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High Ash Non Coking Coal Preparation by Tribo-Electrostatic Technique

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Abstract

Tribo-electrostatic method is applied to beneficiate non-coking Indian thermal coal from Ramagundam coal mines containing nearly 45% ash content. The microscopic studies revealed that quartz and kaolinite are the dominant minerals whereas illite, goethite, siderite and pyrite are the minor inclusions in the coal. Contact electrification of ash forming minerals and coal matter has been carried out using different tribo-charger materials of Al, Cu, brass, perspex and teflon. The Cu tribo-charger found to be optimum to acquire differential charge between ash-forming inorganics and coal matter. The temperature effect on the magnitude of contact charge acquisition found to be significant. Tests on a laboratory in-house built tribo-electrostatic free-fall separator with minus 300 microns size fraction of coal showed that the ash content can be reduced from 45% to about 18% and it is feasible to obtain a clean coal as judged by the washability studies. The results illustrate that the non-coking coals can be beneficiated using the scientific knowledge on the response and behaviour of coal and non-coal matters to electric charges.

INTRODUCTION

Coal being India's the most abundant fossil fuel, rapid increase in the country's future power generation to meet the growing demand for domestic, industrial and agricultural sectors will be based on this fuel. In India, more than 75 % of non-coking coal produced is used for power generation. At present, nearly 200 million tonnes/year of coal is used for power generation and the average ash in coals is invariably above 40%. The majority of non-coking coal reserves in India are inferior in quality because of drift origin. Most of thick seams are banded in nature. The coal matter in these seams is high in ash content and thus the quality becomes poor because of these bands. The bands themselves are usually in carbonaceous nature and very rarely consist of pure sandstones. As a result the Indian coal seams have basically much higher ash content. It was estimated that more than 65% of recoverable resources of non-cocking coals are inferior in quality and contain about 40-45% ash. The higher ash percentage obviously is correlated with poor calorific value. However, the advantages of Indian coals are low sulphur, chloride, phosphorous, less toxic elements, high ash fusion temperature and refractory nature of ash.

The wet beneficiation techniques are accepted for the reason of produce high quality coal product with high recovery. However these techniques are not economical for high ash non-coking coal in fine size fractions. The alternative technique is the dry beneficiation of coal with the advantages like dry handling of coal and retention of high calorific value at same quality of product in comparison with wet process are more attractive. Electrostatic separation is one of such technique. Electrical separation utilises the inherent differences between the minerals in friction charging, electrical conductivity and dielectric constant properties (Manouchehri et al. 2000a and Manouchehri et al. 2000b). The basis for electrical separation is the interfacial resistance offered by different materials to the flow of electrons. The modifying factors are the specific gravity, size, shape, surface state and purity of the particulates as well as the mechanical and electrical attributes of the separator. The composition of the raw material and its electro-physical properties determine the kind of either conductive induction or tribo-electrification or corona charging mechanism device is applied. Among the known electrical beneficiation methods, the tribo-electric separation process is most suitable for finer materials and minerals with relatively similar and varying electro-physical properties (Knoll and Taylor 1984; Mazumder et al. 1994).

The power plants mainly use pulverised coal instead of lump coal for greater efficiency of boilers and the coal fired plants in India are among the most polluting sources as indicated by environmentalists and pollution control agencies. Recent environmental regulations prohibit using high ash coals in power plants due to the generation of huge quantities of fly ash effecting the atmosphere and aesthetics of the nearby plant area. With this background, a project on "Electrostatic Beneficiation of Indian Thermal Coals" has been undertaken at Luleå University of Technology, Luleå, Sweden, in collaboration with Regional Research laboratory, Bhubaneswar and National Thermal Power Corporation, Noida, financially supported by the department for research cooperation of the Swedish international Development Cooperation agency (SIDA). In this paper, the results achieved on coal with 45% ash content by tribo-electrostatic method have been presented and discussed the methods potential for the beneficiation of non-coking thermal coals.

THEORY OF TRIBO-ELECTROSTATIC SEPARATION

Tribo-electric separation involves charging of particles by contact or friction with other particles or with a third material, usually the walls of a container or pipe, followed by transport or free-fall through an electric field that deflects the particles according to the magnitude and sign of their charge. When two dissimilar particles are in contact or rub against each other, there is a transfer of electrons (charge) from the surface of one particle to the other until the energy of electrons in each material at the interface is equalised. The energy of electrons at the surface of the material is characterised in terms of the Fermi level and a measure of relative affinity for electrons of the material is the work function, which is the energy to move an electron from the surface to infinity. The material with higher affinity for electrons gains electrons (i.e., lower Fermi level or higher work function) and charges negatively, while the material with lower affinity loses electrons (i.e., higher Fermi level or lower work function) and charges positively. Thus the particle that is positively charged after the particle-particle charging mechanism has a lower work funct')n than the particle that charges negatively. In the case of wall-particle charging, the work function of the material of the wall should lie in between the work function values of the two types of particles involved for acquiring different polarity. The work function values for various materials such as C, Cu. Al_2O_3, MgO, and SiO_2 are 4.0, 4.38, 4.7, 4, 5, and 5.4 respectively (Kim et al. 1997).

When two metals of different work functions, ϕ_{M1} and ϕ_{M2} (eV), are brought into contact and then separated, the Fermi levels of the two metals coincide and a potential difference V_c is established across the interface. Harper (1951) suggested that they will exchange electrons by tunnelling so that thermodynamic equilibrium is maintained. The contact potential difference is given by:

$V_C = \dfrac{(\phi_{M1} - \phi_{M2})}{e}$ where e is the electron charge = 1.6×10^{-19} C .

The charge transfer Q during the contact is:

$$Q = CV_C = C\frac{(\phi_{M1} - \phi_{M2})}{e}$$

where C is the capacitance between two adjacent bodies. The capacitance C is given by: $C = \frac{\varepsilon_0 A}{z}$

where A is the effective area of contact, z is the separation at contact, ε_0 is the permittivity of free space = 8.85 x 10^{-12} Fm^{-1}. Then, the transfer of charge Q is:

$$Q = \frac{\varepsilon_0 A}{z} V_C$$

The surface charge density that can be generated during contact is:

$$\sigma = \frac{Q}{A} = \frac{\varepsilon_0}{z} \frac{(\phi_{M1} - \phi_{M2})}{e}$$

When two bodies are separated after contact the capacitance C decreases and Q decreases until charge exchange by tunnelling ceases. Harper (1951) investigated that at about 1 nm distance the cut off of tunnelling current is abrupt and for a sphere plane geometry, C is given by:

$$C = 4\pi\varepsilon_0 r\left\{0.577 + 0.5\left(\frac{2r}{z}\right)\right\}$$

where r is the radius of sphere and z is the distance of at which tunnelling ceases. A semi-quantitative agreement between theory and experiment had obtained by using the tunnelling cutoff distance of z = 1 nm. Lowell (1975) investigated with real material with rough surfaces and showed that the capacitance can be better estimated by taking into account the fact that most of the two surfaces are separated by much larger distances when closest point of separation is at 1 nm.

Inculet and co-workers (1982) analysed maceral fractions of electrostatically beneficiated coal and found that different maceral types acquired different charge polarities. By petrographic analysis they found that a major portion of the vitrinite charged positively while inertinite charged negatively. The larger pores present in inertinite are thought to cause the preservation of the original plant cell structure in this maceral type harbouring negatively charged minerals not liberated by grinding. Several studies showed that clean coal generally charges positively and ash-forming minerals or high-ash coal charge negatively (Carta et al. 1976; Lockhart 1984; Alfano et al. 1988). Coal matter can acquire negative and positive charge when the carbonate (e.g., limestone and dolomite) and silicate (e.g., shale, slate or marls) gangue are present respectively. In both cases, good separation was achieved (Ciccu et al. 1991). Test results indicate that a variety of coals and different classes of particle size sulphides and silicate impurity minerals can be removed efficiently by triboelectrostatic beneficiation process under appropriate conditions (Finseth et al. 1993). Temperature and moisture played an important role in charging the coal. Large moisture content reduces the degree of charging, but it is not clear whether the driest materials had the best charging properties (Mazumder et al. 1995; Kwetus 1994).

EXPERIMENTAL

Sample Preparation

Ramgundam coal was ground, classified into different size fractions and a representative sample from each size fraction was prepared by standard sampling procedure. The washability study was carried out for each size fraction by sink and float method by using a mixture of acetone and bromoform medium at different specific gravities ranging from 1.3 to 2.0. The sink and float products were washed thoroughly with acetone, dried and analysed for ash. The proximate analysis of float and sink products were carried out with Thermo Gravimetric Analyser (TGA-601). The TGA was operated under N_2 atmosphere for moisture and volatile matter analysis whereas oxygen atmosphere is used for ash analysis. Approximately 10 mg sample was used for proximate analysis. The heating rate was maintained at 10°C min^{-1} while air flow rate was maintained at 6 litre min^{-1}.

Tribo Charging and Charge Measurement

The effect of tribo-charger material on charge acquisition by the independent mineral phases has been studied using a cylindrical rotating drum (diameter 0.095m and length 0.095 m) where the inside lining can be replaced by copper, brass, steel, aluminium, Teflon, Perspex and PVC materials. A 10 g of minus 100 microns size mineral particles are tribo-charged for a fixed time interval and after contact charging, the particles charge polarity and magnitude are measured by Keithley electrometer.

The coal samples were dried in an oven at 100°C. Then the coal is passed through the vibratory feeder fitted with a copper plate. On sliding through the copper plate, the maceral and mineral particles acquired charge based on their work functions due to frictional charging. The charge acquired by the samples collected at different bins after passing through the electric field have been measured using Keithley electrometer fitted with Faraday cup.

Tribo-Electrostatic Test Procedure

The tribo-electrostatic experimental set-up for the separation of coal macerals from ash forming minerals is presented in Fig. 1. It consists of Perspex box fitted with two copper plate electrodes, high voltage Dc voltage supply source (VS), vibratory feeder with hopper (V_1), heater (H_1), digital thermometer (T_1) and Keithley electrometer (KE). There exists a provision to adjust the distance between the copper electrodes and the angle of inclination. The vibratory feeder plate can be replaced with different tribo-charger plates made up of Cu, Al, Steel, Perspex, PVC and Teflon. The thermostat beneath the feeder plate maintains the tribo-charger at constant temperature and the temperature has been monitored with digital thermometer. The rectangular Perspex box height, width and thickness are 1 m, 0.52 m and 0.52 m respectively. Two electrode copper plates A and B of length 0.84 m and breadth 0.43 m have been fixed within the box. The electrode plate is connected in such a way that its top and bottom gap between the plates can be adjusted.

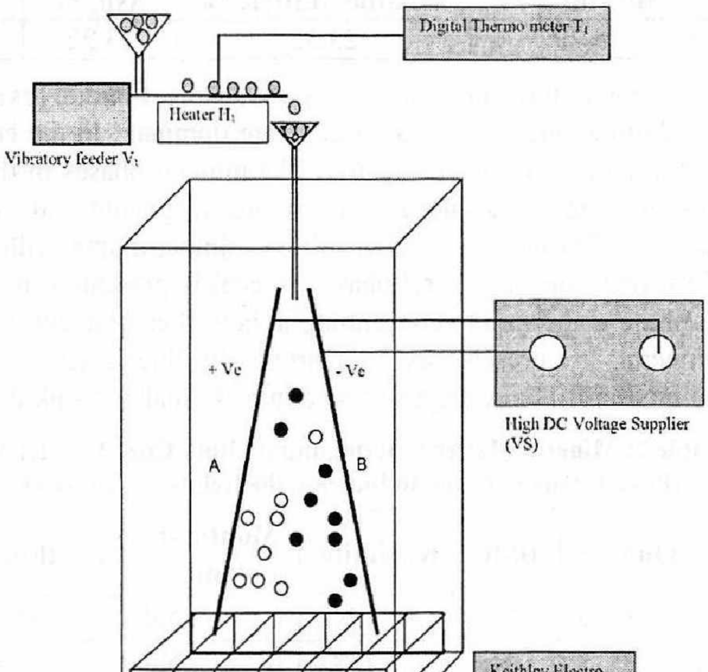

Fig. 1: Schematic Diagram of Experimental Set Up

For the present investigation the top and bottom electrode plate gap is maintained at 0.075 and 0.325 m respectively. The electrode A has been connected to +ve supply source while electrode B is connected to –ve supply source. The electrodes can be charged with a high DC voltage power supply. There are six collecting bins of 0.52x0.065x0.008 m size below the electrode plates to collect the material after passing through the electric field.

Ramagundam coal of -300 micron size fraction has been used in the present investigations. The D_{90} size is 238 microns and the mean diameter of the particles is 88.91 microns. The coal sample was dried at 100°C in an oven before subjecting to the vibrating feeder (V_1). A copper plate on the top of vibrating feeder plate acts as copper tribo-charging medium. The feed rate was slow enough that only a single layer of particles sliding over the tribo-charger. Then the particles travel through the funnel shaped copper pipe and fall between the electrode plates. The negatively charged particles are attracted by the positive electrode and collected at bin 1 while the positively charged particles are attracted towards negative electrode and collected at bin 4. The uncharged and weakly charged particles are collected at bin 2 and 3. The collected samples in all the bins are subjected to proximate analysis. Tests were conducted at three electrode voltages of 10, 15 and 20 KV. The temperature maintained during tribo-charging was in the range of 18-78°C (18, 63, 78°C).

RESULTS AND DISCUSSION

Coal Characterisation

The proximate analysis of Ramagundam coal is presented in Table 1, which shows a high ash content of 43.2%. Washability studies for two coal size fractions of -150 mm and -1 mm were performed to evaluate the potential of clean coal separation and the results are shown in Fig. 2. It can be seen that a clean coal with only 25% ash and about 65% yield is obtainable from both the coal samples, illustrating the non-liberation of coal at these size ranges. Accordingly, a finer coal size fraction of -300 microns is prepared for the tribo-electrostatic separation tests.

Table 1: Proximate Analysis of Coal Samples

Name of coal	Moisture, %	Volatile Matter, %	Ash, %	Fixed Carbon, %
Ramgundam coal	5.79	23.52	43.22	33.26

Microscopic study reveals that all three maceral groups of vitrinite, liptinite (exinite) and inertinite are present in the coal. The collotelinite of vitrinite groups are dominant in the coal. Vitrinite group of macerals includes very fine grains of mineral matter. The mineral phases in the coal detected under visible light with decreasing order are quartz, clay, pyrite, magnetite and goethite. However, the mineral matter identified by XRD includes quartz, illite, kaolinite, montmorillonite, goethite, siderite and pyrite. The relative proportion of mineral phases in coal is presented in Table 2. Quartz is the most dominate mineral phase and found to concentrate in both float and sink fractions of washability studies. Though clay minerals are present next to quartz, only illite is detectable in size fractions of bulk coal. Kaolinite and montmorillonite are also found in both float and sink fractions.

Table 2: Mineral Matter of Ramgundam Bulk Coal Ash (LTA)
(Peak Intensity Given to Indicate the Relative Quantity)

Details of sample	Quartz	Illite	Kaolinite	Montmori -lonite	Goethite	Siderite	Pyrite
Bulk	3588	142	Nil	Nil	117	Nil	Nil
+150mm 1.8 Sink	3318	Nil	1183	Nil	196	110	67
+100mm 1.8 Float	3745	Nil	449	202	Nil	Nil	42
+100mm 1.4 Float	2704	Nil	756	Nil	Nil	Nil	48

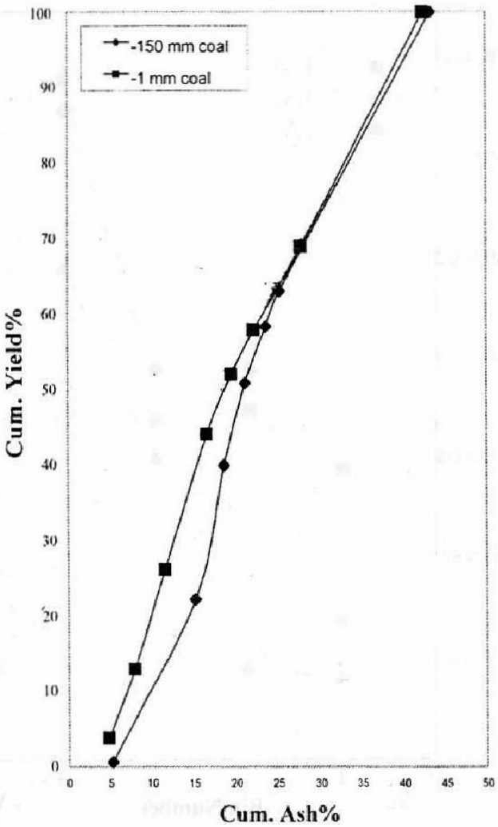

Fig. 2: Washability Study of Ramagundam Coal

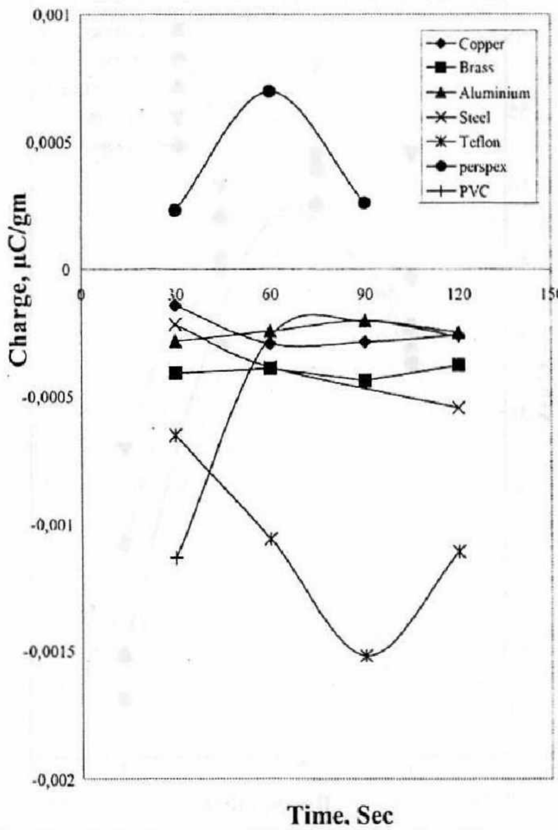

Fig. 3: Influence of Tribo-Charging Time on Charge Acquisition by Quartz Particles

Effect of Tribo-Charging Medium

The results obtained for quartz after contact electrification with different tribo-charger materials are shown in Fig. 3. It can be seen that quartz acquired negative charge while contacting most of the materials except Perspex where it acquired positive charge. These results are in good agreement with the reported work function values of copper, brass, steel, aluminium and PVC of 4.38, 4.28, 4.10, 4.28, and 4.85 respectively (Davies 1969; Trigwell et al. 2001). Quartz has higher work function 5.4 (Kim et al. 1997) than the tribo-charger materials and accepted the electrons from these materials and charged negatively whereas it charged positively with Perspex which has higher work function than quartz. The results also show that with increasing the contact charging time the charge acquisition increased marginally for copper, brass and steel.

The effect of tribo-charger medium on coal separation is shown in Fig. 4. In these tests, a particle size fraction of -300+210 µm coal was tribo-charged for 5 min with each of the tribo-charger materials of copper, aluminium, brass, teflon and perspex. After tribo-charging with a specified material, the particles are allowed to fall freely between the two electrode plates. The applied voltage is kept constant at 15 KV. The results show that copper tribo-charger gave better separation in comparison to other tribo-chargers and therefore the copper tribo-charger has only been used as the tribo-charging medium in further tests.

Effect of Voltage

The effect of voltage on the electrostatic separation of particles tribo-charged at three different temperatures of 18, 63 and 76°C has been studied. The applied voltages in these tests are 10, 15 and 20 KV. The charge acquired by the particles has been plotted against the particles collected at different bins in Figs. 5-7. As shown in the experimental set-up, bin 1 is close to the positive electrode while the bin four is nearer to the negative electrode. The particles collected at different bins are

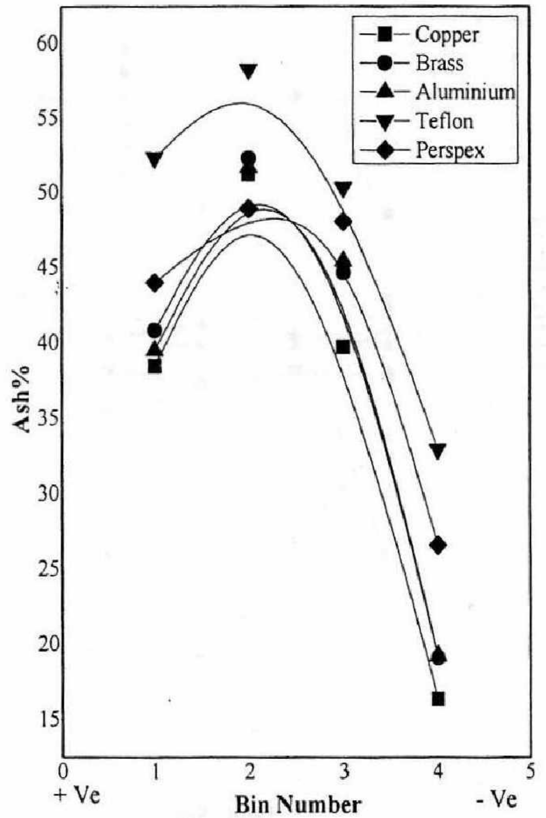

Fig. 4: Bin Number Verses Ash% of Coal Collected at 15KV Applied Voltage After Tribo Charging with Different Materials

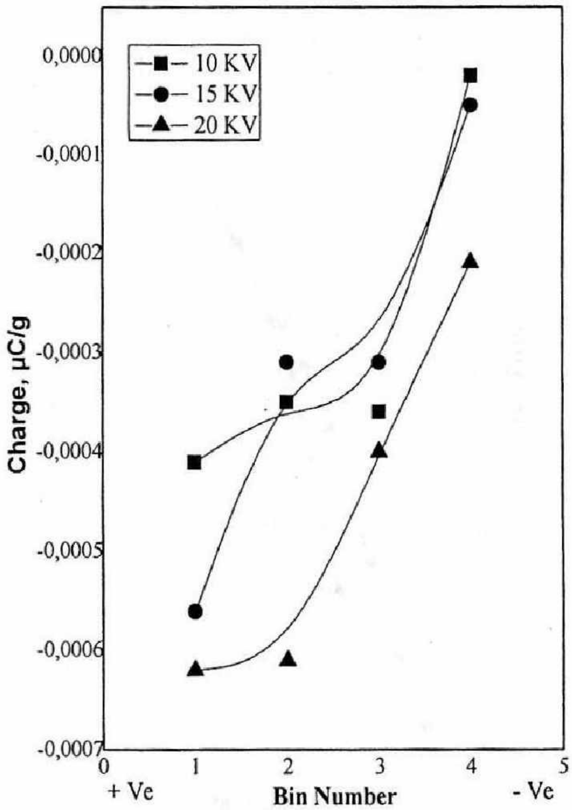

Fig. 5: Effect of Votage on Charge Acquired by Particle at Different Bins at 18°c

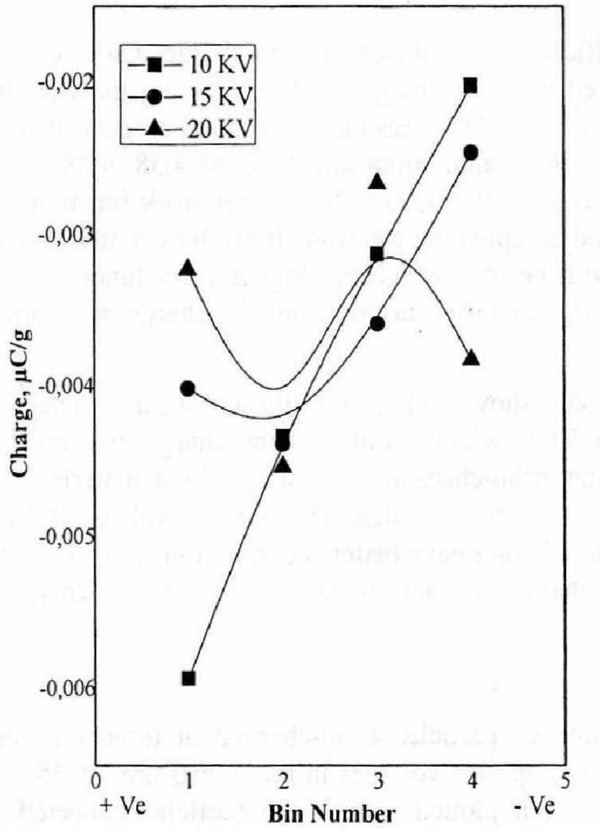

Fig. 6: Effect of Votage on Charge Acquired by Particle at Different Bins at 63°c

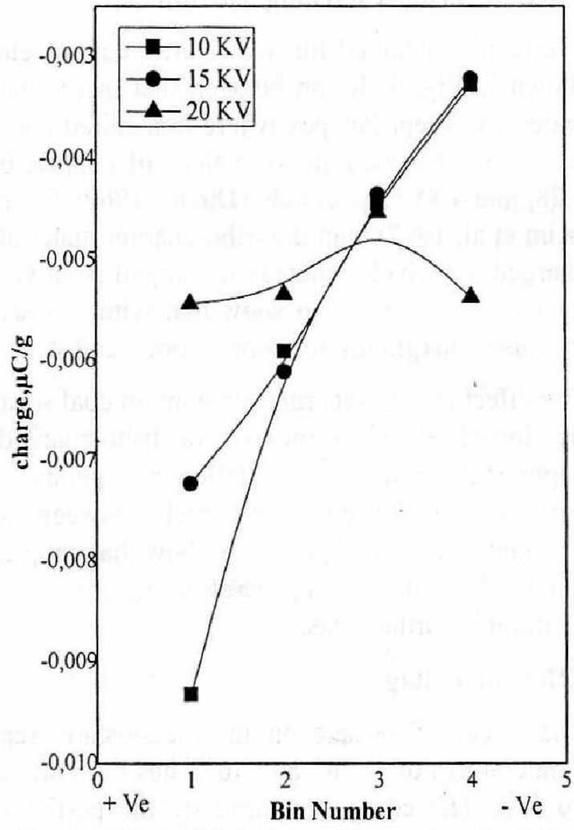

Fig. 7: Effect of Votage on Charge Acquired by Particle at Different Bins at 76°c

negatively charged but the magnitude of charge decreases with the bins from positive to negative electrode (Fig. 5). Generally, the more negatively charged particles are attracted by the positive electrode and collects in bin one while the positively charged particles get attracted towards negative electrode and fall in bin four. The net charge acquired by the particles collected in bin four is found to be negative. This may be due to non-liberated coal particles and/or coating of fine coal particles over mineral particles where the overall charge acquisition of particles became negative and the particles are deflected towards positive electrode. Thus the particles are widespread based on the magnitude of particles negative charge. Ciccu et al. 1991 observed that coal matter acquires negative and positive charge when the carbonate (e.g. limestone and dolomite) and silicate gangue are present respectively. In both the cases, good separation was achieved. It is interesting to note that with the increase in voltage from 10 to 20 KV, the charge acquired by the particles collected at each bin also increases. With increasing voltage, the electrostatic field generated within the electrodes also increases which intern pulled more oppositely charged particles and the net acquisition of charge increases. The particles collected at bin 2 and 3 are almost constant for 10 and 15 KV voltage where as there is a difference in charge for 20 KV voltage.

Figure 6 shows the results of particles charge collected at different bins when the particles are tribo-charged at 63°C. It can be seen from the figure that at 10 KV voltage, the charge acquired by the particles increases with increasing bin number, i.e., the bins from positive to negative electrode. At a higher voltage, the charge of the particles collected at bin one decreases and in bin four, the charge increases. The higher temperature during tribo-charging causes more electron transfer from outermost orbit due to excited electrons and a different magnitude of negative charge acquisition by the particles takes place leading to a different distribution of particles in the bins.

The charge acquisition of particles collected at different bins after copper tribo-charging at 76°C is shown in Fig. 7. These results are comparable to the results shown in Fig. 5. The particles negative charge decreases from bin one to four at 10 and 15 KV voltage whereas at 20 KV, the charge is almost the same. Since all the particles acquired negative charge, there is an optimum voltage for a good separation between strong negatively charged particles containing more mineral matter and weak negative particles with more coal matter.

Effect of Temperature

The influence of temperature on charge acquisition by the particles collected in bin 1 (close to positive electrode) and in bin 4 (close to negative electrode) at different voltage is shown in Fig. 8 and 9 respectively. The results show that the charge acquired by the particles increases with increasing temperature. The increase in temperature during tribo-charging bring about more excited state of electrons in the outermost orbit leading to better electron transfer from the tribo-charger to the particles and vice-versa. Similar behaviour of particles charge with temperature also reported by Alfano et al 1985. At 18°C the charge acquired by the particles in bin one at 10 KV voltage is less than at 20 KV applied voltage. But with increase in temperature, the charge is higher with decreasing voltage. Similar charge acquisition behaviour with increasing temperature is also seen with the particles collected in bin 4 (Fig. 9).

Tribo-Electrostatic Separation of Coal

The results of electrostatic coal separation after contact electrification with copper tribo-charger at 18, 63 and 76°C are presented in Figs. 10, 11 and 12 respectively. The effect of applied voltage on coal separation is also depicted in these figures. It can be seen from Fig. 10 that low ash coal is recovered at the bin close to negative electrode (bin 4) whereas high ash coal is collected at the positive electrode (bin 1) and the ash percentage decreases from bin one to bin four. The results once again illustrate that coal particles are positively charged relative to the inorganic matter and accordingly the low ash coal particles are collected at the negative electrode. A clean coal of 18% ash is collected at

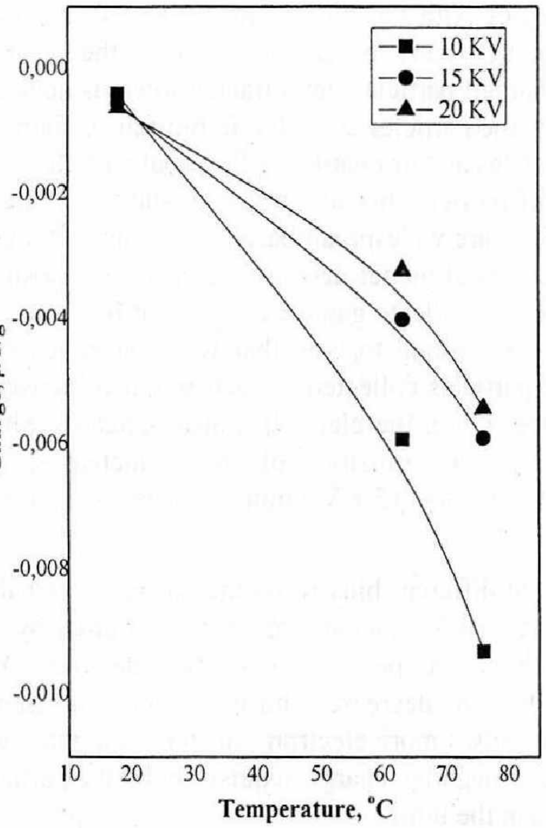

Fig. 8: Effect of Temperature on Charge Acquired by Particle at Bin 1

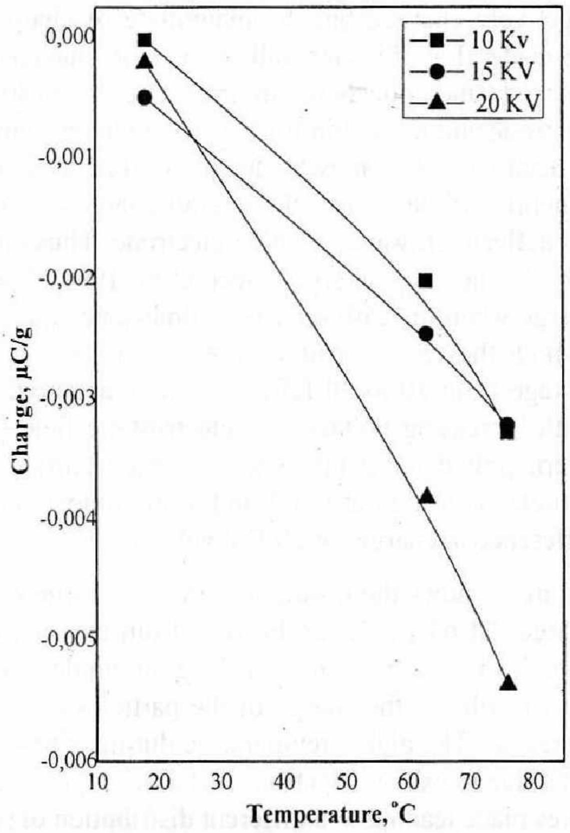

Fig. 9: Effect of Temperature on Charge Acquired by Particles at Bin 4

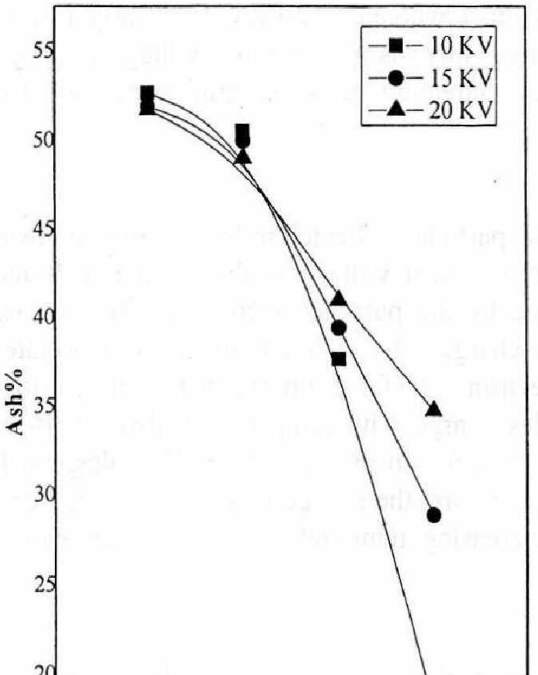

Fig. 10: Bin Number Verses Ash% of Coal at 19°c Charger Temperature

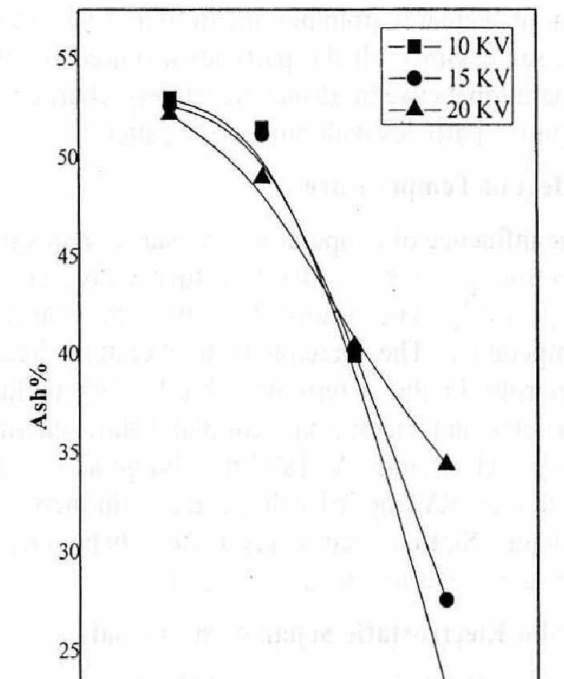

Fig. 11: Bin Number Verses Ash% of Coal at 63°c Charger Temperature

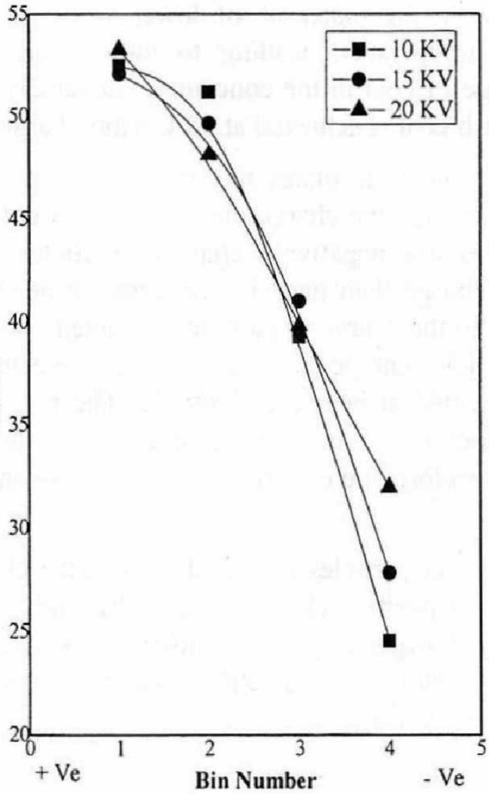

Fig. 12: Bin Number Verses Ash% of Coal at 76°c Charger Temperature

bin 4 and it is possible to beneficiate the 43% ash coal by tribo-electrostatic method. The increase in applied voltage is seen to increase the ash percentage of clean coal. The results at higher temperatures during tribo-charging also show similar behaviour and the low ash coal is recovered at the negative electrode. In these cases, a coal with an ash percentage of 23.12 and 24.57 is respectively obtained at 63 and 76°C tribo-charger temperatures. Although the charge polarity of inorganic matter and coal particles expected to be different after copper tribo-charging, the charge measurements on the collected particles in different bins showed only negative charge acquisition with a difference in magnitude. Thus, the applied voltage is an important parameter for the deflection of relative magnitude of highly negative inorganic matter and weakly negative coal particles in the electric field.

SUMMARY

1. Three groups of vitrinite, liptinite and inertinite macerals are found in Ramgundam coal where vitrinite and inertinite are predominant. The inorganic mineral matter in the coal contains quartz, illite, kaolinite, goethite, siderite and pyrite. Since the mineral particulates, significantly quartz, observed to be visibly free from coal matter, the Ramagundam coal is suitable for dry electrical beneficiation.
2. The charge acquisition of quartz after contact electrification with different tribo-charging media has been studied since quartz is the major mineral phase in the coal. The results show that quartz is negatively charged with copper, brass, aluminium, steel, copper, PVC and Teflon materials whereas it charged positively with Perspex. However, the magnitude of negative charge acquired with copper, brass, steel and aluminium is comparable to each other. Evidently the materials having the work function values in between the work functions of macerals and minerals are suitable to acquire different charge polarity for the coal and non-coal matter during contact electrification and copper found to be optimum tribo-charger material for coal beneficiation.
3. The temperature of the tribo-charging medium plays an important role in the net charge acquisition of coal particles. With increasing temperature, the charge acquired by the particles also increases.

The electron transfer between the materials of lower work function to higher work function increases with increasing temperature leading to more charge acquisition by the particles. However, the ash percentage of coal in the concentrate adversely effected with increase in tribo-charger temperature. Low ash coal is achieved at 18°C tribo-charger temperature.

4. The applied voltage to the electrode plates has significant influence on the separation of coal macerals from minerals. Although the charge measurement of collected particles at different bins shows that all the particles are negatively charged, particles collected at positive electrode measured higher negative charge than particles collected at negative electrode. With increasing voltage there is an increase in the charge of particles collected at both the electrodes at 18°C but at higher temperatures the particles charge collected at positive electrode decreased and reverse is the case with the particles collected at negative electrode. The higher electric field strength caused redistribution of weakly/bipolar charged particles due to considerable deflection of the particles effecting the separation. Therefore, the effective applied voltage need to be optimum for obtaining good separation.
5. The results clearly indicate that particles collected at negative electrode contain low ash percent whereas particles collected at positive electrode comprise high ash percent. This shows that the mineral particles are charged negatively with copper tribo-charger while the macerals charged positively and collected near the negative electrode. The present studies showed that it is possible to reduce the 45% ash coal to 18% ash clean coal.

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