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SEPARATION OF PARTICLES IN THE CORONA–DISCHARGE FIELD

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Abstract A model of particle behaviour under the influence of corona discharge is developed and the effect of particle conductivity on the separation process is outlined. The model can be used to calculate the minimum difference in conductivities of particles to be separated, as a function of particle size. The critical angular velocity of the rotor, the limiting particle size and the angle of separation can be derived.

INTRODUCTION

Electrostatic separation is a process of sorting particles based on the competing influence of electrical force, mechanical forces and surface forces. These forces combine to act differently on particles of differing electric properties.

Although the overall physical picture of electrostatic separation is similar to that of magnetic separation, and although the development of the first production–scale electrostatic and magnetic separators occurred at the same period of time, subsequent developmental processes of these separation techniques differ considerably.

In contrast to magnetic separation, and in spite of generality of the response of matter to the influence of an electric field, electrostatic separation has been applied, as a concentration process, to only a small number of minerals.

Furthermore, the existing theoretical description of electrostatic separation is very rudimentary, while magnetic separation attracted a considerable interest of scientists, which resulted in a considerable improvement of understanding of the fundamental physical aspects of the process.

Electrostatic separation is based on selective creation of electric charges on the surface of different components of the feed, with subsequent differences in trajectories of the particles under the influence of electric, surface and mechanical forces.

The feed is thus split into several fractions, as a function of their response to the interplay of the above–mentioned forces. In addition to the interaction of an electric field with an electric charge, dielectrophoretic forces can also be generated. Such forces, being smaller, are the result of polarization of the material under the influence of the nonuniform electrostatic field.

Three basic charging mechanisms are usually considered in electrostatic separation [1, 2]:

a. Charging by contact and frictional electrification
b. Charging by conductive induction
c. Charging by corona discharge.

Although all three charging mechanisms are usually present in any electrostatic separation process, only one mechanism predominates. Charging and separating dry materials by corona discharge (ion bombardment) is the most common form of electrostatic separation.

Electrification of particles by means of corona discharge is an effective way of placing a charge of known polarity on particles. All particles, under ion bombardment from corona glow region, will acquire a charge of the same polarity as that of the electrode in the corona glow region.

The conducting particles rapidly share their charge with the grounded rotor and are thrown from the rotor. The non–conductors lose their charge more slowly and are held to the surface of the rotor by the electric image forces. The general arrangement of such a corona discharge (high–tension) electrostatic separator is shown in Fig. 1.

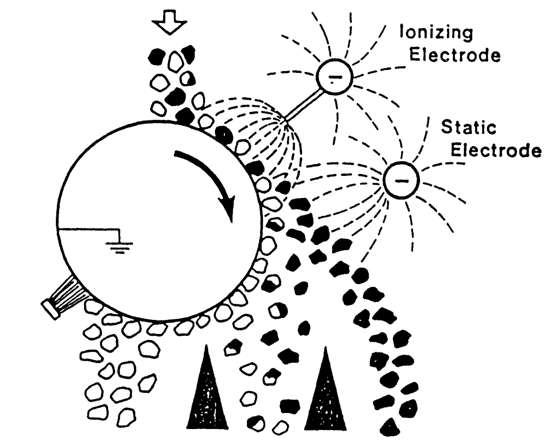


FIGURE 1 General arrangement of high–tension electro–static separator

In order to improve the picture of particle separation in such a separator, a model of particle behaviour under the influence of corona discharge was developed and the effect of particle conductivity on the separation process was outlined. The model allows us to calculate the minimum difference on conductivities of particles to be separated, as a function of particle size; and the critical angular velocity of the rotor, the limiting particle size and the angle of separation can be derived.

THEORY OF HIGH–TENSION ELECTROSTATIC SEPARATION

In high–tension electrostatic separation, a mixture of conducting and non–conducting particles is fed onto the surface of the grounded rotating rotor. All particles receive a surface charge as they pass through the corona discharge. As the particles leave the corona region, they lose their charge at a rate which a function of their electric conductivities.

Good conductors share their charge rapidly with the grounded rotor and are thrown free of the rotor by a combination of centrifugal, gravitational and frictional forces. The insulating particles are attracted to the rotor by their electric image force.

The Image Force

The method of images concerns itself with the problem of a point charge in the presence of a boundary surface, e.g. grounded conductor. It can be assumed that a suitably placed charge of appropriate magnitude, external to the region of interest, can simulate the required boundary conditions. These charges are called image charges. Figure 2 depicts a simplified situation of a point charge located in front of an infinite plane conductor at zero potential.

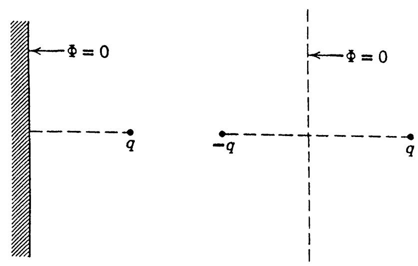


FIGURE 2 Method of images. The original potential problem is on the left; the equivalent image problem is on the right.

Let us consider the problem illustrated in Fig. 3, of a point charge q (particle) located at distance r relative to the origin around which is centered a grounded conducting sphere (rotor of an electrostatic separator) of radius R. It can be shown [3] that the magnitude and the position of the image charge are:

$$q' = \frac{R}{r} q \qquad r' = \frac{R^2}{r} \tag{1}$$

When the charge q is just outside the surface of the sphere, the image charge is equal and opposite in magnitude and lies just beneath the surface.

The force acting on charge q is given by Coulomb's law and, using (1) we get:

$$F_i = \frac{q^2}{4\pi\epsilon_0 R^2} \left[\frac{R}{r}\right]^3 \left[1 - \frac{R^2}{r^2}\right]^{-2} \tag{2}$$

where ϵ_0 is the permittivity of free space (dielectric constant).

The Motion of a Particle in a High–Tension Separator

The motion of a charged particle in contact with the grounded surface of the rotor in a high–tension separator is determined by the interplay between the image force F_i, the centrifugal force F_c, the force of friction F_f and the force of gravity F_g, as is shown in Fig. 4. The electric field force is neglected.

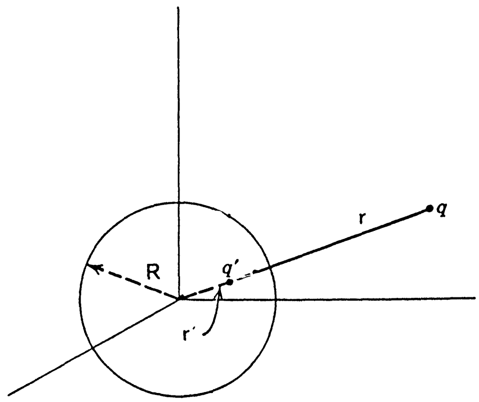


FIGURE 3 A conducting sphere of radius R, with charge q and image charge q'

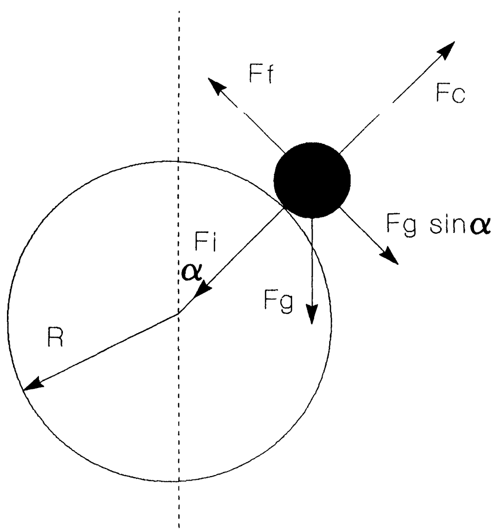


FIGURE 4 Forces acting on a spherical particle on a rotating grounded rotor of an electrostatic separator

The image force is given by eq.(2), while the centrifugal force, normal to the surface of the rotor, can be written as:

$$F_c = \frac{mv^2}{R} \tag{3}$$

where m is the mass of a particle and v is the peripheral velocity of the rotor.

The image and centrifugal forces are plotted versus particle radius in Fig. 5. It can be seen that for a given value of conductivity, the image force is dominant for small conducting particles which thus remain pinned to the rotor. Selectivity of separation of conductors from insulators is thus impaired at these particle sizes.

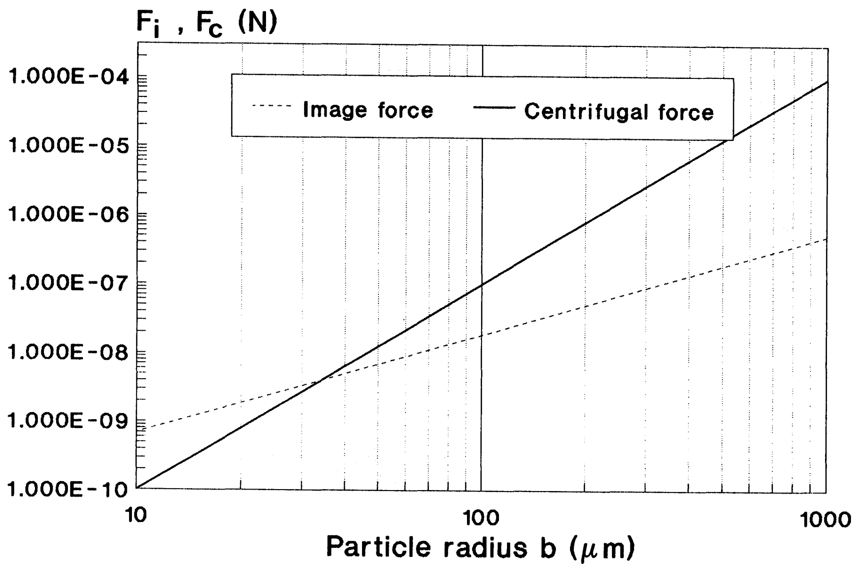


FIGURE 5 The image force F_i and the centrifugal force F_c as a function of particle radius. The values of the forces were calculated under the following conditions: $R = 0.18$ m, $\omega = 2\pi\ s^{-1}$, $\epsilon_r = 3.5$, $\rho = 2650\ kgm^{-3}$, $\gamma = 5.10^{-10}\ Sm^{-1}$, t = 0.25 s.

Owing to a different functional dependence of image and centrifugal forces on the particle radius, as follows from eqs.(2) and (3), the centrifugal force becomes greater than the image force only for particles greater than a certain threshold particle radius, as shown in Fig. 5. Particles greater than this threshold size will be thrown away from the rotor and will thus report into the conducting fraction.

The conducting particles will be thrown away from the rotor if the following condition is satisfied:

$$F_i + F_g \cos\alpha \leq F_c + F_g \frac{\sin\alpha}{\mu} \tag{4}$$

where $F_g = mg$ is the force of gravity and μ is the coefficient of friction between the particle and the rotor. Using eqs. (2) and (3) we get from eq. (4):

$$\frac{q^2 R}{4\pi\epsilon_0 r^3}\left[1 - \frac{R^2}{r^2}\right]^{-2} - \frac{mv^2}{R} + mg\cos\alpha \leq \frac{mg\ \sin\alpha}{\mu} \tag{5}$$

which implies that the surface charge of a particle must satisfy the condition given by eq.(6), for the particle to be thrown away from the rotor:

$$q \leq \left\{ \frac{16}{3}\pi^2\epsilon_0\rho b^3 \frac{(r^2 - R^2)^2}{r}\left[\frac{g}{R}\left[\frac{\sin\alpha}{\mu} - \cos\alpha\right] + \omega^2\right]\right\} \tag{6}$$

where ρ is the density of the particle, b its radius and ω is the angular velocity of the rotor.

The limiting charge given by eq.(6) is affected by the rate at which the particle loses its charge to the rotor. The time constant for the transfer of the charge (or the relaxation time) is [4]:

$$\tau = \epsilon/\gamma \tag{7}$$

where ϵ is the permittivity of the material and γ is its conductivity. The permittivity can be written as $\epsilon = \epsilon_0\epsilon_r$ where ϵ_r is the relative permittivity of the material.

The time dependence of the surface charge density σ is given [4] by:

$$\sigma = \sigma_0 \, e^{(-\gamma t/\epsilon)} \tag{8}$$

where σ_0 is the surface charge density at t = 0.

For a typical case of a material with $\epsilon_r = 3.5$ and $\gamma = 5x10^{-10}$ Sm^{-1} we get from eq.(7) that the relaxation time $\tau = 6x10^{-2}$ s, so that the decay of the charge is quite rapid.

The minimum conductivity of a particle

Since $q = \sigma A$, where A is the surface area of the particle, eq.(6) can be rewritten, using eq.(8) as:

$$\gamma \geq -\frac{\epsilon}{2t} \ln\left\{\frac{\epsilon_0 \rho (r^2 - R^2)^2}{3\sigma_0^2 br}\right\} \left[\frac{g}{R}\left[\frac{\sin\alpha}{\mu} - \cos\alpha\right] + \omega^2\right]\Bigg\} \tag{9}$$

Equation (9) expresses the minimum conductivity of the particle to be thrown away from the rotor, as a function of permittivity, particle size and density, drum radius and its angular velocity, coefficient of friction and of the position of a point at which the particle is to be thrown away.

The maximum sustainable surface charge density depends on the curvature of the surface, i.e. on particle size. The maximum surface charge density σ_0 as a function of particle radius [5] is:

$$\sigma_0 = 8.18x10^{-6} \, b^{-0.3} \tag{10}$$

so that, with increasing particle size, the maximum sustainable charge density increases. Eq.(9) can be rewritten, taking into account eq. (10):

$$\gamma \geq - \frac{\epsilon}{2t} \ln\left\{\frac{16}{27}.10^{-10}\rho\epsilon_0 b^{-0.4} \frac{(r^2 - R^2)^2}{r} \left[\omega^2 + \frac{g}{R}\left[\frac{\sin\alpha}{\mu} - \cos\alpha\right]\right]\right\} \tag{11}$$

Equation (11) indicates that with increasing particle size the required minimum particle conductivity decreases.

The values of the minimum particle conductivity, as a function of particle radius, calculated from eq.(11), for a specific case, are plotted in Fig. 6. Two cases were considered, namely with the force of gravity included in eq. (4), and with the force of gravity neglected. It can be seen that the inclusion of the force of gravity into the balance of forces reduces the value of the minimum conductivity.

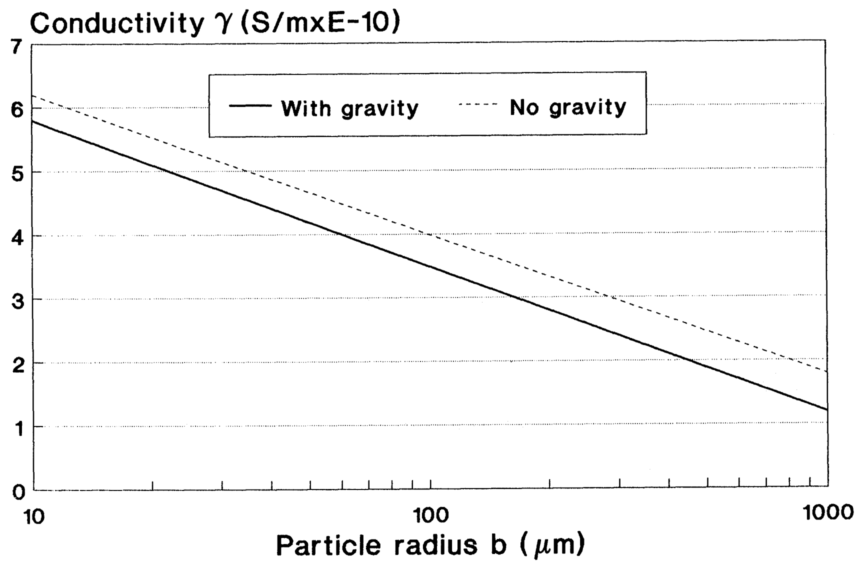


FIGURE 6 The dependence of minimum conductivity of a particle to be thrown away from the rotor , on particle radius. $R = 0.18$ m, $\omega = 2\pi\ s^{-1}$, $\epsilon_r = 3.5$, $\mu = 1$, $\rho = 2650\ kgm^{-3}$.

The effect of the radius of the rotor on minimum conductivity is depicted in Fig. 7. It can be seen that with increasing radius of the rotor the minimum conductivity decreases more steeply when the force of gravity is neglected. This dependence implies that larger radii of the rotor cause a higher recovery of material into the conducting fraction, at the expense of selectivity of separation. Smaller radii of the drum improve the grade of the conducting concentrate.

Similar trend can be observed when the effect of particle density is investigated.

High selectivity of separation can be achieved at low values of density, while high density of particles improves the recovery into the conducting fraction.

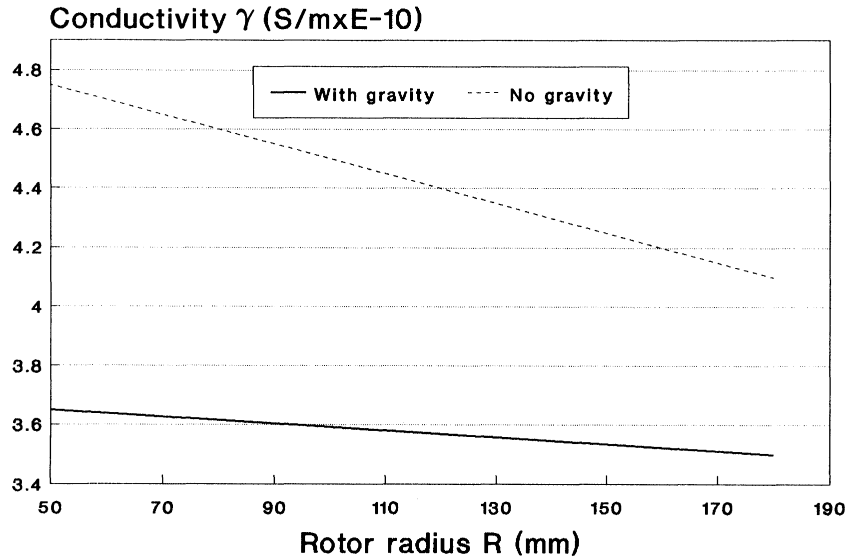


FIGURE 7 The effect of radius of the rotor on the minimum conductivity of a particle to be collected into the conducting fraction. $b = 100\ \mu m$, $\omega = 2\pi\ s^{-1}$, $\epsilon_r = 3.5$, $\mu = 1$, $\rho = 2650\ kgm^{-3}$.

The minimum particle conductivity is also affected by the relative permittivity ϵ_r, as follows from eq. (11). It can be seen in Fig. 8 that for increasing values of ϵ_r the selectivity of separation increases, at the expense of the recovery into the conducting fraction.

Similarly, with increasing angular velocity of the rotor the minimum particle conductivity increases and, therefore, the selectivity of separation improves. A similar effect can be observed by increasing the coefficient of friction between the particle and the rotor.

The Critical Angular Velocity

As follows from the equation of the balance of forces, a particle will be detached from the rotor when the magnitude of the centrifugal force exceeds that of the electric image force. The critical angular velocity ω_C at which the centrifugal and electric forces are in balance can be found from eqs. (2) and (3) to be:

$$\omega_C = \left[\frac{2x10^{-10} b^{0.4} r \ \exp\ (-2\gamma t/\epsilon)}{\epsilon_0 \rho (r^2 - R^2)^2} \right]^{1/2} \tag{12}$$

or, in the first approximation,

$$\omega_C = \left[\frac{\exp\ (-2\gamma t/\epsilon)}{2\epsilon_0 \rho R b^{1.6}} 10^{-10} \right]^{1/2} \tag{13}$$

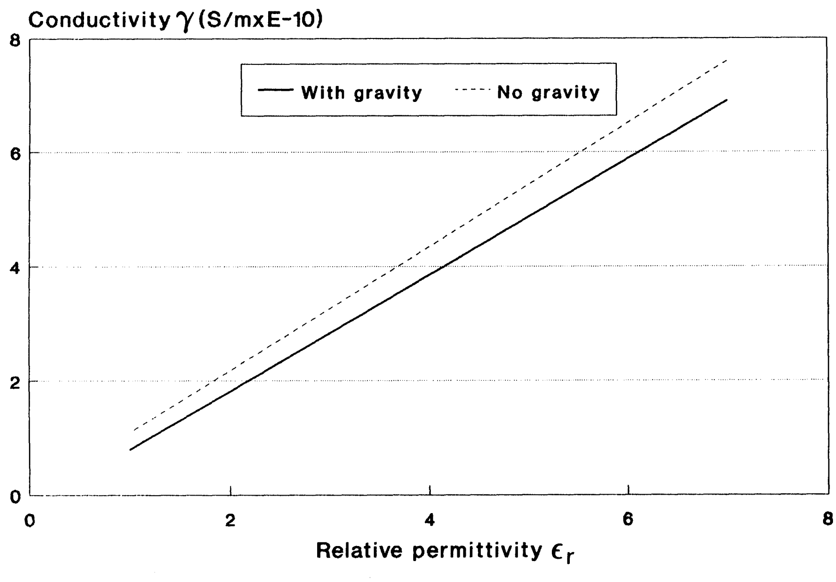


FIGURE 8 The effect of relative permittivity on minimum conductivity of particles to be thrown away from the rotor.
$R = 0.18$ m, $b = 100\ \mu m$, $\omega = 2\pi\ s^{-1}$, $\mu = 1$, $\rho = 2650\ kgm^{-3}$.

Fig. 9 depicts the dependence of the critical angular velocity on particle size. An obvious conclusion can be inferred from this Figure and from eq.(13), namely that with increasing particle size the critical angular velocity decreases, and that by adjusting the speed of rotation of the rotor the selectivity of separation can be enhanced.

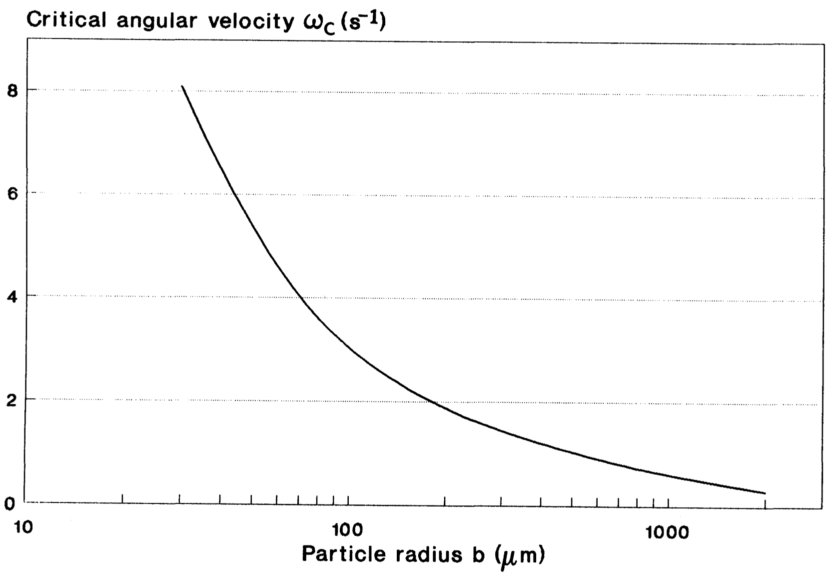


FIGURE 9 The dependence of critical angular velocity of the rotor on particle size.
$R = 0.18$ m, $\gamma = 5\times10^{-10}$ Sm^{-1}, $\epsilon_r = 3.5$, $\rho = 2650$ kgm^{-3}.

The Limiting Particle Size

We have seen earlier that the performance of an electrostatic separator is determined by the interplay of forces acting on a particle; namely, between the electric image force on one hand and centrifugal, frictional and gravitational forces on the other. All these forces depend, in various ways, on particle size, and particle size is a most important factor that limits the applicability of electrostatic separators.

Of great importance is the establishment of the lowest size limit of a particle that can be separated. This limit affects not only the recovery and the selectivity of the electrostatic separation process, but has an impact on the efficiency of the overall technological flowsheet, part of which electrostatic separation often is.

The lower limit of particle size can be evaluated from the equation of the balance of forces, as given by eq.(5). If we assume that $r = R + b$ and that the surface charge density obeys eq.(10), we obtain,

$$b \geq \left\{2.01x10^9\pi^2\epsilon_0\rho R\left[\frac{g}{R}\left[\frac{\sin\alpha}{\mu}-\cos\alpha\right]+\omega^2\right]e^{2\gamma t/\epsilon}\right\}^{-0.625} \tag{14}$$

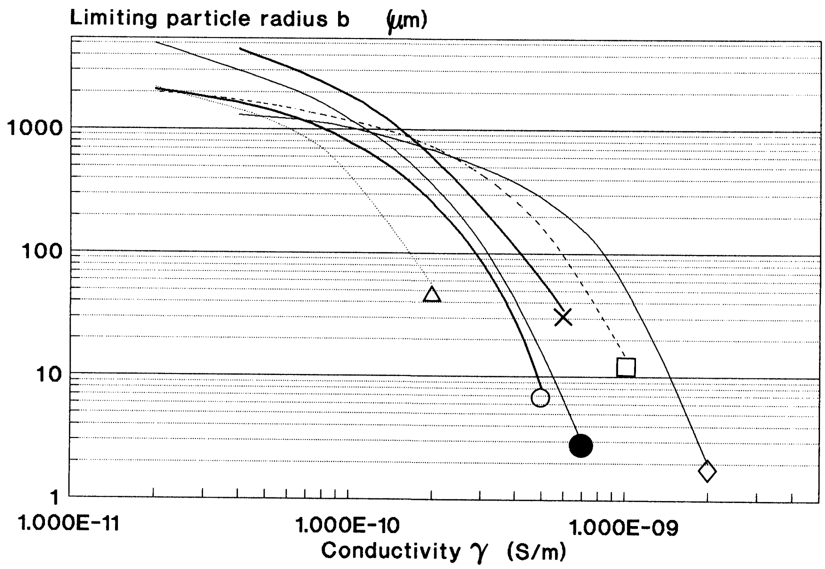
Particles with radii satisfying the condition given by eq. (14) will be thrown away from the rotor, while particles smaller than this value will remain pinned to the surface of the rotor.

The dependence of such a limiting particle size on the particle conductivity is plotted in Fig. 10. It can be seen that for poor conductors (e.g. $\gamma < 10^{-10}$ Sm^{-1}) the minimum radius of a particle to be detached from the rotor is greater than 1000 μm, and is weakly dependent on conductivity. For better conductors this limiting particle size rapidly decreases and becomes strongly dependent on conductivity.

It can be seen from eq. (14) that with increasing density the limiting particle size decreases, although the dependence is rather mild.

The effect of angular velocity of the rotor can be assessed from eq. (14) and Fig. 10. It can be seen that for good conductors the minimum particle size increases with increasing angular velocity. The reason for this behaviour is that at increased angular velocity the time required for a particle to reach the point of detachment is reduced and the conducting particles do not have a sufficient time to transfer their charge to the rotor and they thus remain attached by the electric image force.

For poor conductors this time dependence is less important in view of low value of γ in eq. (8) and the centrifugal force becomes the dominant interaction. Thus, for poor conductors, the limiting particle size decreases with increasing angular velocity of the rotor.



	ρ	ω	t
●	2650	2π	0.25 s
○	5000	2π	0.25
△	2650	2π	0.5
□	2650	4π	0.125
◇	2650	6π	0.08
×	2650	2π	0.25

(× is based on pinning factor)

FIGURE 10 The limiting particle size as a function of conductivity. $\epsilon_r = 3.5$.

The Angle of Separation

The angle α at which the particles detach from the rotor is a function of their size and conductivity, and of the radius and angular velocity of the rotor and of the rate of decay of electric charge.

The angle α can be calculated from the balance of forces given by eq. (5). We thus obtain:

$$\left[\frac{3q^2}{64\pi^2\epsilon_0\rho g b^5}-\frac{\omega^2 R}{g}\right] = \sin\alpha - \cos\alpha \tag{15}$$

Taking into account that

$$q = 32.72x10^{-6}\pi b^{1\cdot 7}\exp(-\gamma t/\epsilon) \tag{16}$$

and that $\alpha = \omega t$, we get

$$\frac{5.02x10}{\epsilon_0\rho g b^{1\cdot 6}}\exp(-2\gamma\alpha\epsilon\omega) - (1-\sin 2\alpha)^{1/2} = \frac{\omega^2 R}{g} \tag{17}$$

The angle of separation can be calculated from eq. (17) by numerical methods.

The Pinning Factor

In early works on high–tension separation, the so–called pinning factor was used to describe the tendency of a particle to be pinned to the surface of the rotor [6]. The pinning factor p is defined as the ratio of the image and centrifugal forces, viz.

$$p = \frac{F_i}{F_c} \tag{18}$$

If $p > 1$, particles will adhere to the surface of the rotor, while for $p < 1$ particles will be thrown from the rotor. It can be seen that the pinning factor is equivalent to eq. (4) where the force of gravity has been neglected.

Using eqs. (2) and (3), the pinning factor can be rewritten, in the first approximation ($R \gg b$):

$$p = \frac{e^{-2\gamma t/\epsilon}}{2\epsilon_0 \rho \omega^2 R b^{1\cdot 6}} 10^{-10} \tag{19}$$

It can be seen that the pinning factor decreases with increasing particle size, rotor diameter and angular velocity of the rotor.

The condition for separation of conducting particles, namely $p < 1$ can be expressed in terms of the particle conductivity as:

$$\gamma \geq -\frac{\epsilon}{2t} \ln \frac{\epsilon_0 \rho \omega^2 (r^2 - R^2)^2}{2rb^{0\cdot 4}} 10^{10} \tag{20}$$

or, in the first approximation:

$$\gamma \geq -\frac{\epsilon}{2t} \ln (2x10^{10} \epsilon_0 \rho \omega^2 R b^{1\cdot 6}) \tag{21}$$

Eq. (21) indicates that with increasing particle size the pinning factor decreases and it can be shown that for poorly conducting particles ($\gamma < 1x10^{-10}$ Sm^{-1}) even an order of magnitude difference in the conductivities causes only a small difference in the value of the pinning factor.

Therefore, the selectivity of separation of a mixture of poorly conducting materials with a wide size distribution will be poor, despite considerable difference in their conductivities.

For better conductors (e.g. with $\gamma > 1x10^{-10}$ Sm^{-1}) even a small difference in the values of conductivities causes a substantial change in the value of the pinning factor and wide size distribution can be tolerated. The selectivity of separation thus improves with increasing values of conductivity of both components.

The effect of particle conductivity on the pinning factor is depicted in Fig. 11. It can be seen that for poor conductors the variation of the pinning factor with

conductivity is mild, and with increasing conductivity the dependence of the pinning factor on conductivity becomes much steeper.

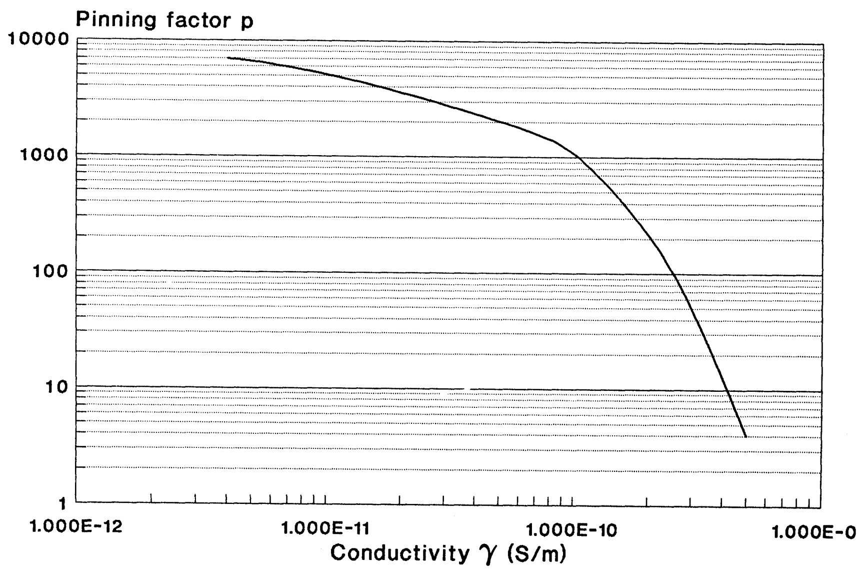


FIGURE 11 The effect of particle conductivity on the value of the pinning factor.
R= 0.18 m, b = 25 μm, $\omega = 2\pi$ s^{-1}, $\epsilon_r = 3.5$, $\rho = 2650$ kgm^{-3}

Similarly, the dependence of the threshold particle radius b_t, for which p = 1, on particle conductivity, is illustrated in Fig. 12. It transpires that for poor conductors only very large particles will be thrown away from the rotor, while medium–sized and small particles will be held onto the rotor by image forces. For particles with $\gamma > 1\text{x}10^{-10}$ Sm^{-1} even small particles rapidly transfer their charge to the rotor and will be thrown from the rotor by the centrifugal force.

The diagram indicates that under the conditions used to construct the graph in Fig. 12, for $\gamma < 1\text{x}10^{-10}$ Sm^{-1} the selectivity of separation is low, even for narrow size distribution. the selectivity improves considerably for more conducting of separability of a mixture of particles, Figs. 6, 7 and 8 show that the conditions of separability, as given by the pinning factor considerably overestimate the limiting particle conductivity. For more rigorous analysis, the full balance of forces, as given by eq. (4) should be used.

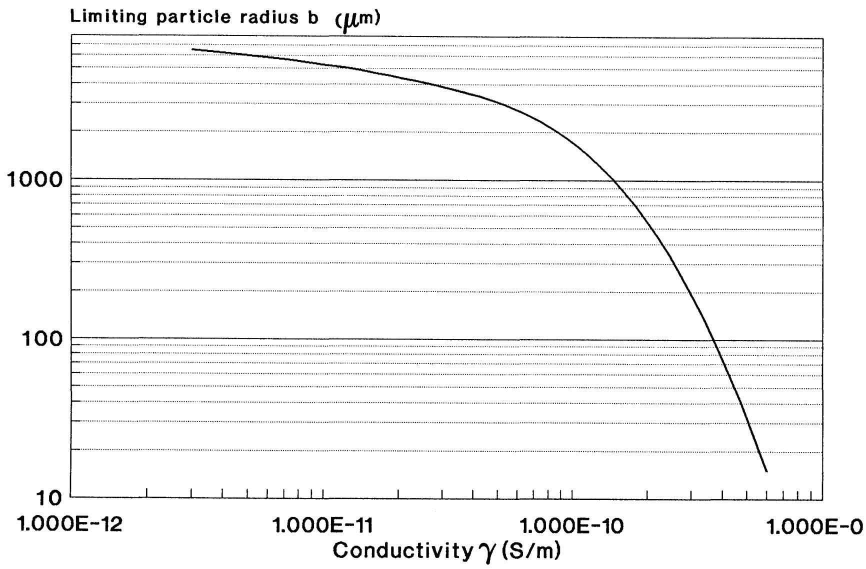


FIGURE 12 The effect of particle conductivity on the value of the threshold particle radius.
$p = 1$, $R = 0.18$ m, $\omega = 2\pi\ s^{-1}$, $\rho = 2650\ kgm^{-3}$, $\epsilon_r = 3.5$, $t = 0.25$ s

CONCLUSIONS

It has been shown from the balance of forces in a corona–discharge separator that the minimum conductivity of a particle to report into the conducting fraction decreases with increasing particle size, diameter of the rotor and density of particles.

On the other hand, the minimum conductivity increases with increasing relative dielectric constant and angular velocity of the rotor. The critical angular velocity of the rotor, at which the centrifugal and electric forces are in balance, decreases with increasing particle size.

The minimum particle size that reports into the conducting fraction decreases with increasing conductivity and density of the particles. It has also been shown that the pinning factor overestimates the limiting conductivity and minimum size of particles that are to report into the conducting fraction.

Our model can be used to assess functional dependence of the separability on various operational variables, such as angular velocity of the rotor, its diameter, the point of detachment of particles from the rotor, and on physical properties of the feed particles, such as particle size, density, permittivity and conductivity.

NOMENCLATURE

A	surface area of the particle
b	radius of the particle
F_c	centrifugal force
F_f	force of friction
F_g	force of gravity
F_i	image force
g	acceleration of gravity
m	mass of the particle
p	pinning factor
q	electric charge
r	distance
R	radius of the rotor
t	time
v	peripheral velocity of the rotor
α	angle of separation
γ	conductivity
ϵ	permittivity of the material
ϵ_o	permittivity of free space
ϵ_r	relative permittivity
μ	coefficient of friction
ρ	density of the particle
σ	surface charge density
τ	relaxation time
ω	angular velocity of the rotor
ω_c	critical angular velocity

REFERENCES

1. F.S. Knoll and J.B. Taylor: *Min. Metall. Proc.* , May 1985, 106
2. O.C. Ralston: *Electrostatic Separation of Mixed Granular Solids*, (Elsevier, Amsterdam 1961)
3. J.D. Jackson: *Classical Electrodynamics* (J. Wiley and Sons, New York, 1975)
4. A.D. Moore (Ed.): *Electrostatics and its Applications* (J. Wiley and Sons, New York, 1973)
5. A.G. Bailey: *Powder Technol.* 37, 71 (1984)
6. J.E. Lawver and D.M. Hopstock: Electrostatic and Magnetic Separation, in *SME Mineral Processing Handbook* (Ed. H.L. Weiss, SME, Littleton, Colo., 1985), Section 6

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