Hydrometallurgy 158 (2015) 157–164

Contents lists available at ScienceDirect

Hydrometallurgy

journal homepage: www.elsevier.com/locate/hydromet

Magnetic resonance imaging characterisation of the influence of flowrate on liquid distribution in drip irrigated heap leaching

Marijke A. Fagan-Endres [a,b,*], Susan T.L. Harrison [b], Michael L. Johns [c], Andrew J. Sederman [a]

[a] Department of Chemical Engineering and Biotechnology, University of Cambridge, Pembroke Street, Cambridge CB2 3RA, UK
[b] Centre for Bioprocess Engineering Research, Department of Chemical Engineering, University of Cape Town, Rondebosch 7701, South Africa
[c] School of Mechanical and Chemical Engineering, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form 25 September 2015
Accepted 3 October 2015
Available online 9 October 2015

Keywords:
MRI
Heap leaching
Hydrometallurgy
Flowrate
Interfacial area
Irrigation

ABSTRACT

Liquid irrigation is one of the key process control parameters following the construction of an ore leaching heap. This study uses 3D magnetic resonance imaging (MRI) to examine non-invasively the effect of liquid flowrate changes on heap hydrology when drip irrigation is used. Experimental results from a vertical column show that the increase in flowrate causes an increase in the number of rivulets in the ore bed. The new rivulets were found to be thicker, and their development caused an increase in liquid–solid contacting area which is considered advantageous for metal ion recovery. Experiments performed on larger samples showed that the effects of flowrate changes were limited to the region directly below the drip emitter because the increase in flowrate caused an increase in macro-pore flow and not capillary retention of liquid. Therefore the increase in flowrate was not found to perturb liquid distribution patterns in a way that would be substantially advantageous to heap leaching recoveries.

1. Introduction

Heap leaching is a (bio)hydrometallurgical extraction technique that is commonly used for the recovery of copper from low grade ores and for the pre-treatment of gold ores to oxidise metal sulphides (e.g. iron and arsenic) prior to cyanidation. The ore to be processed is crushed and typically agglomerated to improve the particle homogeneity before it is packed into large heaps which may be hundreds of metres in length and breadth and up to 20 m in height. In operation the heaps are unsaturated systems which are irrigated from the top with an acidic leaching solution and aerated from the base to supply sufficient oxygen for the leaching reactions and, in the case of bioleaching, carbon dioxide for microorganisms in the heap to fix as biomass. It is in the liquid/solid interphase that the leaching reactions occur, thus contacting of the ore with the liquid is essential to metal recovery. The leaching solution flows downwards through the ore bed under gravity and is collected at the base at which stage it is termed the pregnant leach solution (PLS). The liberated metal ions are transported out of the heap by this flowing liquid, hence the relative distribution of the flowing and stagnant liquid hold-up has a substantial influence on the efficiency of the process. The liquid phase holds further importance in bioleaching operations because it is where the sulfur- and iron-oxidising microorganisms populate.

The liquid feed application is one of the only process control parameters following the construction of the heap. Consequently it is desirable to understand the effect of flowrate changes on the liquid distribution. Heaps are typically irrigated via drip emitters spaced in a 0.5 to 1 m grid-structure and the applied liquid fluxes range between 4 and 18 L m^{-2} h^{-1} (Petersen and Dixon, 2007). Flowrates that are too high can cause short circuiting of the liquid and flooding which deprives the system of oxygen. It can also result in a dilute PLS thereby increasing the difficulty and cost of recovery. On the other hand, flowrates that are too low can result in excessively long leaching times and in extreme cases the heap may dry out. The flowrate also affects the microbial populations in biological heap leaching systems with Chiume et al. (2012) having demonstrated that faster colonisation of the ore in laboratory columns occurs at lower flowrates, attributed to the reduced detachment of cells and a potential response to nutrient concentration and the degree of oxygen saturation of the liquid.

The choice of flowrate is further complicated by the inhomogeneity of the ore particles and the overall heap structure coupled with the complex nature of unsaturated fluid flow. Liquid distribution in heaps occurs via two mechanisms: gravitational flow downwards through the heap in larger channels and dispersion of the liquid under capillary forces. Capillary distribution of the liquid is the slower of the two and largely accounts for lateral movement of the liquid. This can result in poor wetting of heaps overall, with preferential flow channels forming in

---

* Corresponding author.
E-mail addresses: marijke.fagan-endres@uct.ac.za (M.A. Fagan-Endres), sue.harrison@uct.ac.za (S.T.L. Harrison), michael.johns@uwa.edu.au (M.L. Johns), ajs40@cam.ac.uk (A.J. Sederman).

http://dx.doi.org/10.1016/j.hydromet.2015.10.003

the regions below the drip emitters and poor recovery of the desired metals being achieved in the remaining regions (O'Kane Consultants Inc., 2000; Petersen and Dixon, 2003; van Hille et al., 2010). This is well demonstrated in the photographs of a heap cross-section in Petersen and Dixon (2003) which shows clear evidence of solution channels below the drip emitters.

Optimisation of heap irrigation has been approached through a number of studies aimed at improving the understanding of heap hydrodynamics. Direct comparison of heap wetting with trickle bed reactors, as are commonly applied in chemical engineering processes, is not possible due to the comparatively slower flows used in heap leaching (Bouffard and Dixon, 2001). Some success has been had in relating heap hydrodynamics to unsaturated soil theory, based on Darcy's law, specifically with respect to describing how flowrate relates to preferential flow through regions of different particle sizes (Bartlett, 1998; Decker and Tyler, 1999; O'Kane Consultants Inc., 2000; Wu et al., 2007). Gravimetric and tracer studies have also aided the design and validation of mathematical models to describe heap performance (Bouffard and Dixon, 2001; Bouffard and West-Sells, 2009; De Andrade Lima, 2006; Ilankoon and Neethling, 2012). However a limitation of these studies is that they are all ‘black-box’ techniques which only allow for approximations of the heap hydrodynamics. Furthermore, laboratory scale studies tend to underestimate the degree of inhomogeneity that is present at full scale operation. This is highlighted by the industrial scale investigations by Guzman et al. (2006) that used Electric Resistivity Tomography (ERT) to measure moisture content throughout a series of heaps. They reported pronounced heterogeneous solution distribution in the heaps and found that this significantly impacted the metal recovery rate and the uniformity of extraction and concluded the core issue in sulfide leaching is reagent delivery rather than leaching kinetics.

We have shown in a previous study that maps of the liquid distribution in representative leaching systems can be acquired using a specialist magnetic resonance imaging (MRI) technique called spin echo single point imaging (SESPI) which is immune to the detrimental influence of para- and ferromagnetic species in the ore (Fagan et al., 2013; Fagan et al., 2012) and is able to detect liquid both external and internal to the ore. This technique may be used to determine the liquid distribution and position relative to the solid ore and through analysis of temporal changes in signal magnitude, changes in the flow patterns in the bed may be projected.

The aim of this paper is to use this approach to quantify the effect of flowrate changes on liquid distribution in representative drip irrigated heap leaching systems, applying the techniques developed in Fagan et al. (2013). Two aspects are considered: the liquid flow in a leaching column at steady state and the transient liquid distribution in the immediate vicinity of the drip irrigation point source using a setup with a greater ore bed breadth. The desired application is to ascertain if a change in flowrate can be used to manipulate liquid flow in a packed bed in order to facilitate improved liquid distribution and hence contacting of the leaching solution with the ore.

2. Materials and methods

2.1. Ore

A low grade copper ore (average composition 2.95% Fe, 0.69% Cu and 2.02% S by weight) which had a particle size distribution as detailed in Table 1 was used in the experiments. The average internal porosity of the ore was 4.6%. The ore was agglomerated with 0.1 M sulfuric acid using a liquid to ore ratio of 5 mL per 100 g.

2.2. Column leaching experiment

2.2.1. Preparation and operation

A sample of agglomerated ore (600 g) was packed into the glass column shown schematically in Fig. 1, the inner diameter of which was restricted to 50 mm by the spectrometer's internal bore. The gravimetric voidage of the packed ore was determined to be 38.0 ± 0.8% by flooding the column from the base upwards following construction of the bed, after which the column was drained. The bed was irrigated drip-wise using a peristaltic pump at flowrates of 10, 20 and 40 mL h^{-1}, approximately equivalent to 5, 10 and 20 L m^{-2} h^{-1}. The liquid feed was water that had been doped with 0.8 g L^{-1} of $GdCl_3 \cdot 6H_2O$ in order to shorten the MRI acquisition time. The system was considered to have reached steady state at each flowrate when the outlet and inlet flows matched. A minimum of 12 h was allowed once the bed had achieved this condition before any MRI experiments were conducted. The liquid hold-up was determined gravimetrically at the steady state condition for each flowrate by performing a balance on the liquid based on the approach of Bouffard and Dixon (2001). This accounted for the agglomeration liquid, the liquid that had been added to the column (during flooding and subsequent irrigation) and the liquid that had been drained from the column (drainage following flooding and subsequent drainage during normal unsaturated irrigation). Following acquisition of all desired data at a given flowrate, the flowrate was stepped up to the next highest rate without any disruption in the flow and steady state allowed to re-establish.

Table 1
Particle size distribution for the ore.

Size (mm)	Weight (%)
25.4–13.2	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

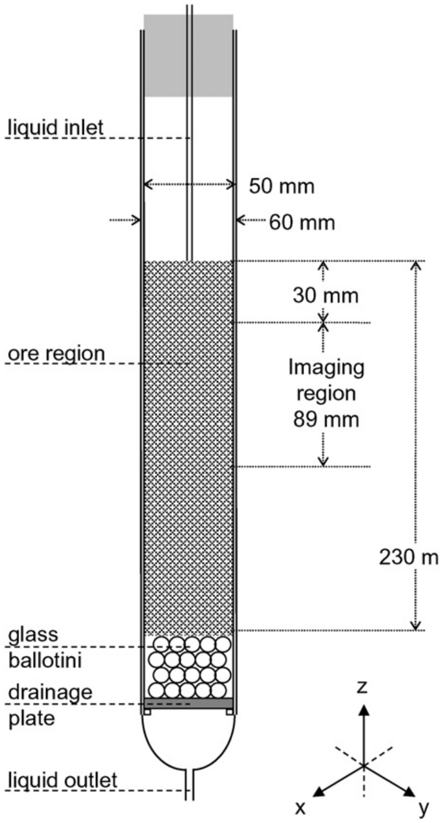

Fig. 1. Schematic of the leaching column with the ore bed and imaging region heights indicated.