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Particle separation by horizontal deflection in paramagnetic fluid

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ABSTRACT

This paper describes the horizontal deflection behaviour of the streams of particles in paramagnetic fluids under a high-gradient superconducting magnetic field, which is the continued work on the exploration of particle magneto-Archimedes levitation. Based on the previous work on the horizontal deflection of a single particle, a glass box and collector had been designed to observe the movement of particle group in paramagnetic fluids. To get the exact separation efficiency, the method of "sink–float" involved the high density fluid polytungstate (dense medium separation) and MLA (Mineral Liberation Analyser) was performed. It was found that the particles were deflected and settled at certain positions on the container floor due to the combined forces of gravity and magneto-Archimedes forces as well as a lateral buoyancy (displacement) force. Mineral particles with different densities and susceptibilities could be deflected to different positions, thus producing groups of similar types of particles. The work described here, although in its infancy, could form the basis of new approach of separating particles based on a combination of susceptibility and density.

1. Introduction

Magnetic separators exploit the difference in magnetic properties between the minerals and are used to separate valuable minerals from non-magnetic gangue, e.g. magnetite from quartz [1]. The same objective is often achieved in a very different way, the common features being a competition between a wide spectrum of forces of various magnitudes and ranges [2]. This method can be widely used in many areas such as in the separation of slurry mixed with a fine powder of α-hematite [3], physical coal cleaning [4], removal of aerosols from waste water [5], treatment of landfill [6] and others [7–9]. However, these techniques are restricted to treat ferromagnetic substances as the separation criteria are based on the repulsion/attraction in a magnetic field [10].

Since Beaugnon and Tournier succeeded in levitating water and some diamagnetic materials in 1991 [11], magnetic levitation has become one of the interesting topics in high magnetic field science where the diamagnetic levitation of bismuth [12] and the stable levitation of living frogs [13] have been reported. It has also been extended to investigate the growth of ionic crystals in a levitated solution and the levitation of molten glass without a crucible [14].

AVCO Corporation and NASA (USA) pioneered the use of ferrohydrostatic separators (FHS) in 1973 by employing a kerosene-based ferrofluid to separate automobile scrap [15].

Over the past decade a considerable amount of research has been conducted at the University of Nottingham on the levitation of particles under high magnetic gradients [16–18]. Building on previous results, this paper reports on the work conducted in separating streams of particles and minerals by horizontal deflection in paramagnetic fluids. The results show the potential of this approach to separate materials through a combination of density and/or susceptibilities.

2. Experimental procedure

2.1. Materials

2.1.1. Paramagnetic liquid

The magneto-Archimedes solution used in this chapter is $MnCl_2$ solution. Different concentrations of $MnCl_2$ solution were prepared (i.e., 2 M, 3 M and 4 M) by dissolving the $MnCl_2$ crystal in distilled water to get a clear pink solution.

The mass susceptibility of the $MnCl_2$ solution at 2 M, 3 M, 4 M can be obtained by calculation from Andres [19], which stated that the mass susceptibility of an aqueous solution of a paramagnetic salt could be obtained from the formula below [19]:

$$x_{total} = C_{salt}x_{salt} + (1-C_{salt}) \times x_{water} \quad (1)$$

$$C_{salt} = \frac{m_{salt}}{m_{total}}. \quad (2)$$

The susceptibilities of $MnCl_2$ x_{salt} and water x_{water} are given as 114×10^{-6} and -0.724×10^{-6} $cm^3.g^{-1}$ in cgs units respectively

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[19–22]. The volume susceptibility (k) of a 2 M $MnCl_2$ solution can be obtained by satisfying the following formulas as below [23]:

$$x_{salt} = \frac{m_{salt}x_{salt} + m_{water}x_{water}}{m_{salt} + m_{water}} \quad (3)$$

$$k = \rho x \times 4\pi \times 10^{-3}. \quad (4)$$

The corresponding volume magnetic susceptibility of 2 M, 3 M and 4 M $MnCl_2$ solutions was calculated and summarised in Table 1.

2.1.2. Ore mineral particles

Ore mineral materials were prepared and investigated about the separation efficiencies in this paper. They were nickel ore located at Australia, copper ore A located at South Africa and copper ore B located at Atacama Desert, Northern Chile. These particles were crashed to the various size fractions needed in experiments by Retsch milling. MLA (Mineral Liberation Analyser) was used to quantify the mineralogical characteristics of each kind of ore minerals.

The mineralogy compositions of the three kinds of ore samples obtained by MLA are listed in the following tables: Tables 2 (nickel ore), 3 (copper ore A) and 4 (copper ore B). The magnetic susceptibility values from various references are to give an understanding on how strong paramagnetic mineralogy is.

2.1.3. The preparation and properties of run-of-mine coal samples

The run-of-mine coal used in this paper is bituminous coal [24]. Bituminous coal is a soft, dense, black coal. Bituminous coal is used for generating electricity, making coke, and space heating and has calorific values ranging from 6.8 to 9 kW/kg approximately [25].

2.2. Superconducting magnet

The experiments were performed using an Oxford Instruments Minimum Condensed Volume (MCV) superconducting magnet, which had a 5 cm diameter open bore with the maximum magnet central field being about 17 T in the magnet bore, and the maximum BdB/dZ field gradient about ± 1470 T^2 m^{-1}. The picture of the superconducting magnet is shown in Fig. 1a. The maximum field strength position is about 19 cm down into the bore from the top plate of the superconducting magnet. The magnetic field strength plot is shown in Fig. 1b.

2.3. Design of glass box

As mentioned in our previous research work, the particles levitated in the magneto-Archimedes fluid were repulsed to the wall of a container in the superconducting magnet field centre area.

In order to explore this interesting behaviour a rectangular glass box was made with dimensions, 145 × 195 × 25 mm (Fig. 2a). The box was placed on top of the magnet with one of the end faces being positioned over the centre of the magnet bore. This was the point where the particles were fed or introduced in the fluid. Besides that, a collector was designed to be installed in the container and capture deflected particles as shown in Fig. 2b. The collector was put into the box during the experiment. After the particles were fed in, separation occurs (under the influence of the forces mentioned above) and they settle at different positions on the collector. The collector was then extracted from the container. The particles were collected from the collector based on several zones which depends on the distance from the magnet bore for analysis. For example, the zone of 0–40 mm means that the area on the collector is from the edge of 0 mm distance to 40 mm distance from the magnet centre displayed Fig. 2b.

Table 1
The density and volume magnetic susceptibility of different concentrations manganese(II) chloride solution.

Solution	Density (kg.m^{-3})	k × 10^{-6}
2 M manganese(II) chloride	1227	345
3 M manganese(II) chloride	1301	502
4 M manganese(II) chloride	1395	660

2.4. Heavy liquid analysis

After removing from the collector, the mixture of particles on every zone of the collector was separated by putting it into the solution of sodium polytungstate (SPT). The density of SPT solution was set to 3100 kg.m^{-3} so the sand particles in it floated and the pyrite in it sank to the bottom. The density of the SPT can be increased by vaporising or decreased by adding distilled water. In this way, the sand with a density 2650 kg.m^{-3} and pyrite with a density around 4654 kg.m^{-3} were separated and measured about the weight percentages.

3. Results and discussion

3.1. Effect of magnetic field and particle size

The size of particles and strength of the magnetic field are important factors to be investigated for the potential application of this technology. A series of experiments was carried out to study the effect of the magnetic field and particle size on the separation of pyrite and sand. During the experiments, the mixture of pyrite and sand (total 10 g) with size fraction 0.15–0.6 mm was fed into the experimental setup illustrated in Fig. 2a. The results are shown in Figs. 3 and 4 after heavy liquid analysis using SPT. Pyrite particles settled at the 0–40 mm zone due to their high density and paramagnetism, their data were not included in the graphs. So if more sand particles were deflected away from the 0 to 40 mm zone, better separation can be achieved. It can be seen from Fig. 3 that the effect of particle size (0.15–0.6 mm) on the separation of sand and pyrite was negligible.

However, the intensity of magnetic field had a strong influence on the separation of particles as shown in Fig. 4. It is possible that at a field strength of 9.5 T the sand and pyrite particles all stayed in the 0–40 mm zone so were mixed and could not be separated. Most of the sand particles were deflected into the 40–80 mm zone at 12.5 T, in this case, there was some separation of the sand and pyrite particles. When the field strength increased to 16.5 T, the sand particles were deflected to a position far from the magnet bore whilst the pyrite particles were not deflected. This resulted in a complete separation of the sand and pyrite particles.

3.2. Effect of feeding positions on particle separation

In order to optimise the operating parameters to achieve better separation, several experiments were carried out to determine the effect of the feeding position on separation. In these experiments, the injector tube is inclined to form an angle with the top board surface of the magnet as shown in Fig. 5. The angle (α) was defined as the angle between the tube and the top board surface of the magnet. The velocity of particles as they leave the tube should be zero. The end of the injection tube was above 4 M $MnCl_2$ solution surface. The injection distance shown in Fig. 5 is half of the glass box length.

As the inclined injection tube was pointing to the magnet bore, the particles would drop to the zone of the collection system which was quite close to the magnet bore centre without the magnet field. The results of sand particle deflection were shown in Fig. 6, it could be indicated that the effect of feeding position on the sand particle deflection was negligible, as more than 99% of sand particles were deflected far away from the magnetic bore centre by 3 different feeding methods.