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Phase distribution identification in the column leaching of low grade ores using MRI

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ABSTRACT

Heap bioleaching is gaining importance as an approach for the recovery of valuable metals (e.g. Cu^{2+}) from low grade ores. In this process iron and/or sulfur oxidising microorganisms are used to aid the oxidation of base metal sulfides in the ore, thereby liberating the metal ions into solution. Leach performance is strongly influenced by the contacting of the leach solution and the ore particles. In order to better understand the distribution of the leaching solution on the pore scale in these heaps, Magnetic Resonance Imaging (MRI) was used to acquire images non-invasively of a section of an irrigated ore bed. This was made possible by the use of specialist MRI acquisition sequences suited to the magnetically heterogeneous environment as presented by the ore material. From the images we were able to determine the pore-occupancy of the liquid and gas phases and to provide novel measurement of the interfacial area between air, leach solution and ore.

1. Introduction

In recent decades heap bioleaching has become an established method for the extraction of copper and other base metals from low grade ore (Brierley, 2008). The growth in the importance of bioleaching has lead to a greatly improved understanding of the processes and microorganisms involved. Still, there are a number of challenges associated with heap leaching in general, many of which are the result of the sheer size of the heaps combined with their inhomogeneous nature. This study focuses on the issue of heap hydrology, with a specific interest in how the liquid is distributed through the packed ore.

Solution flow in heaps needs to be fast enough to ensure that leaching occurs in an economically feasible time period, while the flow must also be sufficiently uniform that areas of the heap are not left unleached. However, heaps are unsaturated systems of often highly inhomogeneous nature which makes the hydrology of the leaching systems complex and spatially variable, leading to issues such as flooding and preferential flow (O'Kane Consultants Inc., 2000). Most of the studies done on heap hydrology have adopted a macroscopic approach via analysis of heap feed and effluent and have focused primarily on the issue of preferential flow and on the development of models to predict heap hydrodynamics. The research group of Lin and Miller took a microscopic experimental approach, using X-ray computed tomography (CT) to image leaching systems before and after leaching (Lin et al., 2005). X-ray CT however provides limited signal contrast between the air and liquid phases in the presence of comparatively high density solids. In the context of bioleaching X-ray radiation could also sterilise the column. Hence complementary methods for real time imaging and analysis of the liquid flow in leaching systems are desirable.

The application of Magnetic Resonance Imaging (MRI) to heap leaching has the potential to provide additional measurement capability by acquiring 3D images of the liquid in an ore-packed column non-invasively as a leach progresses. It can readily differentiate between air and water, as signal is only detected from the water. MRI would not typically be thought of as a viable tomographic technology for use with such ores because the high concentration of ferro- and para-magnetic species in the ore and leach solution may cause significant image distortions due to magnetic susceptibility gradients and other physical effects. It has been found that such image distortions can be minimised through the use of Spin Echo Single Point Imaging (SESPI), a specialist MRI acquisition sequence (Ouriadov et al., 2004). In a previous study we have shown via direct, unambiguous comparison with X-ray CT images of saturated ore beds that the SESPI technique is compatible with the ore material used and is able to provide accurate and hence quantitative images (Fagan et al., 2012). This compatibility with the ore is largely because the spatial dependence of the signal is phase encoded during SESPI and thus measurement

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of the time evolution of the signal (as is the case for conventional MRI pulse sequences) is avoided. As a result, the extent to which chemical shift, magnetic susceptibility and dipolar and quadrupolar image distortions are observed is significantly reduced, a phenomenon that is described in detail in Gravina and Cory (1994).

The aim of the current study is to use SESPI to acquire images of a flowing, partially saturated ore column. These images are used with images of a fully flooded column to produce a 3D phase map to illustrate the relative positions of the gas, liquid and solid phases within the column. This map is used subsequently to quantify various parameters characterising the system hydrodynamics including holdup, contact between phases and distribution of phases with respect to the solid matrix.

2. Materials and methods

2.1. Leaching column

Low grade copper ore was used in the experiments. It had an average composition of 2.95% Fe, 0.69% Cu and 2.02% S on a weight basis. The particle size distribution, measured by sieving, is given in Table 1. The ore (400 g) was agglomerated with 20 ml of 0.1 M sulfuric acid and packed into the column illustrated in Fig. 1. The inner diameter of the column was 50 mm which was restricted by the magnet's internal bore. The total height of the ore bed was 135 mm and the gravimetric voidage of the packed ore was found to be 38.5 ± 0.8%. Distilled water was used for the liquid phase. The column was irrigated drip-wise from the top at a rate of 40 ml h^{-1} during the main flowing experiment as well as at 20 ml h^{-1} and 60 ml h^{-1}. This is approximately equivalent to 10, 20 and 30 L m^{-2} h^{-1}. The system was allowed 2 h to stabilise before any images were acquired, at which point the outlet flow rate matched the inlet. For the flooded images, water was used to fully saturate the bed.

2.2. Magnetic resonance imaging

Imaging was conducted on a Bruker DMX 200 4.7 T vertical-bore spectrometer with an RF coil with internal diameter of 63 mm and an imaging region of approximately 70 mm in length. A single echo per excitation SESPI pulse sequence with split phase-encoding gradients was used. Further details can be found in Fagan et al. (2012). The field of view was 60 mm × 60 mm in the horizontal plane (x and y) and 72 mm in the vertical direction (z). The acquisition size was 64 × 64 × 32, which corresponded to a resolution of 938 μm in the horizontal plane and 2250 μm in the vertical plane. The resolution was limited by the maximum allowable gradient strengths and time restrictions. The acquisitions had a repeat time (TR) of 50 ms, a total gradient encoding time (t_p) of 350 μs and an echo time (TE) of 870 μs. Four repeat scans were done for phase cycling and eight points were acquired along the echoes and added together in order to improve the final signal to noise ratio (SNR).

Table 1
Particle size distribution for the ore used in the leaching column.

Size (mm)	Weight (%)
>13.2	13.9
13.2–9.5	18.4
9.5–5.6	20.3
5.6–2.0	19.8
2.0–0.71	9.1
<0.71	18.5

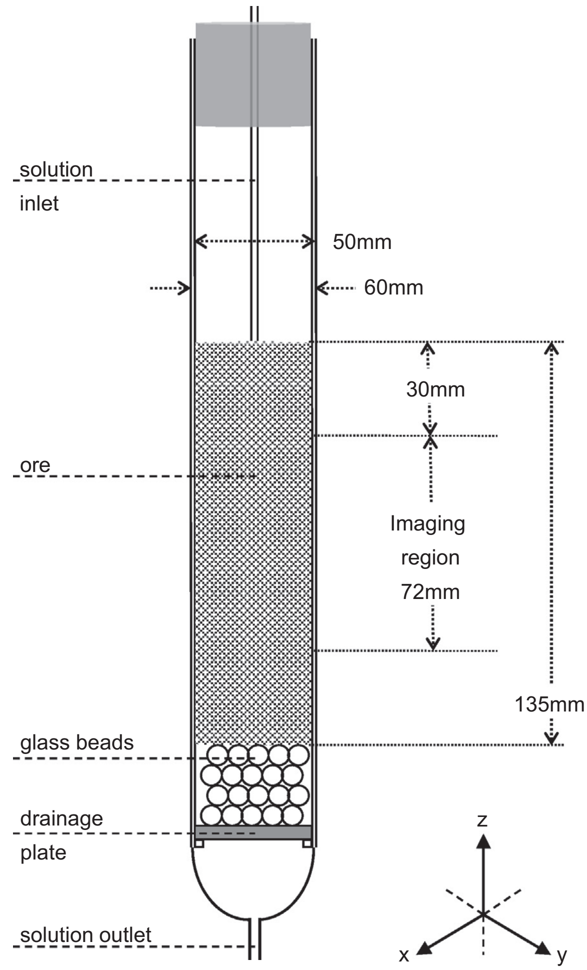

Fig. 1. Schematic of the leaching column with the ore bed and imaging region heights indicated.

3. Results and discussion

3.1. Production of phase map

Since signal in the MRI images is obtained only from the liquid phase, the flooded column images could be used to identify the void space within the column whilst the flowing images only showed where the solution was present in the partially saturated system. The positions of the solid, liquid and gas phases could therefore be identified by combining the two acquisitions to produce a 3D phase map (Sederman and Gladden, 2001). Fig. 2a shows a representative 2D slice (from the 3D image) of the flooded column, binary gated to liquid (white) and solid ore (black) in Fig. 2b. The corresponding slice for the unsaturated 40 ml h^{-1} flowing system is shown in Fig. 2c with the binary gated image shown in Fig. 2d (here black indicates solid ore or air). By addition of Fig. 2b and d we produced Fig. 2e, a phase map where white represents the gas phase, grey is the liquid phase and black is the solid ore phase or outside the sample. In the phase map we had to account for partial volume effects where pixels are occupied by more than one phase. They were identified as those pixels that were assigned to be non-void (solid) pixels in the flooded image gating, but were subsequently identified as being occupied by liquid in the flowing system images. It was not possible to determine what fraction of these pixels was liquid filled, therefore two boundary scenarios were considered for the calculation of the various phase distribution properties. In the one case the partial volume pixels were assumed to be liquid