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Direct mineral tracer activation in positron emission particle tracking of a flotation cell

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ABSTRACT

Understanding the complex interplay of physics and chemistry inside a flotation cell is the ultimate goal of most flotation research. Key to the development of a model of flotation is the ability to validate it from measurements of a real flotation system.

This work uses positron emission particle tracking (PEPT) to track directly activated mineral particles, hydrophobic and hydrophilic, in a lab-scale flotation cell. In contrast to other particle activation methods the direct activation technique allows mineral particles with their original surface characteristics to be used in PEPT experiments. In this work the flotation separation investigated was the separation of hematite from quartz from a synthetic ore using a combination of an oleic acid collector and sodium silicate depressant. This work represents the first time in which particles of typical flotation size (−106 + 90 μm diameter) with real bulk mineral properties and surface chemistry have been tracked in a flotation cell. The results illustrate small particles flow behaviour in the cell for a hydrophilic particle. The trajectory and velocities of the tracer particle are shown as it is transported inside the flotation cell.

1. Introduction

1.1. Flotation characterisation

Flotation is a common separation technique in mineral beneficiation used to process base metal ores and industrial minerals, to name but two. This separation technique has been the subject of extensive research over the past century focusing on improving the understanding of the inherent chemistry and physics which control the performance of a flotation cell (Fuerstenau et al., 2007). This subject has been thoroughly investigated in terms of the bulk and surface chemistry of mineral particle-reagent interactions, as well as two and three-phase hydrodynamic experiments and models. This work aims to add to these efforts by presenting a means of observing the motion and interaction of particles and fluid in a lab-scale flotation cell.

Within a flotation machine, the pulp and froth zones consist of three-phase dynamic suspensions of solid particles, liquid and dispersed gas bubbles. Empirical measurements (bubble size, gas velocity, froth and pulp level, *etc.*) are often used to assess the flotation process under different operating conditions (Gomez and Finch, 2007). These techniques provide important inferences on the hydrodynamic conditions within a flotation cell, however they typically rely on correlations rather than direct measurement of the conditions within a given portion of the cell. While the underlying mechanisms of particle-bubble interactions and particle recovery are well explained in literature, the operating conditions of a flotation cell (small particle sizes, high solids concentrations, opaque suspensions *etc.*) make the direct observation of these interactions difficult. Thus, techniques capable of observing particle motion in opaque systems are required, one of which is positron emission particle tracking.

1.2. Positron emission particle tracking

The technique of positron emission particle tracking (PEPT) presents an opportunity to assess particle-fluid interactions in mineral processing equipment without the need for a constrained experimental setup. This technique allows the precise localisation of a tracer to be determined over time (Parker et al., 1993). When averaged over a long period of time (based on the assumed ergodicity

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of the flotation process) this localisation data can provide useful information about particle motion and particle-fluid interactions in a flotation system (Cole et al., 2014; Cole et al., 2010a, 2010b).

PEPT uses back-to-back γ-rays emitted from a tracer particle to triangulate the location of the particle while in motion (Parker et al., 1993). A pair of γ-rays is generated from the annihilation of a single positron resulting from the β^+ decay of radioisotopes on the tracer surface (Parker and Fan, 2008). When a γ-ray pair comes into contact with a set of opposing scintillation crystals (the detector system), the two contact points define a line in space (line of response) along which the tracer particle may be assumed to lie. Positron decay is a continuous process resulting in constant yet discrete production of γ-ray pairs. The tracer location is determined by grouping a number (N) of consecutive lines of response detected over a short time interval. After grouping, an iterative routine determines the point with the shortest perpendicular distance to all lines and then rejects the lines of response furthest from this point. The iterative procedure is repeated until a given fraction (f) of the original lines remain. This ensures that the majority of the corrupt lines resulting from photon scattering, chance coincidences, *etc*., are rejected in the determination of the point location associated with a given group of lines of response. This point is assumed to be the tracer location for the given time interval.

Different radioisotopes can be used for labelling tracer particles, the most common include ^{18}F, ^{66}Ga, ^{68}Ga, ^{61}Cu and ^{64}Cu (Buffler et al., 2010; Parker and Fan, 2008). In this study, the activation method employed created particles labelled with the ^{18}F radioisotope. This radioisotope is a pure positron emitter which annihilates to produces 511 keV photons in the majority of the time (there is a small probability (~0) for higher multiplicity events which are not 511 keV) (Fan et al., 2006b). Additionally, the half-life of ^{18}F is 109 min, thereby allowing enough time for an experiment to be completed without causing any complications in the handling and disposal of used material.

Two well established centres exist with the capability to produce and track tracers for PEPT applications. The Positron Imaging Centre (PIC) at The University of Birmingham (United Kingdom), where this technique was developed, is the location where the experiments for this study were conducted. A second PEPT research centre is the iThemba LABS at The University of Cape Town (South Africa). The positron cameras available at each centre are well described in the literature (Buffler et al., 2010; Parker et al., 2002, 2009). Recently, researchers at the University of Tennessee-Knoxville have started to develop new tracking algorithms and also have access to a MicroPET P4 camera for experimental evaluation of their algorithms (Langford et al., 2016; Wiggins et al., 2016).

As PEPT allows for the observation of an experimental setup with γ-ray permeability, it can be used to track the motion of a tracer in an opaque or dense mixture so long as the set-up fits inside the field of view of the detector system. This is ideal for the observation of particle flow behaviour inside lab-scale mineral processing systems (Boucher et al., 2014; Chang et al., 2011; Govender et al., 2013; Volkwyn et al., 2011; Waters et al., 2008).

1.3. Flotation observed by PEPT

The original application of PEPT to flotation research was the direct observation of the trajectory of a pyrite particle (−250 + 200 μm) inside a lab-scale Denver flotation cell (Waters et al., 2008). The tracers used by Waters et al. (2008) were created by immersing the particle in pre-irradiated water to adsorb some of the ^{18}F present in the water. Application of this particle labelling technique has not been widely applied as surface adsorption of ions onto mineral surfaces is dependent on a variety of factors (pH, mineral surface characteristics, adsorbed ion type and concentration *etc*.). Additionally, this technique transfers only a small amount of radioactivity to a small mineral particle (limited surface area) so the quality of localisation data obtained from PEPT using this technique is quite poor compared to alternative labelling techniques.

Modification of the surface of the particle before radiolabelling has also been explored to improve tracking. This procedure relies on chemical activation of the surface using metallic ions (*e.g.* Fe^{3+}) to improve surface adsorption of radioisotopes (Fan et al., 2006a). This technique is of interest for certain systems, but has challenges in the investigation of flotation systems as the presence of additional metal cations on the surface will fundamentally alter the surface interactions of mineral particles.

Current research work is focused on developing a technique to provide small tracers with sufficient activity to be tracked in a flotation cell. The work by Cole et al. (2012) produced a tracer particle of approximately 50 μm diameter by the radiolabelling of small resin particles within a solution containing ^{68}Ga. To obtain a hydrophobic or hydrophilic surface, the resin particle was coated with even smaller mineral particles to produce a tracer with surface properties similar to a mineral particle. Similar tracking experiments were also previously conducted using galena and quartz particles coating a radioactive bead of approximately 125 μm in size (Waters et al., 2009). Recently, this technique produced tracer particles in the size range of 450–600 μm (including the coating layer) for tracking in a flotation cell (Cole et al., 2014). The minimum size achievable by this technique seems to be limited by the thickness of the coating which is approximately 60–90 μm under optimum conditions

Another option for the generation of a small tracer particle is presented in this study. This technique involves the direct activation of a large mineral particle followed by the breakage, sizing and selection of one small piece with the highest remaining activity. A summary of the small tracers used in PEPT flotation research to this day is presented in Fig. 1. It should be noted that the handling of small sticky tracers is important to consider when to minimize potential exposure. The dose rate is always carefully monitored using calibrated EPDs, and care taken to ensure that users and operators were within allowed annual dose limits at all times

1.4. Tracer production via direct activation

In the direct activation technique, a particle containing oxygen (glass, mineral, ceramic, *etc*.) is held in a target on which a 35 MeV ^{3}He beam is focused. By scanning the surface of the particle with the beam, some of the surface oxygen atoms (^{16}O) will be converted to the ^{18}F radioisotope. This results in the activation of a surface layer of approximately 300 μm in depth (Fan et al., 2006b; Parker et al., 1993). Considering the low location rate of small tracers with low activity, an advantage of using ^{18}F as a radioisotope is the short range of its emitted positron in water (0.6 mm). This is expected to provide improved tracking precision as the γ-rays are emitted at a smaller distance from the particle compared to ^{68}Ga (range of 2.9 mm) (Valk et al., 2005).

The target at the University of Birmingham is able to accommodate, in practice particles of approximately 1000 μm. This is due to difficulties in loading and unloading particles below 1000 μm due to the design of the target assembly, necessary shielding for the operator and constrained workspace available for particle manipulation. An additional limitation to directly activating particles below 1000 μm in diameter is the requirement for thermal energy dissipation by the particle inside the target. The particle in the beam experiences local surface temperatures that may reach thousands of degrees and in many cases exceed the materials melting