

## FEED PREPARATION FACTORS AFFECTING THE EFFICIENCY OF ELECTROSTATIC SEPARATION

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### Abstract

This paper outlines various feed preparation variables which can affect the separation efficiency and operating parameters of an electrostatic separation. Factors considered include physical and chemical conditioning of feedstocks prior to separation. The effect of particle size and shape on separation is evaluated along with operating temperature and humidity.

### FEED PREPARATION

Raw material preparation is an important stage in electrostatic separation processes. Feed preparation can range from simple attritioning to more complex chemical or physical pre-treatment stages. To accomplish electrical separation of two materials using a rotating drum-type machine, there must be a difference in their relaxation time constants,  $\tau$ . The relaxation time constant is defined as the time required for the initial charge density to decay to  $1/e$  of its original value. In practice, the material surface can also influence  $\tau$  since charging and discharging are surface phenomena.

The effective relaxation time can be altered by adsorbed surface humidity, transient or steady-state temperature changes, or surface contamination. Surface

contamination could be due to a third material or, in the case of soft materials, due to a fine covering of one material on large particles of the other. In the case of minerals, the occurrence of surface alteration, leading to surface films, is probably more important than the primary material lying beneath the film, this taking no part in the contact potential [1].

Low specific gravity gangue materials (e.g. silicates) are often removed in the preliminary stages of concentration using wet gravity methods. This treatment stage leads to the ore minerals surface being cleaned which improves subsequent electrostatic separation efficiencies. Consolidated beach sands require surface cleaning to break up aggregated particles and to remove large quantities of colloidal material. Surface films can be removed by wet attrition cleaning, ranging from simple cleaning in a launder to violent agitation in a mechanical scrubber.

If minerals are prepared by dry crushing, this comminution method leads to the production of particle sizes extending into the sub-micron range. These fines tend to adhere to the surfaces of larger particles as films. These fines could affect charging due to the increased surface area. Such films can be removed in an air elutriator [2]. Dust and fines may cause separation inefficiency as they can become entrained in either the concentrate or tailings products. Dust also tends to build up on insulators which can cause short circuits and result in sparking within the electric field. Highly conductive minerals have a similar effect causing sparking or arcing with a consequent reduction in the potential of the field. Whilst sparking is occurring, separation may be adversely affected.

### PHYSICAL CONDITIONING

Both chemical and physical properties of materials can be altered by temperature change. Electrical conductivity is especially susceptible to temperature change if the material in question is a semi-conductor because the energy levels can be deformed. This phenomenon is related to the material's work function and produces a conductivity dependence relationship [3].

$$\sigma = \sigma_0 \exp[-(V_d - V_c)/2KT] \quad (1)$$

where  $\sigma$  is the electrical conductivity [ $\Omega^{-1}\text{m}^{-1}$ ],  $\sigma_0$  is the conduction constant [ $\Omega^{-1}\text{m}^{-1}$ ],  $T$  is the absolute temperature [K],  $K$  is a dimensionless constant,  $V_d$  is the energy of the donor level and  $V_c$  is the energy of lower level of conductor band [eV].

This is specifically useful if one material is more susceptible to a change in temperature and hence the conductivity difference between two materials increases making them more amenable to electrostatic separation. More notable temperature effects can occur if the material displays phase transformations at elevated temperatures.

### **CHEMICAL CONDITIONING**

Chemical conditioning is generally of more relevance than physical conditioning. This conditioning may be unavoidable, accidental or intentional. Some investigations have been carried out into chemical conditioning of minerals prior to electrostatic separation. This can be achieved by doping semi-conductors to promote either non-conducting or conducting behaviour. For instance, nickel oxide can be made non-conducting by doping with  $\text{Cr}_2\text{O}_3$  and conducting by doping with  $\text{LiO}_2$  [3]. There are limitations since high temperature pre-treating is needed and the dopant must have a selective effect.

Another approach is to use wet chemical pre-treatments using surface-active reagents that selectively adsorb on one component. One component is rendered hydrophobic and acts as a non-conductor, whilst the other component retains its surface moisture causing higher surface conductivity and so separation is feasible in a humid atmosphere. The converse is possible, making one material hydrophylic using a substance like hydrofluoric acid which leaves a moisture conductive layer on one component. For both methods, it seems that the conductivity is due to ions in the moisture layer and not the adsorbed layer itself [3].

Selectivity can be increased by preconditioning silicate minerals with hydrogen fluoride gas and basic minerals with organic acids. The use of acidic gases, applied before or in the separator itself, improves the separation of certain mineral

combinations. For the silicate minerals, such as mixtures of quartz and feldspar, hydrofluoric acid gas appears to be the most effective chemical conditioner [1]. The gas forms a conductive film of potassium and aluminium fluorides on the feldspar particles, whereas quartz particles are merely etched and silicon tetrafluoride vapour passes away. Experiments [1] demonstrated that heating, after hydrofluoric acid treatment, was beneficial.

Numerous methods for selective filming of mineral mixtures are available to enhance the sharpness in electrostatic separations. Basic minerals, such as limestone, dolomite, magnesite, or borax, can be filmed by contacting with air containing vapours of acids such as acetic or benzoic [1].

Treatment with surface-active reagents and oils may be applied either in wet pulps or in the semidry state, followed by drying. The separation of sphalerite from pyrite was made possible by pre-treating the mixture with a solution of copper sulphide coating the sphalerite [1]. The overall reaction involved is an ion exchange reaction:



### THE EFFECT OF PARTICLE SIZE ON ELECTROSTATIC SEPARATION

Close classification is not always required for efficient separation, for example, when separations are based on contact electrification. For conductivity separations carried out on static roller ionising electrode roll types, close classification is essential in order to avoid separation with respect to size [4].

Electric charge will cause attraction or repulsion in the electric field, and this attraction or repulsion will affect the movement of particles. Thus, a given electric force will move or deflect particles of a small size further and faster than particles of a large size. The maximum particles size which can be separated effectively is reached when the forces of gravity and inertial completely counteract the effects of

electrostatic forces. This upper size limit is, on average, 3 mm, and lower size limit is approximately 80  $\mu\text{m}$ .

The maximum particle size capable of being treated by electrostatic means is dependent on density. For high densities the particle size must be smaller than for low density materials due to charge per unit mass [2]. It has been predicted that the time variation of charge,  $q(t)$ , on a spherical particle by corona charging is given by:

$$q(t) = 12\pi\epsilon_0 E a^2 \left[ \frac{\epsilon_s}{\epsilon_s + 2} \right] \left[ 1 + \frac{4\epsilon_0 E}{Jt} \right]^{-1} \quad (4)$$

where  $a$  is the particle radius [m],  $E$  is the electric field [ $\text{Vm}^{-1}$ ],  $J$  is the ion current density [Number  $\text{m}^{-3}$ ],  $\epsilon_s$  is the relative permittivity of the particle and  $t$  is the time of charging [s].

The electrostatic forces give a velocity component  $v_e$  [ $\text{ms}^{-1}$ ] which is given by:

$$v_e = \frac{Eq}{6\pi a \eta} \quad (5)$$

where  $q$  represents charge on particle [C] and  $\eta$  is the viscosity coefficient of the medium [ $\text{Nm}^{-1}\text{s}^{-1}$ ].

The maximum charge,  $Q_{\text{max}}$  [C], on a particle is given by:

$$Q_{\text{max}} = 12\pi\epsilon_0 E a^2 \left[ \frac{\epsilon_s}{\epsilon_s + 2} \right] \quad (6)$$

If the particle is spherical then this can be approximated as

$$\frac{Q}{m} = \frac{9\epsilon_0 E}{a\rho} \quad (7)$$

where  $m$  is the particle mass [kg].

As charging is a surface phenomenon, the finer powders have more surface area available to receive charge and hence the charge/unit mass is greater for particles of small diameter. Hence, according to this relationship, the  $Q/m$  for an isolated

particle should be inversely proportional to the radius of the particle. This leads to a practical upper size limit where electrostatic separation becomes inefficient. Experiments have shown there to be many deviations from this rule which suggests that the surface chemistry of the particles has a more dominant effect on the charging characteristics than the particle size for a powder under corona charging [5, 6].

### **THE EFFECT OF SHAPE ON ELECTROSTATIC SEPARATION**

When particles are completely charged by conduction, the charge is proportional to the surface area. Particles can therefore be classified by electrostatic means according to particle shape [2]. Shape separation is a form of ion bombardment separation using advanced roll construction. Unlike conventional ion bombardment where separation is based on conductivity, shape separation is based on differences in particle's shape and density. The separation characteristics of large particles can be determined by the calculation of the flatness coefficient.

The flatness coefficient is determined by considering a particle resting on a horizontal surface in its most stable position. The maximum dimensions of the particle in the direction parallel and perpendicular to the surface are taken as particle length  $L$ , and thickness  $T$ , respectively. The flatness coefficient  $K$  is the ratio of  $L$  to  $T$ . The greater the value for  $K$ , the flatter the particle. Effective separations can be carried out if the ratio of flatness coefficients  $K_A/K_B$  is greater than 2. The efficiency of separation will increase with the ratio of the coefficients [7].

Examples of current applications of shape separation include the separation of mica from gangue, vermiculite from gangue, and metal shape separation.

There is a definite limitation in the charge that a particle can acquire in air. Another expression for the maximum charge  $Q_{\max}$  is given as:

$$Q_{\max} = 4\pi\epsilon_0 r_p^2 kE \quad (8)$$

where  $r_p$  is the electrical equivalent ellipsoid [m],  $E$  is the electric field strength [ $\text{Vm}^{-1}$ ],  $k$  is a function of ellipticity,  $c/a$ , and the dielectric constant  $\epsilon_r$  of the particle  $c/a$  is equal to 5 for the prolate particle, 1 for the spherical particle, and 0 for flaky particles.

Table 1 Charging shape factor as a function of the shape factor  $c/a$  [8]

Shape factor $c/a$	Charging shape factor	
	Conducting particle	Non-conducting particle
	$\epsilon_r \rightarrow \infty$	$\epsilon_r = 5$
5	36.2	27.15
1	3.01	2.15
0	0.667	0.532

After a certain number of ions have adhered to a particle, other ions can no longer be attracted and so become repelled. From Table 1 it can be seen that the maximum charge is somewhat greater (25 – 30%) for a conductor than a non-conductor. The charge is approximately 12 times greater for an elongated particle as opposed to a spherical one. Therefore, the shapes which have a larger surface area can develop a higher charge [8].

The shape of a particle is also an important factor when considering charge decay. Particles with sharp edges and corners tend to lose their charge more readily than smoother, rounded particles [9].

The separation of flake muscovite mica from isometric granules of feldspar and quartz has been investigated at Muntele Rece in Romania [10]. All constituents were non-magnetic and of almost the same specific gravity. Magnetic and gravitational separation was not applicable but electrostatic shape separation was thought to be suitable for concentration of mica [9].

### **HUMIDITY EFFECTS APPLIED TO ELECTROSTATIC SEPARATION**

For most electrostatic applications, any surface moisture is detrimental and so a drying stage is incorporated immediately before separation. Drying is costly and becomes difficult if the specific application is in geographic regions of high humidity. For humid climates, electrostatic separation may have to be carried out at elevated temperature to compensate for surface moisture problems [10].

Most good insulators have a surface conductivity value which is small but still greatly exceeds their volume conductivity. The difference between the two conductivity values appears to be associated with moisture [8]. Humidity effects are complex, the moisture content affects the conductivity of air which in turn influences particle charging and moisture also affects particle conductivity.

Moisture effects can be considered due to the existence of water films. These films give rise to dissolved ions and their presence affects the surface behaviour of minerals. There are many species which can act as charge carriers in humid environments. Among these are electrons, electron vacancies or holes, hydrogen and hydroxyl ions resulting from dissociation of adsorbed water, ionic impurities in the solid which may have migrated to the surface, or components of the solid itself which could 'dissolve' in a layer of adsorbed water.

Many investigations [2, 4, 11] have demonstrated that temperature and humidity are important variables in electrical separation. The influence of temperature and humidity may be considered a problem for industrial separations as humidity is not normally controlled and so fluctuations could lead to unpredicted quality control problems. These variables have significant effect whether the separation is based on contact electrification or on conductivity differences.

In the case of high-tension separation, using thin-wire electrodes, the corona inception voltage is reduced as humidity increases. At high voltages, the corona current decreases as relative humidity increases. In general, the effect of humidity is less notable in high-tension separation than in electrostatic separation, primarily because of the higher charge levels utilised [3].

Water adsorbs on mineral surfaces within humid atmospheres leading to conductivity changes. Evidence indicates that when a material is in a moist atmosphere a water film forms very rapidly on its surface, but the ionisation of this film takes some time. All materials adsorb atmospheric water to some degree and, in the case of insulators, this can significantly increase the rate of charge dissipation. Small differences in composition or surface finish of the underlying substrate have an important effect on the thickness and tenacity of the film [8].

The conductivity increases with the amount of water adsorbed, i.e. in practical terms, conductivity increases with increasing relative humidity. This phenomenon can be observed even under relatively dry conditions (< 20% RH) where the water occurs in molecular form and no free liquid water layer exists. The water presence can contribute free carriers and/or influence the carrier trapping ability.

$$\sigma = \sigma_0 e^{-(W-\delta)/kT} \quad (9)$$

$$\sigma = \sigma_1 e^{(-\delta/k_1 T)} \quad (10)$$

where  $\sigma_0$  and  $\sigma_1$  are conduction constants [ $\Omega^{-1}\text{m}^{-1}$ ],  $W$  is the potential well depth [m],  $k_1$  is a dimensionless constant and  $\sigma$  is the conductivity [ $\Omega^{-1}\text{m}^{-1}$ ].  $\delta$  is the depth by which the potential well is reduced [m] and is dependent on relative humidity. This predicts an exponential dependence of conductors on relative humidity which is observed over a wide range of humidities and for a large number of insulating materials [14].

An empirical relationship between conductivity and relative humidity exists, where

$$\log \sigma = a + bh \quad (11)$$

where  $a$  and  $b$  are dimensionless constants specific to the material and  $h$  refers to the relative humidity [%] [2, 12].

If this equation is employed as an indication of whether an electrodynamic separation is feasible, i.e. by manipulating the variable  $h$  after determining  $a$  and  $b$  relevant to the system, then this can only be reliable if conductivity is in fact

the most important variable involved in the separation. Charge–decay monitoring seems to indicate that conductivity alone, or its resistivity, cannot completely predict the behaviour of particle charging.

Experiments have been carried out in order to propose models of the effect of temperature and humidity on electrostatic separation [15]. Their investigation studied the behaviour of activated silica gel  $-150+106 \mu\text{m}$ . The influence of temperature and humidity was determined by measuring the average displacement of gel particles dropped from a vibrating feeder through a funnel when a uniform electrostatic field applied into a compartmented sample tray. The results showed that with the partial pressure of water varied in a manner to maintain constant humidity, the charge acquired was nearly independent of temperature.

The effect of adsorbed moisture in preventing electrification is due to:

- Ions at the surface creating high surface conductivity and subsequent leakage of the contact electrification charges as fast as they are formed
- Similarity of electric properties as a result of the same moisture film adsorbed on all the surfaces and so a lack of selectivity during separation.

Quartz when subject to physical conditions of cold temperature and appreciable humidity adsorbs water easily and acts as a conductor. Trace impurities which are capable of ionisation are effective in increasing the conductivity of minerals under high humidity conditions. For example, traces of the alkali elements in quartz have the ability to ionise in a water film on the quartz surface. If a salt film exists on a gangue mineral this can aid selective moisture adsorption and so increase conductivity [2].

The qualitative effect of relative humidity on the amount of charge accepted by quartz and feldspar is represented in the schematic Figure 1 [2, 4]. Feldspar becomes positively charged and quartz negatively charged, as the humidity rises above 20%, thus separation is possible. If the humidity is raised further, neither material will become charged. If the humidity is low, both materials will become

negatively charged and so there is a range of conditions where separation is possible.

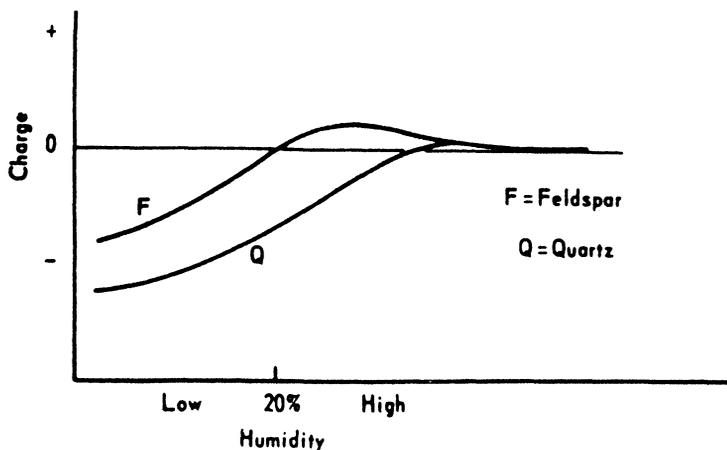


Fig. 1 Humidity dependence of charge acquired by quartz and feldspar in a contact or frictional electrification separator [2].

### THE EFFECT OF TEMPERATURE ON ELECTROSTATIC SEPARATION

Electrical separation is based on differences of one or more electrical properties of the materials being separated. These differences include electrical conductivity, contact potential and dielectric constant which are all influenced by temperature to some extent. The effect of temperature change is particularly applicable to minerals because of their refractory nature.

The conductivity of minerals increases with temperature for either semi-conductive or ionic-conductive materials due to the thermal activation of electrons. Many non-conductors become conductors as temperature increases. All semiconductors tend to a conductivity value of zero as temperature is reduced to absolute zero. The converse is true for metallic conductors whose conductivity reduces as the temperature increases [4].

Some oxidisable minerals change stoichiometric proportions after heating in air and the conductivity does not return to its original value after cooling. Similar changes occur in reducing environment. Other minerals, for example carbonates and hydrates, are completely decomposed and this can be observed, in most instances, by permanent colour changes [4].

Minerals of very high resistivity cannot be separated despite large differences because a high resistivity will not acquire charge by conduction at a rapid enough rate. In such cases, raising the temperature could help. Particles that have too low a resistivity likewise cannot be separated since the charging rate is too high and thus lowering the temperature may be a possible solution.

Fraas [2] demonstrated that, for a large proportion of 100 mineral samples tested, the quantity collected in the conductor fraction increased with temperature as it was raised from 50° to 600°. The few minerals which behaved abnormally were ones that would have been expected to decompose or later at elevated temperatures. This data provides a useful insight into the effects of heating but, unless the conditions can be reproduced exactly, it is not possible to assume the same results will occur when repeating tests. At higher temperatures comparisons are not reliable because the temperature of the particles after it reaches the roll surface is not known because minerals cool considerably between being heated by an overhead heater and striking a rotor at room temperature.

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