There are two types of the rotating drum separators currently applied in the industry: i) conductive drum separators and ii) non-conductive drum separators.

## i) Conductive Drum Separators

Conductive drum separators or conventional high tension separators consist of a conductive rotating drum at ground potential associated with one or more high-voltage ionizing electrodes. It is often desirable to place non-discharge or static electrodes in conjunction with an ionizing electrode to produce a static field that assists centrifugal force in departing the conducting particles from the drum or rotor surface. The drum is usually made of carbon or stainless steel when treating particles finer than 1 mm in size. Nonetheless, later development in drum fabrication suggests non-metallic conducting materials such as rubber impregnated with carbon black when treating particles coarser than 1 mm. The particle size is also a major factor for selecting the feeding system of these separators. Vibratory and belt feeding techniques are favored for coarser sizes, while rotary spline and gravity methods are commonly preferred for the finer particles.

# *ii)* Non-Conductive Drum Separators

Non-conductive drum separator, also called "shape separator," is a new form of the hightension separation. The construction detail of the separating system is somewhat similar to that of the larger conducting-drum separators except for drum construction. Unlike the conventional high-tension separators, the shape separators do not depend on the inherent conductivity of the components. The separation is instead accomplished by using an advanced roll or drum fabrication and controlled charging techniques to separate materials based on the shape and density of the particles. The "flatness" coefficient, K, of particle is a key to determine the separation characteristics. Such a coefficient can be obtained by considering the particle resting on the surface in its most stable position. The coefficient is then determined by the ratio of particle length, L, and thickness, T. It is reported that the efficiency of separation increase with the ratio of the flatness coefficients of the materials. Effective separation can be achieved when the flatness coefficients  $K_A/K_B$  of two particulate materials is >2. Typical applications of the electro-dynamic electrostatic separators are mostly in mineral beneficiations, although the application in coal beneficiation has significantly increased in recent years. In general, these separators are used commercially as a part of an overall flow sheet comprising various combinations of physical separation processes. Aside from the application in coal beneficiation, the electro-dynamic electrostatic separation technology is well recognized in the processing of heavy-mineral beach sands: the separation of rutile and ilminite (conductors) from zircon and other non-conductors found in beach sand, as well as the separation of quartz (insulator) from specularite (conductor). In addition to those, the applications also include the production of iron ore super-concentrates, the separation of all metallic from non-metallic materials (ceramics, plastics, etc.), the shape separation: vermiculite-mica from silicious rock.

### 1.2.3.2 "Electro-Static" Electrostatic Separators

The first electrostatic separators for commercial use employed the principle of contact electrification and they were of this "electro-static" type. These separators were the free-fall plate devices in which charged particles would fall between two near-vertical plates. An electric field was maintained between those two plates. As mentioned earlier, the industrial application of these free-fall separators was unfortunately discontinued by the late 1940s due to their complexities and high operating costs. The complexities arising then included the requirement of an impeccable feeding system for charging particles efficiently by contact electrification, the need of internal humidity control, and the call for five or more stages to attain an effective separation. However, the electrostatic separation," has currently regained much attention. Many developments have been made and a large number of research studies have been published, indicating a prospect of triboelectrostatic separator being commercially available and widely used. In fact, there are some triboelectrostatic separator already developed and available in the market. The details regarding the triboelectrostatic separation will be provided in a separate section: section 1.3.

Nevertheless, the more familiar types of industrial "electro-static" electrostatic separators at present engage in charging by conductive-induction. They are normally used for the final electrostatic cleaning of industrial minerals such as rutile and zircon. In relation to their contribution to coal beneficiation, Grey and Whelan (1956) found that the charging of the particle by conductive induction, when a field electrode alone is used, is very strongly dependent on moisture. Therefore, the field electrodes used without any corona are best for damp, high-rank coal, while the combined corona and field electrodes are suitable for an intermediate range in rank, size or moisture. The pure corona electrodes are best for cleaning very fine dry coal of all ranks at high drum speeds.

The similarity in principle of separating particles by conductive induction and by ion bombardment is that they both are based on the differences in surface conductivity of the particles. The conductive-induction electrostatic separators can be broadly classified into two groups: a) plate-type separators and b) rotor-type or rotating electrode separators.

# *i) Plate-Type Separators*

There are two types of the plate-type separators employed commercially: the plate electrostatic separators and the screen-plate electrostatic separators. Their operating principles are similar, but the screen-plate electrostatic separators represent a further development of the plate electrostatic separators.

In all plate-type separators, the feed particles are normally transported by gravity onto a grounded metal plate slide in front of which is placed a large curve electrode producing an electric field. The separation occurs by particles, both conductors and non-conductors, selectively acquiring an induced charge from the grounded plate; the conductor particles are charged oppositely to the electrode and they are, subsequently, attracted towards the electrode, while the non-conductor particles continue down the plate or through the screen. The screen-plate separators include a metal slide at ground

potential that is extended with a conducting screen of appropriate screen-opening size to allow coarsesize particles being treated passing through.

## *ii)* Rotor-Type or Rotating-Electrode Separators

In principle, the rotor-type separators are similar to the plate-type separators except that a rotating grounded-metal drum or a grounded rotor is used incorporation with a rotating electrode of large surface area and opposite potential. The rotating drum techniques with field electrodes were mentioned by Olofinskii (1969) that they could give good separations of ash and macerals by way of conductive induction and/or triboelectrification.

These separators are also similar in appearance to the high-tension separators noted above; the exception is that the rotor-type electrostatic separator has no ionizing electrode but only a single field electrode producing an electric field. When a field electrode is used alone, charging is only by induction. Also the separation with the use of the rotating-electrode separator is achieved by a different particle charging mechanism from that of the high-tension separator. In "rotor-type" or "rotating-electrode" electrostatic separation, the conductor and non-conductor particles both rapidly develop their surface charge by induction when they are placed on the grounded rotor in the presence of the electric field. Then a conductor particle readily becomes an equipotential surface and has the same potential as the grounded rotor. As the result of that, the conductor particle is attracted toward the electrode and drawn from the rotor surface. At the same time, the non-conductor particle is held to the rotor surface until it falls afterward by its own gravity.

It has been reported that the separation occurring at the grounded surface in these electrostatic separators basically results from the combination of electrical, centrifugal and gravity forces (Frass, 1962; Lawver, 1960; Morrison, 1974). The electrical force is the force of attraction between the charged particle and the electrode. It acts in the direction of the electrical field. The centrifugal force is given by the rotation of the grounded surface, while the gravitational force is due to the charged particle's own gravity.

## **1.3** Triboelectrostatic Separation

Triboelectrostatic separation involves charging of particles by contact or friction, either with other particles or with a contact surface, followed then by passing the charged particles through an electric field that separates these particles according to the magnitude and sign of their charge. The principle of this separation technique is based on the difference in the surface charge developed of various components comprising the mixture. Therefore, most of the research and development attempts have been directed at the charging step -- acquiring sufficient selectivity, producing enough magnitude of charge, and solving the aerodynamic problems associated with charging and transporting fine particles.

According to the available literature in this area, most of the triboelectrostatic separation applications involve a metal-insulator contact, although an insulator-insulator contact is also of substantial interest. (The charging mechanism of metal-insulator or insulator-insulator contact can be read in section 1.3.2.) Usually, the variety of tribo-electrostatic separators that have been in use have a reflection from the variety of the charging arrangement. To generate a charge on particles, early triboelectrostatic separators ordinarily employed the means of sliding particles down, or transporting particles through chutes, pipes or nozzles. Until recently, cyclones and fluidized beds have been developed to serve as the tribocharging devices, for the reason that more frequent and presumably better particle charging from particle-particle and/or particle-wall contacts would enhance the separation efficiency. Grinding has also been accorded as an alternative means of particle tribocharging. It is of interest that simultaneous grinding methods (Brown et.al, 1975) may be capable of sizing and, at the same time, maintaining the triboelectric separation of particles. The other charging device was a "turbocharger," consisting of a rotor provided with radial blades in order to create more intense turbulence and stronger contact forces. It is just recently that an in-line static mixer has been introduced for charging particles triboelectrically (Link et.al., 1990; Finseth et.al., 1992), as it provides a large number of particle-particle and/or particle-wall collisions over a short period of time. It is suggested, though, that any attempts to achieve reliable particle charging should be solidly involved in the applications.

the relevance of the charging devices to the characteristics of the particles to be separated, along with

Probably the most successful application of the triboelectrostatic separation technique is known to be in the potash mineral salt industry. The successful work on electrostatic separation of salt began in 1953 at the Potash Research Institute in Hannover, Germany (Fricke, 1977). It is based on the premise found earlier in the late 1940s that salts -- potassium chloride (sylvite) and sodium chloride (halite) -- would become selectively charged by contact electrification. Later in 1956, the process was improved by using the conditioning reagents (inorganic or organic) to pretreat the mixture prior to charging and separation. In a fluidized bed dryer, the salt particles become charged through heating, controlled humidity and multiple contacts between particles. So far, the free-fall triboelectrostatic separation techniques have been used to treat more than 10 million tons of salts per year.

The applications of triboelectrostatic separation technologies in the beneficiations of various minerals and coals are also of great significant. It appears likely that Inculet and his group (Inculet and Bergougnou, 1973; Inculet et.al., 1979; Inculet et.al., 1980) are among the first researchers who have the best interest in modifying the fluidized bed techniques for minerals triboelectrostatic beneficiation, and the results they obtained were very impressive. Most of the early work on fluidized bed techniques in mineral beneficiation merely involved other particle charging mechanisms, such as corona charging. In the fluidized bed techniques due to fall through the separation cells. It is apparent that the fluidization produces an individualized charged particle through its multiple collisions. This creates the selective tribocharge on the particles so that the electrical separation can be efficiently achieved.

Evidently, fluidized bed techniques have drawn relatively more attention to the tribocharging applications for mineral beneficiation, when compared to the other -- cyclone techniques. Carta and his group, at the University of Cagliari in Italy (Carta, et.al., 1968 and 1970), has developed cyclone tribocharging separators to beneficiate barite, feldspars, fluorspar, and several coals. The separation

Monpilai Hangsubcharoen

processes involving the similar device, cyclone tribocharger, have been carried out for various minerals: i.e., dolomite, quartz and apatite, by Pearse and Pope (Pearse and Pope, 1975), while the cyclone tribocharger has, too, been used for clay and coal beneficiation by Masuda and his colleagues (Masuda et.al., 1981 and 1983). The results acquired by these researchers claimed that a satisfactory separation was accomplished by using a triboelectric cyclone separator. The other charging apparatus commonly used for the applications of the triboelectrostatic separation for various minerals and coals beneficiations is a "dilute-phase loop," or a pneumatic conveyer (Kittaka et, al., 1979; Nieh and Nguyen, 1987; Schaefer, 1995; Kanazawa et.al., 1995). It is used mostly for the very fine particles. The particle charging is accomplished through the contacts of particles with copper (or other materials) wall of the loop, or with multi-blades within the loop (Link, 1990, Finseth, 1994), as well as the particle-particle contacts. Indeed, the loop is similar in principle to the cyclone, in which the particles acquire a charge largely through the particle-wall collisions.

One of the important applications of the triboelectric separation is in plastics and polymers. Many attempts have been made to separate mixed plastics or polymers based on their triboelectric properties. Many studies of triboelectrification of polymers have been carried out in recent years (Lowell and Rose-Innes, 1980), in order to obtain more knowledge regarding the charging behavior of polymers.

### 1.3.1 Triboelectrostatic Separation for Coal beneficiation

For electrostatic beneficiation of coal, many recent studies have focused on utilizing the triboelectrification method for particle charging. The studies have demonstrated various aspects of using triboelectric charging techniques. The earliest experiments were conducted by Blacktin and Robinson in 1931. In their work, the mixture of coal dust and air were blown at high velocities through a large-diameter iron pipe. Later in 1941, Niggermann had his description of a simple free-falling stream separator, in both laboratory and industrial sizes, and tested on several coals. Noticeably, most of the early charging processes for coal triboelectric separation were by sliding particles down, or transporting

particles through pipe or nozzle. These include the work of Von Szantho (1939, 1949), Herzderfer and Krajewski (1951), and Olofinskii (1957). Niggermann's work was performed using an unsized coal containing all the fine dust. On the other hand, Kühlwein (1941) carried out the tests on coals from which the finest dust had been removed. However, both investigators found an agreeable result in which the higher the treated-coal ranks, the more favorable were the electrical characteristics of the coal substance, until an optimum was reached.

Turning now to more recent work on coal beneficiation. Singewald (1974) had his patent in 1974 on the process for triboelectrostatic separation of pyrite from crude coal, using a free falling plate type separator. The process is claimed to be improved by preconditioning substances with selected fatty acid glycerides and recycling the intermediate fraction into the initial state. However, the separation may have to be repeatedly performed for several states.

In trying to improve the separation performance, attempts have been made to establish the most effective charging processes. Many charging techniques have been considered to substitute the ordinary way of particle charging. In the past, fluidized beds were used with corona and/or tribocharging combined with extractive electrodes to beneficiate black and brown coals (Koncar-Djurdevic, 1962 and Bendfeldt, 1969). Until recently, Inculet and his co-workers (1980) have made their effort to study the triboelectrification of coal-clay specimens by using fluidization technique. They concluded that fluidization is a practical way to generate the tribocharge. During the same time, Inculet, et.al. (1980) have also reported their studies on the triboelectrification of ultra-finely ground and finely ground Canadian coal using a closed loop system where the particles can be re-circulated for a more efficient separation. The fluidization technique was also employed by Gidaspow, et.al. (1987) for coal desulfurization. They pioneered a design concept called "electrostatic sieve" and measured the average charge on particles using an electrostatic ball probe, with the addition of a Faraday cage.

The work on cyclone tribocharging separation of coal by Carta and his group (1968, 1970) has been mainly concerned with pyrite removal. The results were mentioned to be fairly good, with 39-71% ash rejects. Mazuda, et.al. (1983) have developed a Cyclone-Tribocharger with a copper and PVC wall, and pointed out that it is important to select the wall materials according to mineral inclusion composition in coal. Laboratory test work with contact charging of minerals using a lined air cyclone prior to electrostatic separation has been reported with success on laboratory/pilot scale (Carta, et.al., 1981).

In 1986, Rich patented a tubular turbocharger and reported the unexpectedly high differential electrical charges to particles in a pulverized mixture of coal and mineral matters. A twin-rotor charging device has been developed by Agus, et.al. (1990) to create a more intense turbulence and, consequently, a stronger contact force.

In more current research, Schaefer, et.al.(1994) have investigated the triboelectrification and electrostatic separation of coal and constituent minerals using two different charger geometry: i.e., a multiple loop coil system and an in-line static mixer. They have developed a non-intrusive, laser based, Phase Doppler velocimeter system to monitor the characteristics of particle charging and the motion of individual charged particles through an electric field. Link et.al. (1990) have studied the triboelectrostatic separation for ultra-fine coal cleaning, in which the tribocharging was accomplished by passing finely pulverized coal through a helix formed from a long strand of copper tubing. The test results using a parallel plate separator showed good separation for Pittsburgh No.8, Illinois No.6, and Upper Freeport coal samples. Finseth et.al. (1994) continued the investigation by using an in-line static mixer charger as a tribocharger.

From the research standpoint, it is interesting to note that the particle charging process plays an important role in the electrical separation for coal beneficiation. The separation efficiency depends critically on the surface charge of the components involved. The premise that coal and mineral matters can be triboelectrically charged differently when a third material is appropriately chosen has brought the tribo- or contact electrification into a great deal of attention.

# 1.3.2. Contact Electrification or Triboelectrification

1.3.2.1 General

Triboelectrification or contact charging is one of the most practical and economical charging processes by which the selective charging of particulate material can be accomplished for electrostatic separation. The phenomenon occurs when two materials are touched or rubbed together and the electrical charge is transferred from one to another. It is well recognized in the term of the electronic property of solid, even though that of fluid is also included with the equal importance. Since the objective of this dissertation is based on the triboelectrification of coal and mineral particles, the following discussion will, therefore, focus entirely on the triboelectrification of solids with other solids.

Despite the fact that tribo- or contact charging is the oldest studied electrical phenomenon, it is still not clearly known why the charge transfers between the two materials, particularly with regard to insulators. The confusion and difficulties can mainly arise from the definitions of various terms involved (such as "contact," "rubbing" or "frictional"), the given combination of materials, the different experimental conditions, the experimental limitations, and insufficiently sophisticated experimental techniques.

Unluckily, earlier works relevant to the triboelectrification phenomenon have been comprehensively reviewed by a relatively small number of authors, compared with those in the other electrical-relating areas. Still, substantial reviews of the early investigations have been well established in considerable work (Vick, 1953; Loeb, 1957; Montgomery, 1959; Harper, 1967; Robinson, 1969; Seanor, 1972; Lowell and Rose-Innes, 1980; and Kelly and Spottiswood, 1989). Many references also include extensive citations to any earlier work in this field that is not listed in this dissertation. In the last few decades, significant progress has been made towards an understanding of the contact electrification, both into the theoretical perception of the charging mechanism and the importance of contact electrification (or static electrification) in industry. The investigations have been spaciously carried out for many combinations of various materials, with great concern in the fundamental processes of triboelectric charging.

A short history of the very early work on contact electrification is well provided by Pounder (1977), while the more recent reviews and discussions which contribute directly to the contact electrification of solids are indicated by Krupp (1971) and Fuhrmann (1977). Pounder surveyed a number of ideas proposed to explain the tribocharging mechanism from the time of 1600 to the end of the 19th century. For the more up-to-date work, the basic concept and recent experimental results dealing with contact electrification of dielectric solids, particularly polymers, were well summarized by Fuhrmann. The review by Krupp mainly included the essential principles involving inorganic materials (i.e., metals and semiconductors, and organic materials), also in particular with polymers. Interestingly enough, in the discussion part of the paper by Krupp, the result from the field effect measurement performed on anthracene crystals was mentioned by Bauser, one of Krupp's colleagues. The positive space charge was found on the anthracite crystals when they were left exposing to air after cleavage. It was presumably explained that there were negatively charged surface states owing to the dislocation moving through the lattice. This dislocation would then transport the negative charge to the crystal surface, whereas the positive space charge remained in the bulk of the crystal. However, the surface charging on the anthracene crystals indicated in the discussion was a result of deformation and cleavage, which is a method of generating electric charge on solid surface and does not share the same complete mechanism with the contact charging.

Seemingly, the most impressive review concentrating on the theory of contact electrification has been made by Lowell and Rose-Innes (1980). A large number of works contributed to the theoretical understanding have been summarized along with the opinion of the authors and the significant discussions. Nevertheless, as in the review of the earlier work on contact electrification is of particular importance to many segments of this dissertation, it is practical that these early experiments will be mentioned whereabouts the relevant issues are made.

# 1.3.2.2 Theoretical Overview

In trying to understand the reason for contact charging or triboelectrification, it appears desirable to start with the interest in its theory. The theory of the contact electrification or triboelectrification has been under research for many years. Still, there remains a largely unsolved problem and some far-from-conclusive points in such phenomenon, especially about true nature of the charge transfer.

In general, tribocharging is the process whereby a charge exists on a material after departing from the contact with dissimilar material and the two materials can be any combination of conductor, semiconductor, or insulator (dielectric). Although it is thought that contact charging is the result of electron transferring from one body to the other (Rose-Innes, 1980), there is evidence in some cases that the charge transfer in contact charging can occur by ion transfer (Harper, 1967; Gaudin, 1971) and material transfer (Salanek et.al., 1976).

It is a common observation that the tribocharging process involves at least two physical mechanisms, which are equally vital in determining the electrification. Those two phenomena are: i) the charge transfer during the contact of two materials (across the interface at the point of contact) and ii) the back-tunnelling of charge (the charge backflow) during separation. The contact electrification of solids are now generally explained by means of the *work function*, whereas some investigators may have controversially proposed their explanations based on the other hypotheses. It is noted that: when two materials with different work functions come into intimate contact, electrons flow from the one of lower work function to the one of higher work function (Figure 1.2). Charge will flow in a direction determined by the work function parameters until the Fermi levels at the surface are equal. The magnitude of the final charge will



**Figure 1.2.** Triboelectrification mechanisms explained by means of the work function (Inculet, 1984).

actually be the outcome of two processes: the charge transfer that occurs during the contact and the charge backflow occurring as the materials are separated (Kelly and Spottiswood, 1989).

Before considering the statements above in any detail, it is helpful to state exactly the definitions of the terms that will be using frequently in the further theoretical discussions.

(a) *Work function* is defined as the energy required to remove an electron from its *Fermi level*,  $E_F$ , the level in which the probability of finding an electron is 0.5. If an electron moves from just outside to inside the solid, it loses energy  $\phi$ , the work function of the solid. The work function of solid, denoted as  $\phi$ , depends on the nature of the solid and not on how much charge it carries. It is governed by the energy of the Fermi level. Nevertheless, the values of the work function have been reported to depend not only on the nature or internal structure of the material but also on its surface condition, such as bearing of oxides and/or surface contamination (Inculet, 1984).

(b) *Surface Potential*: Suppose that the energy of an electron at an infinite distance from the solid is, by definition, zero. If the solid carries a positive charge, an amount of work  $eV_s$  must be done to remove an electron from just outside the solid surface to infinity;  $V_s$  is the surface potential. Basically, the surface potential depends on the charge carried by the solid, but does not depend on the nature of the solid.

(c) *The electrochemical potential*, **x** is the energy which must be given to an electron to move it from the Fermi level to infinity,  $\mathbf{x} = \mathbf{f} + eV_s$ . It is likely that the electrochemical potential has a similar meaning to the work function. But if it is observed more precisely, the electrochemical potential is the free energy of an electron rather than its energy, although the difference is so small for metals at ordinary temperature.

i) Phenomena of Contact Electrification