CHAPTER 1 : INTRODUCTION

1.1 General:

Numerous advanced coal-cleaning processes have been developed in recent years that are capable of substantially reducing both ash and sulfur-forming minerals from coal. However most of the processes involve fine grinding and use water as a medium; therefore, the clean coal products must be dewatered before they can be transported and burned in power plants. Unfortunately, dewatering is an expensive process, which makes it difficult to deploy advanced coal cleaning processes in commercial applications (Yoon *et al.*, 1995). Dry beneficiation technique is an alternate approach to solving this problem. Additionally, dry beneficiation process can be economically competitive and environmentally safe.

1.1.1 *Dry Beneficiation Processes:*

Dry separation essentially relies on separation of components based on some differences in the physical or surface properties of the components. These may be physical/mechanical, magnetic, or electrical. Mechanical separation may be effective down to 1mm particle size, while electrical and magnetic are most suitable below 1mm particle size. In general, all beneficiation technologies respond differently to variations in particle size. But beneficiation itself means cleaning of the particles by removing the impurities that would result in a better product that can be used by the consumers.

Electrostatic separation is a method of separation based on the differential attraction or repulsion of charged particles under the influence of a very high electric field (Ralston, 1961). This is why electrostatic separation is also called "high-tension separation" (Inculet, 1984). Prior to the separation stage, particles have to be electrostatically charged. Electrostatic methods for separation of mineral from the organic phases in coal is based on the differences in the ability of these two phases to develop and maintain charges in different types of separators. There are two such types of electrostatic processes. One uses the difference in electrical resistivities while another uses differences in electronic surface structure (Mazumder *et al*. 1994; Kelly and Spottiswood Part 1989). There are various techniques that can be used for charging

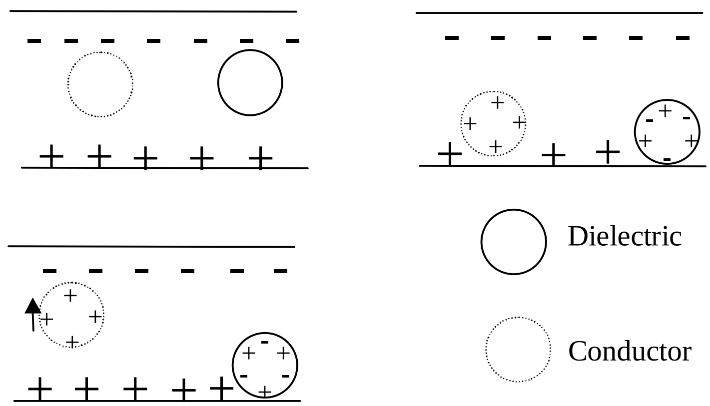

Figure 1.1 Physics of Conductive Induction

particles. These include i) conductive induction, ii) ion bombardment, and iii) triboelectrification (Knoll and Taylor, 1984; Kelly and Spottiswood, 1989; Lawver *et al.*,1986). Regardless of the method of charging, the maximum achievable charge density and the surface area of the particle limit the amount of charge that can be accumulated on a particle. Electrostatic separation of mixed particles is achieved when the electrostatic forces acting on the particles are high enough to overcome the gravity and inertial forces.

An electrostatic mineral separation uses electrophoresis when the force acting on a particle is due to the interaction of an electric field and the charged particle. The electric field can either be that from a high voltage source or from a charged particle's own electric field.

1.2 Principles of Charging Minerals

In the following sections, different electrostatic charging mechanisms will be discussed.

1.2.1 Conductive Induction:

This is the process by which an uncharged particle that comes into contact with a charged surface assumes the same polarity and eventually the potential of the surface (Fig. 1.1). A particle of a good electrical conductor will assume the polarity and potential of the charged surface very rapidly. However, a dielectric particle will become polarized so that the side of the particle away form the charged surface develops the same polarity as the surface. Particles, of intermediate conductivity may be initially polarized but approach the potential of the charged surface at a rate depending on their conductivity. If a good conductor particle and a good dielectric particle are just separated from contact with a charged plate, the charged plate repels the conductor particle and the dielectric particle is neither repelled nor attracted by the plate.

Electrostatic separation between conductors and dielectrics is usually accomplished by means of a single electrode whose charge is opposite in sign to that of the charged plate. The conductor particle is then in the electrical field between the two electrodes and experiences a net electrostatic force in the direction of the second electrode. The dielectric particle, having no net charge, experiences no electrostatic force in a uniform field. Movement of the conductors in the electric field can accomplish electrostatic separation of the conductor and nonconductor (dielectric) particles.

In conductive induction, large differences in particle conductivity are needed to effectively separate materials. Particle charging is less; therefore, the forces generated by this type of separation are generally weaker than that of ion bombardment, and per-stage efficiency is decreased (Knoll and Taylor, 1984).

1.2.2 Ion Bombardment:

Charging and separating minerals by ion bombardment (Fig. 1.2) is the most common

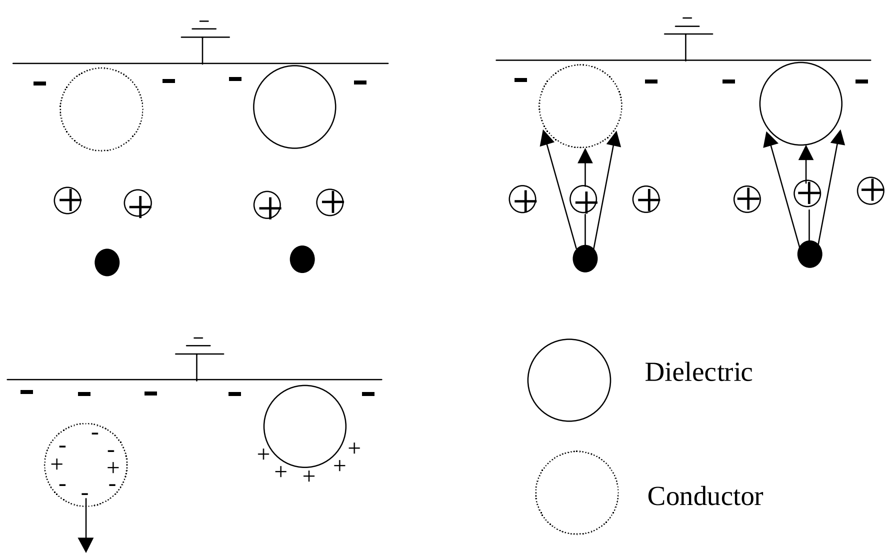

Figure 1.2 Physics of Ion Bombardment

form of electrostatic separation. It is the most positive and strongest method of charging particles for electrostatic separation. Use of ion bombardment in charging materials of dissimilar properties may be visualized by considering conductor and nonconductor (dielectric) particles touching a grounded conducting surface. Both particles are bombarded by ions of atmospheric gases generated by an electrical corona discharge from a high-voltage electrode. Once the ion bombardment ceases, the conductor particle loses its acquired charge to ground very rapidly and there are no electrostatic forces tending to hold it to the conducting surface. On the other hand, the dielectric particle which is coated on the side away from the conducting surface with ions of charge opposite in electrical polarity to that of the surface, experiences an electrostatic force tending to hold it to the surface. If the electrostatic force is larger than the force of gravity or other forces tending to separate the dielectric particle from the conducting surface, the particle is held in contact with the surface (Knoll and Taylor, 1984)

1.2.3 Triboelectrification:

This process utilizes the difference in the electronic surface structure of the particles involved in the charging mechanism. When two dissimilar particles rub against each other, there is a transfer of electrons (charges) from the surface of one particle to the other. This results in one of the particles being positively charged and the other being negatively charged. The charged particles, when under the influence of an electric field, move towards the oppositely polarized electrode. This kind of charging mechanism is called particle-particle charging (Fig. 1.3a). There is another variation to the triboelectrification process. This is particle-wall charging mechanism. In this process, there is a transfer of electrons from one type of particles to the wall, making these

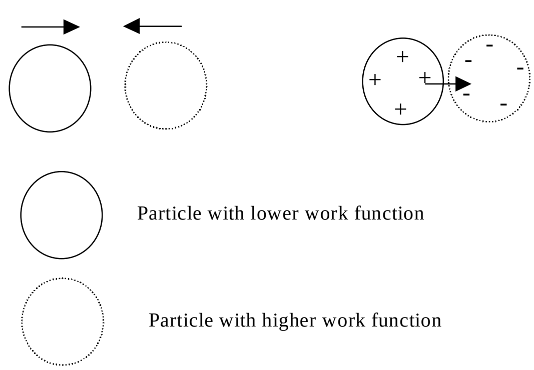

Figure 1.3a Physics of Particle-Particle Charging

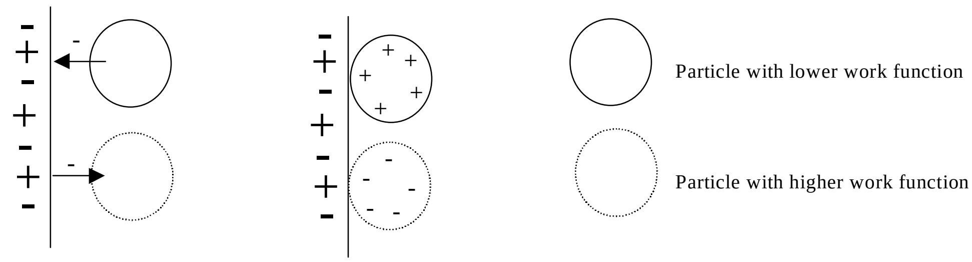

Figure 1.3b Physics of Wall-Particle Charging

particles positively charged and there is a transfer of electrons from the wall to the other type of particles making them negatively charged. This again leads to differential charging of the particles to be separated and hence separation. The surface parameter of the particles that come into play, is the work function. Work function may be defined, as the work required to remove electrons from any surface. The particle that is positively charged after the particle-particle charging mechanism has a lower work function than the particle that charges negatively. In case of wall-particle charging (Fig. 1.3b), the material of the wall has a work function that is in-between the work function values of the two types of particles involved. Of all the methods discussed above, triboelectricfication is the best suited to processing of minerals featuring dielectric properties (Knoll and Taylor, 1984; Mazumder *et al.*, 1994).

A triboelectrification act itself consists of repeated "contact of a mineral with an electrifying surface-break of contact". In spite of collisions of insignificant strength, it is a kind of energy or deformation that affects the mineral lattice. These defects or deformations result in the form of charges on the mineral surface. Finally, it may be inferred that triboelectrification mechanism is a function of the surface states of minerals and is similar to flotation process (Revnitsev, 1970).

The naturally occurring charges that are generated by contact charging are usually weak though and easily dissipated by particle collisions and fluctuations in relative humidity (Knoll and Taylor, 1984). High temperatures and low humidity favor the development of high surface charges through the mechanism of contact electrification. Rubbing the materials together to increase the area of effective contact can also lead to high surface charges.

Horn *et al.* (1993) stated that changing the surface properties of the particles improves the contact electrification process. The authors studied the effect by coating with a single chemisorbed monolayer under a surface force apparatus. They used two silica surfaces one of which is coated with amino-silane. Higashiyama *et al.* (1993) showed a similar effect of an external charge control agent on polymers. The mixture consisted of tri-methyl-phenyl-ammonium and tetra-phenyl-borate powders. The addition of this mixture showed a remarkable increase in charge-to-mass ratio and specific polarity.

1.3 Electrostatic Separation

1.3.1 History of Electrostatic Separation:

Electrostatic separation of ash from coal was first done in 1914 by Withington and subsequently two patents came out in the following year. Larger scale tests and implementations of electrostatic separation were done in 1940 in Germany. These methods could reduce the ash content of German coal from about 15 to approximately 1.5%. Most of these early tests were conducted on intermediate size coal in the range of 10 to 100 mesh. During those days, ultrafine coal was never considered.

In 1976, a US patent described a triboelectric separator with a feed size of about 800 microns and a feed rate of about 5 tons of coal per hour. This separator recovered about 88% of the coal at a purity level of 94.7%, from a feed purity of 57%. Advanced Energy Dynamics (AED) developed separators for fine and ultrafine coal. They designed a pilot-scale separator, which had a continuous belt system for separating pyrites from coal. But this separator was only marginally successful at best.

In 1984, Alfano *et al.*, designed a gaseous stream separator and turbocharger. The process used a triboelectric cyclone separator (originally built in 1965 but later modified by the authors), wherein charged particles were fed through the apex into the lower chamber where they were separated according to their electrical charges and collected in a series of hoppers by means of splitters. The design proved to be satisfactory on fine and very fine size classes of ores of different nature and origin. The authors also discussed the industrial applications and suggested some methods for coal and phosphate and cassiterite ores. Conclusions were drawn concerning the promising prospects of development and application of electric separation methods and in particular those based on triboelectric charging.

About the same time, Masuda *et al.*, designed a cyclone tribocharger and separator system. This was effective in separating mineral matter from coal. The Pittsburgh Energy Technology Center (PETC), now called the Federal Energy Technology Center (FETC), of the Department of Energy (DOE), has been working on triboelectric and electrostatic separation of coal since 1985. They incorporated a copper in-line mixer, through which particles were fed using a jet stream at a high velocity. In order to charge particles, a copper tube was used and this was followed by the in-line mixer. The charged particles were then fed between two plates to which potentials were applied. They showed good separation for Pittsburgh #8 and a few other coals. Subsequently, fluidized bed particle separator in which both particle charge and density were taken into account in the separation process was developed by Gidaspow *et al.*.

Gupta *et al.* (1993) studied the electrostatic separation of powder mixtures based on the work functions of its constituents. They studied the dry separation of a mixture of high-sulfur, high-ash Illinois coals and relatively low carbon-containing oil shales, and separation of synthetic mixtures consisting of charcoal and silica to demonstrate the feasibility of such a separation. The principle behind the electrostatic separation was the observation that carbonaceous and non-carbonaceous matter could be imparted positive and negative surface charges, respectively with a copper in-line mixer. The polarity of surface charge was found to depend on the work function values of the particles and tribocharger. Separation tests in a batch laboratory electrostatic separator showed that the efficacy of the electrostatic separation was strongly dependent on the hydrodynamic conditions such as gas velocity, electric field strength, and particle concentration in carrier gas.

Schmidt and Loffler (1992) conducted investigations on a fine particle separator using an electrostatic nozzle scrubber. Numerical simulations of particle/drop interactions show an increased separation especially in the fine particle range. Using this principle, charged particles are deposited on oppositely electrostatic charged drops. An electrostatic nozzle scrubber for particle separation was developed.

1.3.2 History of Triboelectrostatic Fine Coal Separators:

Gidaspow *et al.* (1987) designed a model to establish the optimum conditions for better separation efficiency of pyritic sulfur from Illinois Coal. The authors noticed that for complete removal of pyritic sulfur coal has to be ground finer. They also designed and constructed an electrostatic sieve conveyor and found that the measurements obtained during the experiments were in reasonable agreement with the results from a simulation of the model. It was experimentally and mathematically derived that an improved electrostatic conveyor can reduce the pyrite concentration to near zero once the pyrites have been liberated by grinding or other methods.

Gupta *et al.* (1993) conducted surface charge tests on Illinois Coal and Pyrites for subsequent electrostatic cleaning. The results from the tests were used to design electrostatic separators. They found that electric charge on pyrites was an order higher than that of coal. Humidity of carrier gas, solids velocity, porosity and particle size were found to have an effect on particle charge. Shih *et al.* (1987) developed a hydrodynamic model for separation of pyrites from coal in a batch electrofluidized bed. Simulations for this model were done on a supercomputer and the input variables that were studied included the surface charge of the particles and the solids stress. Some interesting results were published which gave a better understanding of particle motion and were useful for an improved design of continuous beds.

Finseth *et al* (1992) found that an important parameter in triboelectrostatic separation of coal is the gas-to-solid mass ratio. For a separator to be effective on a large scale, it is vital to know the airflow required and if the amount is economically and physically practical. One possible process arrangement would be to couple the separator to a PC boiler, which would require strict gas-to-solid mass ratios to ensure proper air/fuel stoichiometry. The authors believe that a ratio of 2:1 is needed for efficient separation. At low feed rates, it is believed that the primary charging mechanism to be wall collision which made most of the coal positively charged and report to the clean coal plate. At higher feed rates, owing to higher density of particles, there was a higher probability of particle-particle collision leading to many coal particles being negatively charged and depositing on the refuse plate. This, according to the authors is that in low ash coal, the collisions between coal particles dominate charging mechanism. This could possibly be why the coal particles charged negative. As a result, they concluded that a proper optimization of the feed rate could lead to higher separation efficiency.

Finseth *et al.* (1992) indicated that the separation was essentially complete within first 8-10 inches for both clean coal and refuse components, using the plate type separator. The recovery was particularly high at a distance of 10 inches with regards to ash but the process was not effective when applied to coals containing high organic sulfur. According to the authors, triboelectrostatic separation could be very effective for the removal of both pyrite and silicate minerals from fine coals.

Ban *et al*. (1993 and 1994) have discussed a scheme of triboelectrification and electrostatic separation system and few results that were obtained from them. Other than regular coal samples, physical mixtures of similar sized silica and glassy carbon, and coal were tested and charging and separation characteristics were observed. Temperature, relative humidity, particle size dependence on charging and separation were discussed.

1.4 Theory of Electrostatic Separations

In any separator, suspending the particles in a medium and subjecting them to a separating force that acts on some particle property brings about the separation. In any case of electrostatic separations, the primary separating force is given by,

$$\mathbf{F = Q.E} \quad (1)$$

where, F is the vectorial sum of all the forces, Q is the total charge and E is the electric field intensity at a point in space. In reality, secondary forces like gravitation, force of air stream etc., must also be considered. However the two parameters E and Q are central to an understanding of electrostatic separations (Spitzer, 1984). However, whether or not a particle has a charge as it enters an electric field will depend markedly on its conductivity, and thus knowledge of the relative conductivity of the particles is also important. In the case that a tribocharger is used, the charge developed on the particles is The force of attraction between a charged particle and an electrode surface may be given by the following relationship:

$$\mathbf{F \propto dE/dH} \quad (2)$$

where E is the field strength and dE/dH represents the field gradient. H gives the distance of separation between the electrode surfaces, in the equation. In conventional plate type electrostatic separators, the field gradient is uniform and the force does not change with position. In a non-uniform or an open field gradient set-up, the force of attraction varies with the position of the charged particle in the area of influence. The field strength itself is a function of the potential applied to the electrode surface. So the higher the potential applied, greater is the electric field strength. In any case, there is a minimum distance of separation of the electrodes that has to be maintained in order that the field does not arc.

The bench-scale triboelectrostatic separator used in the present work has radically different features so that it eliminated certain limitations associated with the conventional electrostatic separators. The electrodes are drum-shaped, designed to provide a non-uniform electric field. Changing the curvature of the drum electrodes, i.e. the diameter of the drums can control the gradient. Drums of unequal diameter could possibly maximize the gradient. The physics behind this type of separator has been dealt with in depth in Chapter 2 of this dissertation.

1.5 Report Organization

The first section of Chapter 2 of this dissertation discusses a population balance model developed for the bench-scale unit that was used for the tests. This model was developed based on knowledge acquired as a part of course taken and gives a rough idea of the distribution of the particles after separation. The second part of this chapter details the underlying principles of electrostatics involved in this technique. This is titled the physical model and discusses in length the forces acting on a particle which after being charged is under the influence of the electrostatic field. A system of equations governing the motion of the particle is described and they have been solved step-wise.

The third chapter under "Bench-Scale Triboelectrostatic Separator", talks in detail about the bench-scale unit, which includes the tribocharger and the separator sections. This is followed by the objectives that prompted this research work. Subsequently, the results obtained on the different samples of coal and the grade-recovery curves obtained are elaborated. This section also explains the different calculations that are applied and the procedure for plotting the grade-recovery curves. The last section of this chapter comprises the discussions of the results obtained.

The fourth chapter includes the summary and conclusions of the results obtained from this research work. It also gives recommendations for future work based on conclusions from the current work and the scope for improving the results on triboelectrostatic cleaning of coal.

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