SEPARATION OF SMALL METALLIC NONFERROUS PARTICLES IN LOW CONCENTRATION FROM MINERAL WASTES USING DIELECTROPHORESIS

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Abstract
This paper presents a theoretical study and a method regarding the separation of small nonferrous particles (Au, Ag) in low concentration from mineral wastes, using the dielectrophoresis phenomenon. The main theoretical considerations referring to the dielectrophoresis and the appearance and action of the electric gradient forces, typical for nonuniform fields, are presented. The gradient and superficial electric forces, in competition with gravitational forces act on the dielectric particles from the surface of the material subjected to the separation process. Under the combined actions of all these forces, the metallic particles are concentrated on the surface of the mixture, forming a superficial conductive layer. Finally, the experimental results and comments regarding the concentrations in Au and Ag of the particles collected from the formed layer are presented, based on chemical analysis.
Key words: Electrostatic separation; Particles size; Recycling, Waste

1. Introduction

Electrostatic separation represents an ensemble of methods designed to recover useful materials from mineral and industrial wastes. It is based on the differences between the electrical properties of the contained particles. The wastes are heterogeneous mixtures containing particles of useful and basic materials, which are present in different proportions, with millimetric or submillimetric particle size. Usually these methods are used in recycling of nonferrous metals (Au, Ag, Cu, Pb, Al) from mineral or electro technical wastes as well as for separation of different kinds of plastic materials.

Electrostatic separation techniques are based on either of the two methods: *electrophoresis* or *dielectrophoresis* processes, which involve electrical charged or uncharged particles.

Electrophoresis is based on the electrostatic attraction between the charged electrodes and charged particles producing their motion. The motion direction of the

particles is dependent on the direction of the field; reversing the field the direction motion of the particles reverses, too.

Dielectrophoresis is a phenomenon consisting of the motion of particles placed in a nonuniform electrical field to become polarized and move into regions of highest electrical field strength, as in figure 1. For example, there is no motion in case of uncharged particles placed in uniform fields. The direction of motion for a particle in a nonuniform field is independent of the direction of the field. This will be dealt with in the theoretical part, i.e. either DC or AC voltage can be used.

Dielectrophoresis requires divergent fields for strong effects and gives rise to an effect proportional to the particle volume. Generally, the properties of a dielectrophoretic separation depend on the media in which separation occurs, i.e. in media of low dielectric constant, the field strength $E > 10.000V/m$ for coarse particles (particles size > *2mm)*. When the air is used as media, the separation process is largely based on differences in shape, mass density, dipole moment (dielectric properties) and electric conductivity of the particles.

The method presented in this paper has been used at West University of Timisoara, Recycling Laboratory of Physics Faculty, for the recovery of Au and Ag, having a very low concentration (grams/ton) in a mixture. The material designed to be separated was a mineral waste: a mixture containing useful particles with high electrical conductivity (corresponding to a high concentration of Au and Ag) and dielectric particles, the mean size of mixture particles being about 0.1 - 0.2 mm.

2 Theoretical Considerations

It is known that the electrical translational force *F*, on an electric dipole *p* (induced or permanent) in a nonuniform electric field is [1], [3]:

$$\mathbf{F} = (\mathbf{p}\nabla)\mathbf{E} \tag{1}$$

where *E* is the electric field strength on the particle and *p* the dipole moment of a dielectric particle embedded in a dielectric medium.

For a spherical particle [5]:

$$\mathbf{p} = \upsilon\mathbf{P} = \frac{4}{3}\pi a^3 \mathbf{P} \tag{2}$$

where:

v - volume of the particle,

a - the particle radius,

P - polarization vector (dipolar moment density).

For a spherical particle with relative dielectric permittivity ε_{r1} introduced into a medium with relative permittivity ε_r, the polarization in the sphere is [4]:

$$\mathbf{P} = \varepsilon_0(\varepsilon_{r1} - \varepsilon_r)\mathbf{E}_i \tag{3}$$

where ε_0 is dielectric permittivity of vacuum and $\mathbf{E}_i$ the internal electric field strength in the particle, oriented in the direction of the external field $\mathbf{E}$ [5]:

$$\mathbf{E}_i = \frac{3\varepsilon_r}{\varepsilon_{r1} + 2\varepsilon_r}\mathbf{E} . \tag{4}$$

Accordingly, the effective translational force (1) becomes:

$$\mathbf{F} = 4\pi a^3 \varepsilon_0 \varepsilon_r \frac{\varepsilon_{r1} - \varepsilon_r}{\varepsilon_{r1} + 2\varepsilon_r}\mathbf{E}\nabla\mathbf{E} = 2\pi a^3 \varepsilon_0 \varepsilon_r \frac{\varepsilon_{r1} - \varepsilon_r}{\varepsilon_{r1} + 2\varepsilon_r}\nabla E^2 , \tag{5}$$

The force obtained in equation (5) is proportional to: 1) the cube of particle radius, 2) the difference between its dielectric constant and the surrounding medium, 3) the gradient of the square of the electrical field strength, therefore it can be called *gradient force*. Equation (5) shows that the direction of the force is the same if the sign of the field is reversed. Accordingly, alternating fields can be used for separation. A particle will be "pull" toward to the region of the most intense electrical field, as in the Figure 1. On the other hand, one observes that the existence of the gradient force requires a nonuniform field.
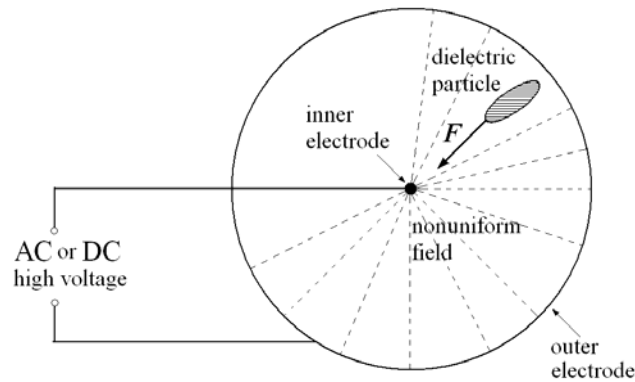

Figure 1: The gradient force acting on a dielectric particle in a nonuniform electric

The specific volume force (force per unit volume of the particle) is [2]:

$$\mathbf{f}_v = \frac{\mathbf{F}}{v} = \frac{3}{2}\varepsilon_0 \varepsilon_r k \nabla E^2 \tag{6}$$

where $k = \dfrac{\varepsilon_{r1} - \varepsilon_r}{\varepsilon_{r1} + 2\varepsilon_r}$ is the *depolarization factor*.

In the separator based on the acting of gradient forces, the field is initially uniform, but the presence of many particles changes the field in their vicinity, leading to the appearance of gradient forces. For a heterogeneous mixture placed in a uniform electric field each particle feels a nonuniform field, due to the presence of the other particles. In this case, we proceed to modify (6), to adapt it to real conditions in such a separator.

Applying the electric flux law, in the absence of free electrical charges $div\mathbf{D} = 0$ as in the case of the separator, where $\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E}$ is the electric displacement vector, we get the following result:

$$\nabla\mathbf{E} = -\frac{1}{\varepsilon_r}\mathbf{E}\nabla\varepsilon_r$$

and the expression (6) becomes:

$$\mathbf{f}_v = -3\varepsilon_0 kE^2\nabla\varepsilon_r \tag{7}$$

As can be seen, the presence of particles in an electric uniform field leads to the appearance of gradient forces. These forces are independent of the sign of the electric field and they are always directed toward the lowest value of the permittivity.

Equation (7) is an appropriate form to express the behavior of particles from the surface of the mixture. Because inside the mixture the permittivity has the proximate value and the metallic particles are insignificant in their proportion, here we can consider $\nabla\varepsilon_r = 0$. Consequently, the force (7) will be reconsidered for mixture - air interface and pass into surface form (force acting per unit surface of a dielectric particle at the mixture - air interface):

$$\mathbf{f}_v \rightarrow \mathbf{f}_s = -3\varepsilon_0 kE^2\nabla_s\varepsilon_r \tag{8}$$

where $\nabla_s\varepsilon_r$ represents the "jump" of permittivity at the mixture - air interface.

The forces (8) act only on the dielectric particles which are lying on the surface of the mixture. Because in a metallic particle $E_i = 0$, electrical gradient forces do not act upon metallic particles which are lying on the surface of the mixture, but act surface electrical forces [3]:

$$\mathbf{f}_m = \frac{\varepsilon_0}{2}E^2\mathbf{n} \tag{9}$$

as in figure 2, where $\mathbf{n}$ is unit vector at the surface of the mixture.
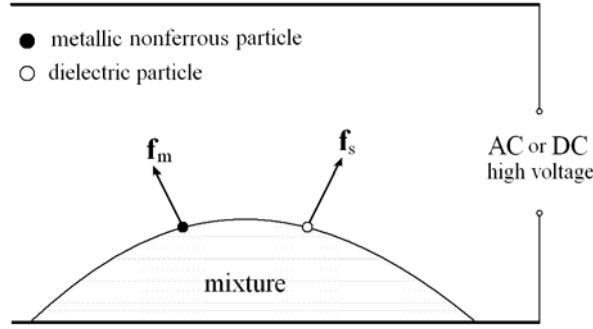
Figure 2: Mixture of dielectric and metallic nonferrous particles placed in a uniform electric field

Consequently, the surface gradient forces (8) act on the dielectric particles lying on the mixture - air interface and the surface electrical forces (9) act on the metallic particles from, both in competition with the gravitational forces. For metallic and dielectric particles inside the mixture, the forces (8) and (9) respectively are very small values and can be neglected. In figure 3, the actions of the electrical and the gravitational forces on a dielectric and a metallic particle at the air - mineral waste interface are shown, where G_d and G_m are the gravitational force on dielectric and metallic particle respectively, lying on the mixture - air interface:
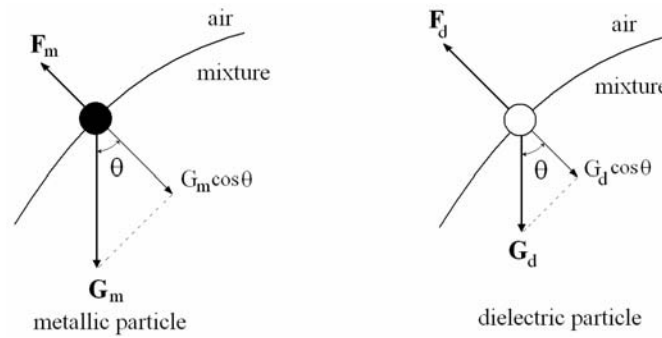

Figure 3: Forces acting on metallic and dielectric particles at the air - mineral waste interface

The condition for a dielectric particle to be removed from the air-mixture interface is:

$$|\mathbf{F_d}| \geq G_d \cos\theta \qquad (\mathbf{F_d} = 2\pi a^2 \mathbf{f_s}), \qquad (10)$$

and for a metallic particle, respectively:

$$|\mathbf{F}_m| \geq G_m \cos\theta \qquad (\mathbf{F}_m = 2\pi a^2 \mathbf{f}_m). \qquad (11)$$

The conditions for the electrical field strength between electrodes, so that the particles from the mixture - air interface to be repelled are (Lungu 1998):

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• for a dielectric particle:
$$E^2 \geq \frac{2}{9} \frac{\rho_d ga\cos\theta}{\varepsilon_0 k\nabla_s \varepsilon_r} \qquad (12)$$

• for a metallic particle:
$$E^2 \geq \frac{4}{3} \frac{\rho_m ga\cos\theta}{\varepsilon_0}$$

where ρ_d and ρ_m are the mass densities for a dielectric and a metallic particle, respectively.

Taking into account that: $\frac{1}{6k\nabla_s \varepsilon_r} < 1$, and $\rho_m > \rho_d$ we obtain:

$$\rho_m > \frac{1}{6k\nabla_s \varepsilon_r} \rho_d \qquad (14)$$

From (12), (13) and (14) it results that for the same electric field strength E, the dielectric particles from the surface of the mixture will be removed first. Consequently, it is considered that after applying the electrical field the dielectric particles will be removed first from the surface of the mixture and the metallic particles will be concentrated, forming a layer on the surface. This fact was experimentally confirmed.

3. Experimental Results

In order to separate the material, a mineral waste with particles sizes under 1 mm, containing gold (Au) and silver (Ag) in low concentration (grams/ton) and dielectric particles, was introduced in an uniform high intensity AC electrical field (~ 4 kV/cm), as in figure 2. Applying the field, a strong movement of the surface particles was observed and in a short time a dark layer containing metallic particles much more than dielectric particles appeared at the surface of the mixture (accordingly with the previous theoretical considerations). Due the shielding effect produced by the metallic formed layer the movement of the particles was rapidly diminished. Figure 4 shows a photo of a mixture after the voltage was applied, where the appearance of the dark layer on the surface can be seen.

Turning off the electric field, the particles of the obtained dark layer were collected and the process was repeated passing the collected material through the separator 2, 4, 6, 8 and 10 times. The separation processes were performed for two versions of the same basic material:

(1) <u>Wet material</u>: mixture at room relative humidity,

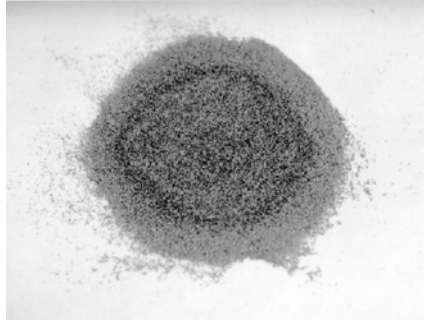(2) <u>Dry material</u>: mixture maintained 24 h at 60° C before separation.

Figure 4: Mixture after applying the electric field

Finally the material resulted from separation was chemical analyzed. In Table 1 we present the obtained values for *grade ratio (Gr)* - ratio between concentration values for Au and Ag after subjecting it to separation for a certain number of times, and before separation. The initial concentration for Au was 1.87 grams/ton and 35.4 grams/ton for Ag, respectively.

Table 1: Grade ratio for Au and Ag in wet and dry versions of the mineral waste, function of the separation times

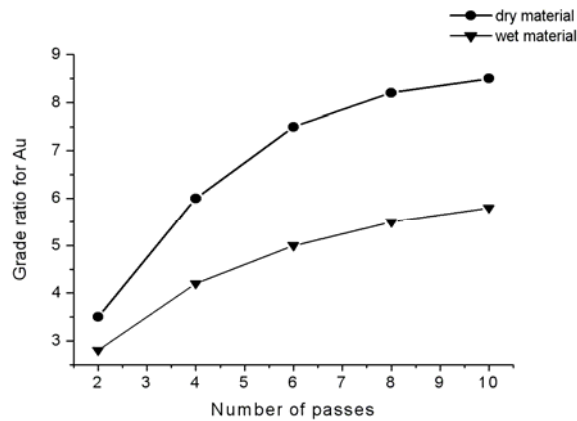| Separation times	$(G_r)_{Au}$		$(G_r)_{Ag}$	
	wet material	dry material	wet material	dry material
2	2.8	4.2	2	3
4	4.2	6	3.4	5
6	5	7.5	4.4	6.5
8	5.5	8.2	5	7.5
10	5.8	8.5	5.4	8

Figure 5: Variation of grade ratio for Au with the number of separations

The variation of the collected material grade ratio for Au with the separation number of times through the separator, for a wet and dry input material, is given in figure 5. From Table 1 and figure 5 it results that the concentrations of gold and silver from

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the collected material (the dark formed layer) increase with the separation number of times through the separator. As we can see, after 6 separations the concentration begins to increase slowly and has the tendency to become constant at a great number of separations. On the other hand, a high efficiency of the separation process was obtained for a dried material in comparison with the material at the room relative humidity. In this case, a higher number of separations of the material is not necessary, what we need is a better drying of the mixture.

5. Conclusions

As it was shown, the presented dielectrophoretic separation method is a technique useful to recover the nonferrous metals (Au, Ag) having low concentration from mineral wastes. The material subjected to the separation process was placed into an electrical field that is initially uniform, but the presence of particles changes the field in their vicinity, leading to the appearance of electrical gradient forces.
Owing to combined action of electrical and gravitational forces, a superficial layer consisting in metallic particles on the surface of mixture was obtained.

The chemical analyze of particles from this superficial layer shows a growing of Au, Ag concentrations on the surface of the mixture subjected to the separation process, especially in the case of dried material.

The best results of separation were obtained for Au in comparison with Ag because the mass density of gold is higher than of the mass density of silver.

Finally, the experiment shows that the separation of fine solid particles from heterogeneous mixtures can be successful from a technical and financial point of view if we use the above mentioned technique. Owing to the simplicity of the system and to the easy control of the operation, this technique can be developed to the industrial scale.

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