígeľ	Handlová
Ash	28.24	48.74	51.58
Carbon	41.24	27.66	27.14
Hydrogen	4.19	3.43	3.24
Nitrogen	0.80	0.51	0.35
Oxygen	22.92	18.30	16.22
CaO	2.25	1.47	1.22
MgO	0.62	0.94	0.61
SiO_2	17.40	31.70	35.54
Al_2O_3	4.48	9.49	9.19
Fe_2O_3	2.44	3.30	3.20
Na_2O	0.24	0.30	0.49
P_2O_5	0.11	0.06	0.04
TiO_2	0.13	0.31	0.31
K_2O	0.523	1.13	0.93
Volatiles	40.18	29.62	26.70
Moisture	8.80	7.47	5.55
Total Sulfur	2.62	1.37	1.46
Sulfate Sulfur	0.33	0.28	0.27
Pyritic Sulfur	0.32	0.49	0.45
Organic Sulfur	1.96	0.60	0.73

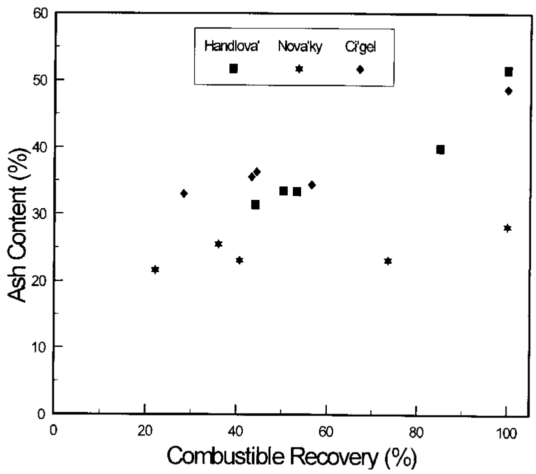

Fig.3. Combustible recovery versus ash content for clean Slovakian Coals.

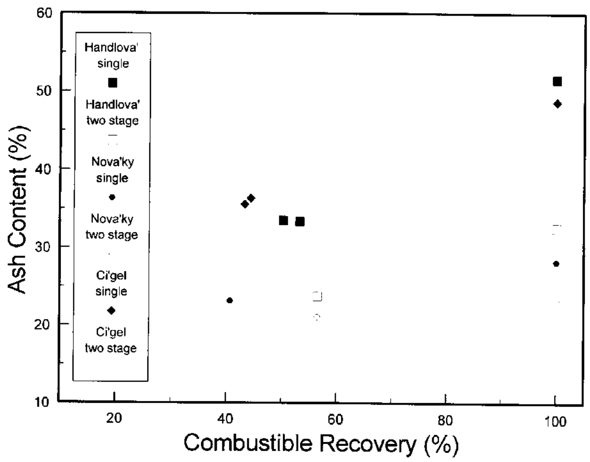

Fig.4. Combustible recovery versus ash content for single and two stages clean.

The recovery of combustible matter in the feed on the negatively charged clean coal side is nearly 85% for Handlová coal with the splitter located to the left-0.635 cm away from the center of the separation chamber. This product, containing 85% of the combustible matter, contains only 39.9 % of the ash which indicates the selectivity of this process. A continuing decrease in the ash content to 33% is observed as the splitter is moved to the center of the separation chamber; however, the combustible recovery drops to around 53.5%. Further reducing the ash content to 31.45 % could be achieved by adjusting the splitter to the right-0.635 cm from the center. This significant reducing of the ash content from 51.58% in the feed to 31.45 % from the product is at the expense of the recovery of the combustible matter. The corresponding combustible recovery for this low ash content of 31.41% is 44.11% for the Handlová coal studied. With this coal the triboelectric separation is particularly effective in removing ash. The trend of the performance curve for Cígeľ coal is similar to that of Handlová coal. The recovery of combustible matter in the feed on the negatively charged clean coal side is nearly 66% for the Cígeľ coal with the splitter located to the left-0.635 cm away from the center position. This product contains 40% of the ash with 66% of the combustible matter. Reducing the ash content to around 35% is obtained by moving the splitter to the center of the separation chamber. The combustible recovery is approximately 44%. Further reducing the ash content to 34% could be obtained by repositioning the splitter to the right-0.635 cm away from the center. This significant reducing of the ash content from 48.74% in the feed to 33% from the clean product is also at the expense of the recovery of the combustible matter. The combustible recovery for this location is 28.29% for Cígeľ coal. For the case of Nováky coal, the performance does not look impressive. With this Nováky coal the triboelectric separation is poorly effective in removing ash. The ash content could be reduced to 21.63% from the feed of 28.24% with the combustible recovery of 22.06%. The reasons behind this poor separation are still under investigation.

The recovery of ash on the positively charged refuse side for Handlová, Nováky and Cígeľ coal is also illustrated in Table 2. The trend of the performance curves for all three coals are similar. The ash content in the refuse is relatively constant around 48 and 28 wt.% for Cígeľ and Nováky coal, respectively. For the case of Handlová coal, the ash content can be increased from 51.58 % of the feed to 58 % with the splitter location adjusted to the left-0.635 cm away from the center.

Table 2. Triboelectrostatic separation results

Handlová	***Feed***	***C+***	***C -***	***C+***	***C-***	***R+1/4***	***R-1/4***	***L+1/4***	***L-1/4***
Weight, gram	100	56	39	52	37	70	31	28	69
Moisture %	5.5	7.2	9.2	6.6	8.5	6.6	8.4	6.5	7.7
Ash %	51.5	57	33	58	33	56	31	58	40
Volatile %	26.7	25	33	23	34	27	35	23	31
Fixed C %	16.2	11	24	12	24	10	25	12	22
Sulfur %	1.46	1.4	1.7	1.3	1.6	1.4	1.6	1.3	1.6
Recov Com%			53		50		44		85
Recov Ash%		62		59		75		31	
Cígeľ	***Feed***	***C+***	***C -***	***C+***	***C-***	***R+1/4***	***R-1/4***	***L+1/4***	***L-1/4***
Weight, gram	100	64	34	60	36	69	22	43	57
Moisture %	7.5	8.6	9.6	8.6	9.6	7.3	8.3	8.7	9.1
Ash %	49	48	36	48	36	49	33	48	40
Volatile %	30	29	36	29	34		42	29	36
Fixed C %	14	14	19	14	20		13	14	14
Sulfur %	1.37	1.3	1.6	1.3	1.6	1.5	1.5	1.2	1.5
Recov Com%			43		44		28.3		66.3
Recov Ash%		64		59		70		42	
Nováky	***Feed***	***C+***	***C -***	***C+***	***C-***	***R+1/4***	***R-1/4***	***L+1/4***	***L-1/4***
Weight, gram	100	52	35	56	38	68	20	25	69
Moisture %	8.8	10	11	11	12	11	12	11	12
Ash %	28	29	25	28	23	28	22	29	23
Volatile %	40	38	38	38	38	39	40	41	40
Fixed C %	23	23	25	22	27	23	26	19	25
Sulfur %	2.62	2.4	2.7	2.4	2.6	2.4	2.7	2.3	2.7
Recov Com%			36		41		22		73
Recov Ash%		53		55		67		25	

** + and - for positively and negatively plate sides, * C, R, and L are the abbreviation for center, right and left positions of the splitter, * 1/4" is 0.635 cm which is the distance from the center.*

The total sulfur content in the separated products can also be seen from Table 2. The sulfur removal is not as impressive on the clean coal plate. We have observed a slight increase in the total sulfur content for the clean coal products. This is probably due to the relative high organic sulfur content of the feed. The majority of the total sulfur in the feed coal is organic sulfur (Table 1). The surface organic sulfur groups will be charged positively and collected in the clean coal side. This will result in the increasing of the total sulfur content in the clean coal side.

The results obtained thus far indicate that this is not exceptional performance for this separator, but it must be remembered that in this simple evaluation test no attempt has been made to optimize separation conditions. Further, this is a single pass experiment with no recycle for recleaning. In an attempt to further reduce the ash content in the clean coal, we have conducted a two stage separation experiment. The two stage separation uses the clean coal products from the single stage separation, as the feed for the second stage of separation. Figure 4 shows the combustible recovery versus ash content for the products obtained from single and two stage separation. For Handlová coal, single stage clean can reduce the ash content to 33 wt.% with 53% recovery of the combustible material. Using the cleaned coal product as the feed for the two stage separation under the same experimental conditions can further reduce the ash content in the cleaned coal product to 23.72 wt.% with a 56.63 % recovery of the combustible material. For the Cígeľ coal, the single stage separation can reduce the ash content to 35% with combustible recovery of 43%. Two stage separation can further reduce the ash content to 27.55 wt.% with up to 60% recovery of the combustible material. For

Nováky coal, the two stage cleaning process does not significantly improve the quality of separation. The two stage separation can only reduce the ash content from 25.54 to 21.95 wt.% while with the recovery of combustible increases from 36% to 56%.

Discussion

Although this technique appears to be widely applicable to different coals, they do respond differently to triboelectrostatic separation. The separation of a 51.58% ash Handlová and a 48.74% ash Cígeľ coal indicated that both coals could be very efficiently beneficiated via triboelectrostatic methods. The quality of separation for the high ash Handlová and Cígeľ coal is far better than that of low ash Nováky coal. The performance of the separator does not show quality separation for the low ash Nováky coal. This poor response could be related to several factors - relative high moisture, particle size, incomplete mineral liberation, some particle charging reversal, particle-particle interaction, and surface oxidation of the coal.

The recovery indicated by this Nováky coal data is low and could be due to the fact that the particle size might be large, reducing the amount of mineral impurity liberated from the combustible matrix. The particle size influences the liberation of the mineral matter, the charging efficiency, and the response of the particle to the electrostatic force in the separator. In order to determine the potential for beneficiation by triboelectrostatic means, we conducted screening tests of the feed coals. Almost 99% of the feed coal samples passed the 200 mesh screens. Nevertheless, during our previous work on triboelectrostatic separation, we have observed that the quality of separation for the 400 mesh coals is significantly improved over that of the 200 mesh coals (Link et al., 1990). The further reducing the size to 400 mesh might improve the liberation of mineral matters; therefore, improves the quality of the separation.

It is also speculated that particle-particle interaction may also play an important role in the separation. We assume just two phases, organic and mineral, one which charges positive on wall collisions and the other which charges negative on wall collisions. Under turbulent flow conditions, with high particle concentrations, particle-particle collisions can also contribute to the overall charging. In a two-phase system, collisions between particles of a dissimilar phase result in the same final charge as particle wall collisions. Collisions between particles of the same phase, which result in exchange of charge, require that one of the two colliding particles acquires a charge opposite to that resulting from a wall collision.

The charging events represented do not include collisions where one or more of the particles are already charged. A number of references discuss the fundamental processes involved in the triboelectrostatic charging of particles but these fundamental processes is not sufficient to predict the behavior of complex, multiphase systems like coal. For the low ash Nováky coal, the organic phase is being deposited on the positive plate and our simple model indicates that the only way this can occur is by having particle/particle collisions between organics as an important charging event. This observation of coal particles on the positive plate suggests that the contribution from the particle-particle collisions cannot be ignored (Finseth et al., 1992).

This model is also consistent with the data for the high ash Handlová and Cígeľ coal. In both cases because of the high ash content, increasing particle/particle collisions will increase organic / mineral collisions which would result in a positive charge for the organic and them still report to the negative plate. It is still not clear why two identical particles will exchange charges after collision, and why the polarity of charge often depends on the particles. The mechanism of charging coal and mineral particles is complicated by the wide range of effective work functions of these particles and the inter-particles collisions between these particles during charging and separation processes.

During our previous work on triboelectrostatic separation, we have noticed that the quality of separation for fresh ground coal is much better than that of coal being ground days earlier. Oxidation of the coal surfaces is also thought to be hindering the tribocharging process (Link et al., 1990). All coal carbon should ideally adopt a positive charge for electrostatic beneficiation. The tendency of liptinite and inertinite to exhibit bipolar charging may be related to their unique chemical structure (Mazumder et al., 1995). If the coal powder is exposed to air, then surface oxidation reduces the tendency of carbon to charge positively. The di-oxygen molecule is paramagnetic and thus has a very low activation energy to form bonds with free radicals present on the coal. Surface peroxides thus formed may accept electrons during tribocharging to decrease the positive charge character of the coal carbons. In addition, the surface peroxides will undergo further reactions to yield a variety of oxidized carbon functions, which may contribute to the altered charge properties.

Bailey (1993) concluded that the contacted charge exchange is sensitive to the oxidative states of the particle surface. Another very important situation in which relatively high surface charge densities may be sustained aries with surface curvature, in particular when dealing with charged particles. Bipolar charging of powder particles has been observed in a number of powders and is dependent on particles size and contacting surface types as well as relative humidity.

These results obtained from this study are similar to those reported by Finseth et al. (1994) and are comparable to results from Pittsburgh coal. The degree of ash removal and combustible recovery was found to be dependant on the type of coal, and to some extent on mineral liberation, humidity, particle-particle interaction, charging reversal and the surface oxidation of the coal. The two stage cleaning process can further reduce the ash content from the clean product generated from a single stage process.

Conclusions

Current results using research on triboelectrostatic beneficiation of fine coal indicate that the principle can be applied to a variety of different coals and under the appropriate conditions, triboelectrostatic separation can be very effective for removal of ash from fine coals. The performance of this separation can be comparable with other advanced fine coal cleaning processes without the need to remove water from the product. The future focus of research is in the area of continuous operation in order to determine the optimum design of a practical separator and to determine the influence of important processing parameters on performance.

The preliminary data obtained from Slovakian coal separation indicates that simple triboelectric separator is effective in producing cleaned coals. The degree of ash removal and combustible recovery was found to be dependant on the type of coal, and to some extent on mineral liberation, humidity, particle-particle interaction, charging reversal and the surface oxidation of the coal. A simple parallel plate separator can quickly evaluate the response of a given coal to this beneficiation approach. The two stage process can further reduce the ash content form the products generated from the single stage cleaning process.

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