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Application of dielectrophoresis for the separation of minerals

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ABSTRACT

Comminution is an energy intensive process, accounting for approximately 29% of total mining energy (Tromans, 2008). Better liberation at coarser size ranges (0.5–2 mm) has been identified by the minerals industry as an opportunity for energy conservation. In order to capitalise on future developments in comminution, an effective coarse particle separation method is required for liberated particles which are too coarse for flotation. This paper reviews the application of dielectrophoresis as a potential technique for the removal of coarse liberated gangue, thereby significantly reducing the volume of ore continuing onto fine grinding. Dielectrophoresis is the translational motion of neutral matter caused by polarisation effects in a non-uniform electric field.

A simple apparatus has been constructed, in which the deflection of a particle in a non-uniform electrical field is used to quantitatively measure the dielectrophoretic force on quartz and galena particles of various sizes. The results show that the force increases as a function of voltage squared and particle radius cubed. This technique can potentially be used to measure the effective permittivity of single mineral particles and quantify the effect of particle composition on separation.

1. Introduction

The current energy environment has resulted in efforts to decrease the amount of energy that is consumed by comminution. A study by the National Materials Advisory Board of America (1981) estimated that comminution constitutes approximately 12–15% of Australian and 3–4% of worldwide energy usage. A more recent study revised this figure to approximately 1.8% of Australia's national energy (Tromans, 2008). Troman's study used data from the Department of Energy, which estimated that beneficiation uses 39% of the total energy used in mining and minerals processing, of which 75% is accounted for by comminution DOE. Therefore, comminution accounts for approximately 29% of the total mining energy in the USA (Tromans, 2008).

Size reduction from 1 mm to 75 μm uses about 75% of the total comminution energy input. Therefore, separating out and removing 50% of waste at any size above 1 mm offers a 37% energy saving (Powell, 2008). Since conventional flotation utilises surface properties, coarse particle (above about 0.5 mm) flotation of metal sulphides is not currently possible, therefore an alternative coarse separation process is required that utilises a bulk, volumetric property.

It is possible that dielectrophoresis can efficiently remove coarse (between 0.5 mm and 2 mm) liberated gangue particles thereby reducing energy in fine grinding. Dielectrophoresis is a separation technique that uses non-uniform electrical fields to separate particles of differing permittivity. The permittivity (or dielectric constant) of a material is a bulk, volumetric property that determines its polarizability in an electric field. Since the surface area to volume ratio decreases as the particle gets larger, dielectrophoresis should be more efficient for larger particles than the surface forces used in processes such as flotation and electrostatic separation. Applying a stress by a force field is also one of the most efficient separation techniques (Andres, 1980). In some cases, permittivity may be less useful as a separation property than density, magnetic susceptibility, wettability, etc.; however, it adds another useful dimension to the art of separation (Pohl, 1978).

Thales of Miletus was the first to record the effects of dielectrophoresis, in about 600BC (Pohl, 1978). His experiment involved the rubbing of amber to charge it and attract insulated (dust and fluff) particles. Hatfield (1924a) was the first to apply dielectrophoresis to minerals processing. The basic principle involved using a liquid with a permittivity between the two components in order to push the low permittivity elements towards the weaker region of an electrical field, while at the same time attracting the high permittivity elements towards the stronger region of the field. Although many changes have since been made in the design of dielectric separators, the fundamental principles of dielectrophoresis have remained constant since Hatfield's early experiments.

The design of the dielectric separator has gone through many phases from precipitation-type, to isomotive, to screen-type and most recently the travelling-wave separators. Contemporary

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dielectric separation may be enhanced by the adjustment of the frequency, temperature or the electrical conductivity of the liquid dielectric (Andres, 1996). However, the major issue standing in the way of dielectrophoresis is the absence of a suitable medium with a variable permittivity, low conductivity and a high breakdown threshold which is also safe and environmentally friendly.

2. Theory

2.1. Permittivity

Before discussing the theory of dielectrophoresis, an understanding of the underlying physical property, permittivity, is required. The permittivity of a substance is an electrical property that determines its polarizability in an electrical field. It can also be referred to as the dielectric constant, dielectric permeability, electric susceptibility or electrical polarizability, but for consistency, permittivity will be used throughout this paper. Dielectrophoresis uses differences in permittivity in order to separate particles.

The main factors that determine the permittivity of a material are the density and ease of charge displacement which in turn depend on the atomic weight, coordination number, etc. There is, therefore, a relationship between mineralogy and permittivity (see Fig. 1). Sulphide minerals in general have much higher permittivities (5–230) than all other mineral groups due to the combination of the sulphur anion with a highly polarisable cation (Parkhomenko, 1967). Oxides have intermediate permittivities, with a few exceptions such as rutile. All the other mineral group tend to have permittivity in the low to very low range, averaging between 6 and 9. Textural factors (i.e. matrix vs. mixture) are very important in determining both the permittivity and resistivity of rock samples (Parkhomenko, 1967).

Permittivity is difficult to measure, especially for sulphides, because it depends not only on the chemical makeup, but also the frequency and temperature at which the measurement is made, as well as the crystallographic direction. Low frequency permittivity measurements compiled from the literature are given in Tables 1 and 2.

When two miscible liquids are combined, the permittivity of the mixture is a simple weighted average of the two liquid's permittivities. Solid mixtures, however, are more complex and show a non-linear relationship. This is due to interfacial and space-charge polarisation which causes large-scale field distortions through build up of space charges in the volume or of surface charges at the interfaces (Von Hippel, 1954).

There are many different equations that can be used to describe how the permittivity of a solid mixture changes with the volume fraction and permittivity of each phase (see Table 3). The Lichtenecker, Looyenga (Landau–Lifchitz) and Brown equations can all be used to model binary mixtures of minerals in a particle. Sharif (1995) used the Looyenga equation to predict the permittivity of dust with various compositions. Zheng et al. (2005) used the Lichtenecker's mixture formula to calculate the permittivity of mineral powders in a polythene matrix. Briggs (1992) modelled the permittivity of mixtures of mineral sands using the Looyenga and Brown models and found that the Looyenga equation fitted the data better. Fig. 2 shows a comparison between the Lichtenecker, Looyenga and Brown mixing equations applied to the composition of galena (permittivity 190) in a quartz (permittivity 4) matrix. The Looyenga and Lichtenecker mixing models show a gradual increase in permittivity as the galena ratio increases. This gradual increase means that a large volume of high permittivity material is required to change mixture permittivity significantly. The Looyenga model has a relationship that is closest to linearity. The Brown model is able to fit mixtures with smaller permittivity differences, however, for galena and quartz the mixture permittivity is negative for compositions of less than 20% galena. Further research is required to investigate which of these models best describes the permittivity of semi-liberated mineral particles.

In order to understand the effect of composition on dielectrophoretic force, the Clausius–Mossotti function (Eq. (3)) was evaluated as a function of medium permittivity (Fig. 3). It can be seen theoretically that particles of different galena to quartz ratio can be separated from each other simply by altering the medium permittivity. It also shows that as the medium permittivity is increased, the dielectrophoretic force increases until a maximum is reached, at which point it decreases, intercepting the *x*-axis when the medium permittivity equals the particle permittivity. Experimental work is currently investigating whether these theoretical results can be reproduced in practice.

2.2. Dielectrophoresis

Dielectrophoresis can be defined as the translational motion of neutral matter caused by polarisation effects in a non-uniform electric field. When a neutral particle is polarised by a non-uniform electric field, the two charges on the body are equal, but the fields operating on the two regions are unequal creating a force impelling

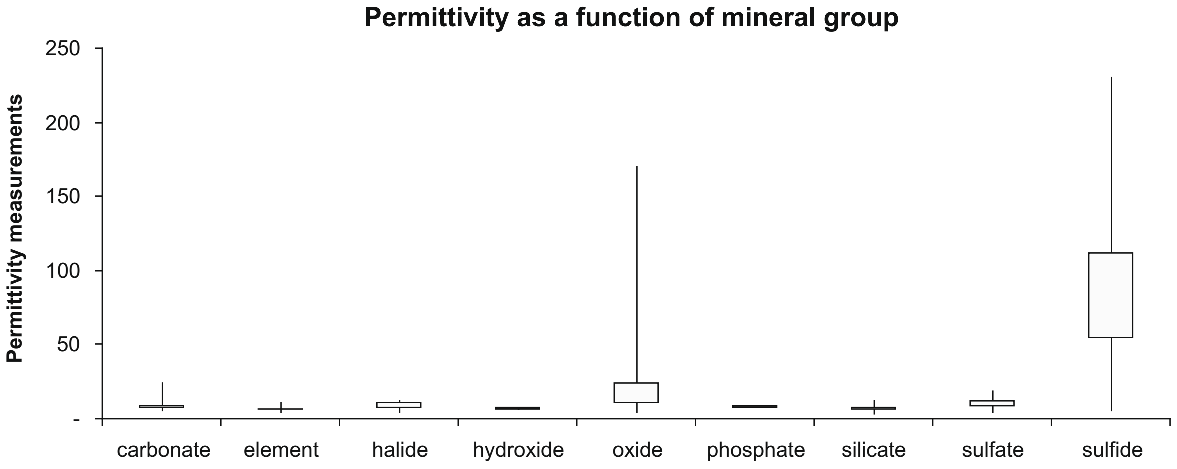

Fig. 1. Box plot of permittivity as a function of mineral group (Berg, 1936; Church et al., 1988; Cumbane et al., 2008; Goossens and Van Biesen, 1989; Keller, 1981; Parkhomenko, 1967; Salsman, 1991; Tarjan, 1986; Tickell, 1931; Young and Frederikse, 1973; Jordan and Sullivan, 1985).